

Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region

A Compilation of Scientific Literature

Final Report

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EXECUTIVE SUMMARY

This report provides a first-ever compilation of what is known—and not known—about climate change effects on marine and coastal ecosystems in the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). The U.S. Fish & Wildlife Service funded this report to help inform members of the newly established NPLCC as they assess priorities and begin operations. Production of this report was guided by University of Washington’s Climate Impacts Group and information was drawn from more than 250 documents and more than 100 interviews.

Information in this report focuses on the NPLCC region, which extends from Kenai Peninsula in southcentral Alaska to Bodega Bay in northern California west of the Cascade Mountain Range and Coast Mountains. The region contains approximately 38,200 miles (~ 61,500 km)¹ of coastline and is home to iconic salmon and orca, a thriving fish and shellfish industry, and a wide range of habitats essential for the survival of fish, wildlife, birds, and other organisms. Many of these species, habitats, and ecosystems are already experiencing the effects of a changing climate.

Carbon dioxide, temperature, and precipitation

The atmospheric concentration of carbon dioxide (CO₂) is increasing in the earth’s atmosphere, leading to increases in temperature, altered precipitation patterns, and consequent effects for biophysical processes, ecosystems, and species.

- **Atmospheric CO₂ concentrations have increased** to ~392 parts per million (ppm)² from the pre-industrial value of 278 ppm,³ higher than any level in the past 650,000 years.⁴ By 2100, CO₂ concentrations are projected to exceed ~600 ppm and may exceed 1000 ppm.⁵ As CO₂ levels increase, a concomitant decline in ocean pH is projected for the NPLCC region,⁶ hampering calcification processes for many calcifying organisms such as pteropods,⁷ corals, and mollusks.⁸
- **Annual average temperatures increased** ~1-2°F (~0.6-1°C) from coastal British Columbia to northwestern California over the 20th century⁹ and 3.4°F (~1.9°C) in Alaska from 1949 to 2009.¹⁰ By 2100, the range of projected increases in the NPLCC region varies from 2.7 to 13°F (1.5-7.2°C), with the largest increases projected in Alaska.¹¹ These temperature increases will drive a rise in sea surface temperature and contribute to declining oxygen solubility in seawater,¹² species range shifts,¹³ and potential uncoupling of phenological interdependencies among species.¹⁴
- **Seasonal precipitation varies but is generally wetter in winter.** Cool season precipitation (Oct-March) increased 2.17 inches (5.51 cm) in Alaska from the 1971-2000 to 1981-2010 period.¹⁵ In Washington and Oregon winter precipitation (Jan-March) increased 2.47 inches (6.27 cm) from 1920 to 2000.¹⁶ In California, winter precipitation increased between 1925 and 2008,¹⁷ while in British Columbia, both increases and decreases in winter precipitation were observed, depending on the time period studied.¹⁸ Over the 21st Century, winter and fall precipitation are projected to increase 6-11% in BC and 8% in Washington and Oregon, while summer precipitation is projected to decrease (-8 to -13% in BC and -14% in WA and OR).¹⁹ In southeast Alaska, however, warm season precipitation is projected to increase 5.7%.²⁰ Projected increases in winter rainfall, declining snow accumulation²¹ and glacial extent,²² and decreased summer precipitation (where occurring) will shift the frequency, volume,²³ and timing²⁴ of freshwater inflow to marine systems. Coastal areas with enhanced riverine input such as the Columbia River estuary will see

greater stratification associated with increases in precipitation,²⁵ a condition that exacerbates low-oxygen conditions associated with harmful algal blooms and hypoxic waters.²⁶

Impacts of climate change on marine and coastal systems

Increases in CO₂ and air temperature, combined with changing precipitation patterns, are already altering conditions and processes in marine and coastal ecosystems. These trends are projected to continue.

- **The oceans are increasing in acidity.** Increasing atmospheric CO₂ concentrations have caused global ocean pH to decline from 8.2 to 8.1 since pre-industrial times, increasing the ocean's acidity by approximately 26%.²⁷ pH declines in the NPLCC region are generally consistent with those observed globally, although some coastal areas such as Hood Canal (WA) report significantly lower pH (less than 7.6 in 2008).²⁸ By the end of this century, global surface water pH is projected to drop to approximately 7.8, increasing the ocean's acidity by about 150% relative to the beginning of the industrial era.²⁹ If atmospheric CO₂ levels reach 550 ppm, pH in the NPLCC region is projected to decline approximately 0.14 units³⁰ and the saturation state of aragonite will approach the critical threshold for undersaturation ($\Omega < 1$), below which the shells of some marine organisms may begin to dissolve or have difficulty forming.³¹ Ocean water detrimental to shell-making has already been observed in shallow waters from Queen Charlotte Sound (BC) south to Baja California.³² Aragonite-shelled pteropods, which are prey for salmon³³ and other fish,³⁴ appear particularly vulnerable to continued ocean acidification.³⁵
- **Sea surface temperatures are rising.** Global mean sea surface temperature (SST) increased approximately 1.1 °F (0.6 °C) since 1950.³⁶ By 2050, an increase in winter SST of 1.8 to 2.9 °F (1.0-1.6 °C) is projected for most of the northern Pacific Ocean (compared to 1980-1999).³⁷ Warmer SST contributes to sea level rise, increased storm intensity, and greater stratification of the water column.³⁸ Increased SST is also associated with species range shifts,³⁹ altered nutrient availability and primary production,⁴⁰ and changes in algal, plankton and fish abundance in high-latitude oceans.⁴¹
- **Storm intensity and extreme wave heights are projected to increase.** Off the Oregon and Washington coasts, the heights of extreme storm waves increased as much as eight feet since the mid-1980s and deliver 65% more force when they come ashore.⁴² During the 21st century, extra-tropical storms are likely to become more intense in the NPLCC region.⁴³ This will combine with higher sea levels to increase storm surges, the height of extreme waves⁴⁴ and the frequency of extreme events.⁴⁵ Increased extreme wave heights and more intense storms are projected to increase beach and bluff erosion⁴⁶ and lead to shoreline retreat,⁴⁷ loss of coastal habitat,⁴⁸ and damage to coastal infrastructure.⁴⁹
- **Sea levels are rising, but the relative effect varies by location.** Since the end of the 19th century global sea levels have risen approximately 6.7 inches (17 cm).⁵⁰ In the NPLCC region, however, relative sea level change from 1898 to 2007 ranges from -0.67 to +0.23 inches/yr (-1.7 to 0.575 mm/yr).⁵¹ Relative sea level rise in the NPLCC region is less than the global average at most monitoring stations because of localized increases in land elevation as a result of glacier recession, plate tectonics, and/or sediment accretion.⁵² By the end of the 21st century, global sea level is projected to increase 5.1 to 70.0 inches (13-179 cm) compared to the end of the 20th century.⁵³ In the NPLCC region by 2100, relative change in sea levels are projected to range from

-25.2 inches (-64 cm) to +55 inches (+139.7 cm).⁵⁴ Sea level is projected to rise in British Columbia and parts of Washington, Oregon, and California,⁵⁵ while sea level is projected to decline or remain relatively stable in southcentral and southeast Alaska and the northwest Olympic Peninsula (WA).⁵⁶ Rising sea level often results in loss of nearshore or coastal habitat⁵⁷ and harm to dependent species.⁵⁸

- **Recent anomalous hypoxic events in the California Current Ecosystem may be characteristic of future change.** Severe hypoxia, corresponding to dissolved oxygen (DO) levels ranging from 0.21 to 1.57 mL/L, was observed off the central Oregon coast in 2002.⁵⁹ Dungeness crab surveys showed mortality rates of up to 75% in some regions during this period.⁶⁰ In 2006 off the Washington coast, the lowest DO concentrations to-date (<0.5 mL/L) were recorded at the inner shelf.⁶¹ During an anoxic event in 2006 off the Oregon coast, surveys revealed the complete absence of all fish from rocky reefs⁶² and near-complete mortality of macroscopic benthic invertebrates.⁶³ While anomalous events such as these are consistent with potential climate-induced changes in coastal systems, it has not been shown that climate change is the cause of the anomalies.⁶⁴

Implications of climate change for ecosystems, habitats, and species

Climate change effects, independently or in combination, are fundamentally altering ocean ecosystems.⁶⁵ Effects on habitats (habitat loss and transition) and species (invasive species interactions, range shifts and phenological decoupling) are highlighted here.

Coastal Erosion and Habitat Loss

Rising sea-level and increases in storms and erosion are projected to result in significant habitat impacts. In Alaska, low-lying habitats critical to the productivity and welfare of coastal dependent species could be lost or degraded,⁶⁶ including staging areas that support millions of shorebirds, geese, and ducks.⁶⁷ As sea level rises along Puget Sound's armored beach shorelines, most surf smelt spawning habitat is likely to be lost by 2100.⁶⁸ In Skagit Delta marshes (WA), the rearing capacity for threatened juvenile Chinook salmon is projected to decline by 211,000 fish with 18 inches (45 cm) of sea level rise.⁶⁹

Habitat loss due to sea level rise is likely to vary substantially depending on geomorphology and other factors. In Washington and Oregon, analysis of coastal habitats under 27.3 inches (0.69 m) of sea level rise projects loss of two-thirds of low tidal areas in Willapa Bay and Grays Harbor and a loss of 11 to 56% of freshwater tidal marsh in Grays Harbor, Puget Sound, and Willapa Bay.⁷⁰ Much of these habitats are replaced by transitional marsh.⁷¹ However, the Lower Columbia River may be fairly resilient to sea level rise because losses to low tidal, saltmarsh, and freshwater tidal habitats are minimized (-2%, -19%, -11%, respectively), while gains in transitional areas are substantial (+160%).⁷²

Invasive Species, Range Shifts, and Altered Phenology

Climate change will affect species in varying ways. Ocean acidification significantly and negatively impacts survival, calcification, growth and reproduction in many marine organisms, but thus far, has no significant effect on photosynthesis.⁷³ Among calcifying organisms, corals, calcifying algae, coccolithophores, and mollusks are negatively affected, while crustaceans and echinoderms are positively affected.⁷⁴ Warmer waters are likely to promote increased populations of Pacific salmon in Alaska while promoting decreased populations elsewhere in the NPLCC region.⁷⁵ If oxygen levels decline⁷⁶ and coastal upwelling strengthens as some studies project,⁷⁷ oxygenated habitat will be lost.⁷⁸ A few species, such as

sablefish and some rock fishes, tolerate low-oxygen conditions and may expand their territory.⁷⁹ However, most species will be forced to find shallower habitat or perish.⁸⁰ Overall, smaller specimens seem to be the winners under low-oxygen conditions, as they outcompete larger organisms due to their advantageous body-mass to oxygen-consumption ratio.⁸¹

Many sea and shorebirds have medium or high vulnerability to climate change.⁸² These include the Aleutian Tern, Kittlitz's Murrelet,⁸³ beach-nesting black oystercatchers,⁸⁴ and the Cassin's auklet.⁸⁵ For coastal birds, loss of habitat and food sources are the largest climate change-related concerns.⁸⁶ Reproductive failure among seabirds has been documented as a result of changes in marine productivity, often observed during El Niño years when sea surface temperatures are warmer than average.⁸⁷ Population recovery is less likely if climate change results in catastrophic events that are more frequent, more intense, or of longer duration.⁸⁸

Climate change may enhance environmental conditions such that some species are able to survive in new locations, known invasive species expand into new territories, and species that currently are not considered invasive could become invasive, causing significant impacts.⁸⁹ Invasive and non-native species that appear to benefit from climate change include *Spartina*, Japanese eelgrass, and New Zealand mud snail.⁹⁰

In response to warming temperatures and changing currents, many marine species are expanding their ranges toward the poles.⁹¹ The abundance and distribution of jumbo squid in the NPLCC region increased between 2002 and 2006, with sightings as far north as southeast Alaska.⁹² Loggerhead turtle, brown pelican, and sunfish are reported recent arrivals to the northern Washington coast.⁹³

Climate change may also lead to significant phenological decoupling, such as occurred in the Pacific Northwest in 2005 when the upwelling season occurred three months later than usual, resulting in a lack of significant plankton production until August (rather than the usual April-May time period).⁹⁴ The delay was accompanied by recruitment failure among plankton-reliant rockfish species, low survival of coho and Chinook salmon, complete nesting failure by Cassin's Auklet, and widespread deaths of other seabirds (common murre, sooty shearwaters).⁹⁵ Similar mismatches also occurred in 2006 and 2007 when upwelling began early but was interrupted at a critical time (May-June).⁹⁶

As a result of these effects, novel assemblages of organisms will inevitably develop in the near future due to differing tolerances for changes in environmental conditions.⁹⁷ These novel communities will have no past or present counterparts and are likely to present serious challenges to marine resource managers.⁹⁸

Adaptation to climate change for marine and coastal systems

Given that CO₂ concentrations will continue to increase and exacerbate climate change effects for the foreseeable future,⁹⁹ adaptation is emerging as an appropriate response to the unavoidable impacts of climate change.¹⁰⁰ Adaptive actions reduce a system's vulnerability,¹⁰¹ increase its capacity to withstand or be resilient to change,¹⁰² and/or transform systems to a new state compatible with likely future conditions.¹⁰³ Adaptation actions typically reflect three commonly cited tenets: (1) remove other threats and reduce non-climate stressors that exacerbate climate change effects;¹⁰⁴ (2) establish, increase, or adjust protected areas, habitat buffers, and corridors;¹⁰⁵ and, (3) increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management.¹⁰⁶

Adaptation actions may occur in legal, regulatory, or decision-making processes, as well as in on-the-ground conservation activities.¹⁰⁷ For example, to counteract loss of coastal habitat due to erosion and sea

level rise, options include removing shoreline hardening structures,¹⁰⁸ enhancing sediment transport,¹⁰⁹ establishing ecological buffer zones,¹¹⁰ and acquiring rolling easements.¹¹¹ To manage invasive species, whose spread is exacerbated by increased sea surface temperatures and other climate-related effects, options include restoring native species, physically removing invasive species, and strengthening regulatory protections against invasive species introduction.¹¹² Decision-makers may also create or modify laws, regulations, and policies governing coastal management to promote living shorelines that protect coastal property and habitat,¹¹³ incorporate climate projections into land use planning to safeguard coastal habitats,¹¹⁴ and implement coastal development setbacks to address rising sea levels and increased storm intensity, maintain natural shore dynamics, and minimize damage from erosion.¹¹⁵

Although uncertainty and gaps in knowledge exist, sufficient scientific information is available to plan for and address climate change impacts now.¹¹⁶ Implementing strategic adaptation actions early may reduce severe impacts and prevent the need for more costly actions in the future.¹¹⁷ To identify and implement adaptation actions, practitioners highlight four broad steps:

1. Assess current and future climate change effects and conduct a vulnerability assessment.¹¹⁸
2. Select conservation targets and a course of action that reduce the vulnerabilities and/or climate change effects identified in Step 1.¹¹⁹
3. Measure, evaluate, and communicate progress through the design and implementation of monitoring programs.¹²⁰
4. Create an iterative process to reevaluate and revise the plan, policy, or program, including assumptions.¹²¹

Adaptive approaches to addressing climate change impacts will vary by sector and management goal, across space and time, and by the goals and preferences of those engaged in the process.¹²² In all cases, adaptation is not a one-time activity, but is instead a continuous process, constantly evolving as new information is acquired and interim goals are achieved or reassessed.¹²³ Ultimately, successful climate change adaptation supports a system's capacity to maintain its past or current state in light of climate impacts or transform to a new state amenable to likely future conditions.¹²⁴

¹ USFWS. (2010)

² NOAA. (2011c)

³ Forster et al. (2007, p. 141)

⁴ CIG. (2008).

⁵ Meehl et al. (2007, p. 803)

⁶ Feely et al. (2009, Table 2, p. 46). By 2100, the projected declines are associated with a doubling (~550 ppm) or tripling (~830 ppm) of atmospheric CO₂ compared to ~1750: -0.14 to -0.15 or -0.30 to -0.31, respectively.

⁷ Hauri et al. (2009, p. 67-68)

⁸ Kroeker et al. (2010, p. 1424, 1427)

⁹ Mote (2003, p. 276); Butz and Safford (2010, 1)

¹⁰ U.S. Global Change Research Program (2009, p. 139)

¹¹ For AK, Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. (2008, Table 3) and Mote et al. (2010, p. 21). For CA, California Natural Resources Agency. (2009, p. 16-17) and PRBO. (2011, p. 8).

¹² California Natural Resources Agency (2009, p. 66); Levin et al. (2009, p. 3568); Najjar et al. (2000, p. 226)

¹³ Cheung et al. (2010, p. 31); IPCC. (2007e, p. 8); Karl, Melillo, and Peterson. (2009, p. 144)

¹⁴ NABCI. (2010, p. 7)

¹⁵ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011. Data for 1971-2000 are official data from the National Climatic Data Center (NCDC). Data for 1981-2010 are preliminary, unofficial data acquired from Tom Ainsworth

and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The NCDC defines a climate normal, in the strictest sense, as the 30-year average of a particular variable (e.g., temperature).

¹⁶ Mote (2003, p. 279)

¹⁷ Killam et al. (2010, p. 4)

¹⁸ Pike et al. (2010, Table 19.1, p. 701)

¹⁹ For BC, BC Ministry of Environment. (2006, Table 10, p. 113); For OR and WA, Mote and Salathé, Jr. (2010, p. 42-44); Seasonal precipitation projections for California were not available.

²⁰ Alaska Center for Climate Assessment and Policy. (2009, p. 31).

²¹ Elsner et al. (2010, Table 5, p. 244); Pike et al. (2010, p. 715); PRBO. (2011, p. 8)

²² AK Department of Environmental Conservation (DEC). (2010, p. 2-3); Chang and Jones. (2010, p. 84); Howat et al. (2007, p. 96); Pike et al. (2010, p. 716)

²³ AK DEC. (2010, p. 2-3, 5-2); Chang and Jones. (2010, p. 94); Mantua, Tohver and Hamlet. (2010, p. 204-205); Pike et al. (2010, p. 719); Stewart. (2009, p. 89); Tohver and Hamlet. (2010, p. 8)

²⁴ Chang and Jones. (2010, p. 192); Pike et al. (2010, p. 719); Stewart. (2009, p. 89)

²⁵ Peterson, W. & Schwing, F. (2008, p. 56)

²⁶ Levin et al. (2009, p. 3567)

²⁷ Orr et al. (2005); Feely, Doney and Cooley. (2009)

²⁸ Feely et al. (2010, Table 1, p. 446).

²⁹ Feely et al. (2009, p. 37)

³⁰ Feely et al. (2009, Table 2, p. 46). The projected decline is associated with a doubling of atmospheric CO₂ compared to ~1750, to ~550 ppm by 2100. With a tripling of atmospheric CO₂ (~830 ppm by 2100 compared to ~1750), pH is projected to decline -0.30 to -0.31 in North Pacific Ocean waters.

³¹ Feely et al. (2009, p. 39); Hauri et al. (2009, p. 67-68)

³² Feely, Sabine, et al. (2008, p. 1491)

³³ Sigler et al. (2008, p. 7)

³⁴ Sigler et al. (2008, p. 12)

³⁵ Hauri et al. (2009, p. 67-68); Sigler et al. (2008, p. 12)

³⁶ Nicholls et al. (2007, p. 320)

³⁷ Overland and Wang. (2007, Fig. 2b, p. 7)

³⁸ Hoegh-Guldberg and Bruno. (2010, p. 1524)

³⁹ IPCC. (2007e, p. 8)

⁴⁰ Hoegh-Guldberg and Bruno. (2010, p. 1524)

⁴¹ IPCC. (2007e, p. 8)

⁴² OCMF. (2009, p. 66)

⁴³ Field et al. (2007, p. 627)

⁴⁴ Field et al. (2007, p. 627)

⁴⁵ Hoffman. (2003, p. 135)

⁴⁶ Bauman et al. (2006); OCMF. (2009)

⁴⁷ OCMF. (2009, p. 17)

⁴⁸ AK State Legislature. (2008); Brown and McLachlan. (2002, p. 62); Littell et al. (2009); Nicholls et al. (2007, p. 325-326).

⁴⁹ OCMF. (2009)

⁵⁰ IPCC. (2007f, p. 7)

⁵¹ NOAA. (2007)

⁵² B.C. Ministry of Environment. (2007, p. 26); Bornhold. (2008, p. 6); Mote et al. (2008)

⁵³ Grinsted, Moore and Jevrejeva. (2009, Table 2, p. 467); IPCC. (2007c, Table 3.1, p. 45); Meehl et al. (2005, p. 1770-1771); Rahmstorf. (2007, p. 369); Vermeer and Rahmstorf. (2009, Table 1, p. 21530-21531).

⁵⁴ AK DEC. (2010, p. 2-4); Bornhold (2008, Table 1, p. 8); CA Natural Resources Agency. (2009, p. 18); Mote et al. (2008); Ruggiero et al. (2010, p. 218)

⁵⁵ Bornhold (2008, Table 1, p. 8); CA Natural Resources Agency. (2009, p. 18); Mote et al. (2008); Ruggiero et al. (2010, p. 218)

⁵⁶ AK DEC. (2010, p. 2-4); Mote et al. (2008)

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- ⁵⁷ AK State Legislature. (2008, p. 91); Glick, Clough and Nunley. (2007); Philip Williams and Associates, Ltd. (2009)
- ⁵⁸ AK State Legislature. (2008, p. 91); Krueger et al. (2010, p.176)
- ⁵⁹ Grantham et al. (2004, p. 750)
- ⁶⁰ Grantham et al. (2004, p. 750)
- ⁶¹ Connolly et al. (2010, p. 1, 8)
- ⁶² Chan et al. (2008, p. 920)
- ⁶³ Chan et al. (2008, p. 920)
- ⁶⁴ PISCO. (2009)
- ⁶⁵ Hoegh-Guldberg and Bruno. (2010, p. 1523)
- ⁶⁶ AK State Legislature. (2008, p. 91). Report by the Alaska State Legislature, available online at http://www.housemajority.org/coms/cli/cli_final_report_20080301.pdf (last accessed 12.14.2010).
- ⁶⁷ AK State Legislature. (2008, p. 91)
- ⁶⁸ Krueger et al. (2010, p.176)
- ⁶⁹ Martin and Glick. (2008, p. 15). The authors cite Hood, W.G. (2005) for this information.
- ⁷⁰ DU. (2010a); DU. (2010c); DU. (2010d)
- ⁷¹ DU. (2010a); DU. (2010c); DU. (2010d)
- ⁷² DU. (2010b)
- ⁷³ Kroeker et al. (2010, p. 1424)
- ⁷⁴ Kroeker et al. (2010, p. 1424)
- ⁷⁵ ISAB. (2007, p. 64)
- ⁷⁶ Whitney, Freeland and Robert. (2007)
- ⁷⁷ Snyder et al. (2003, p. 8-4); Wang, Overland and Bond. (2010, p. 265)
- ⁷⁸ Whitney, Freeland and Robert. (2007, p. 197)
- ⁷⁹ Whitney, Freeland and Robert. (2007, p. 197)
- ⁸⁰ Whitney, Freeland and Robert. (2007, p. 197)
- ⁸¹ Ekau et al. (2010, p. 1690)
- ⁸² NABCI. (2010, p. 8)
- ⁸³ NABCI. (2010, p. 8)
- ⁸⁴ NABCI. (2010, p. 8)
- ⁸⁵ Wolf et al. (2010, p. 1930)
- ⁸⁶ NABCI. (2010, p. 8)
- ⁸⁷ NABCI. (2010, p. 6)
- ⁸⁸ NABCI. (2010, p. 6-7)
- ⁸⁹ U.S. EPA. (2008, p. 2-14)
- ⁹⁰ Boe et al. (2010); Davidson et al. (2008); Mach, Wyllie-Echeverria and Rhode Ward. (2010)
- ⁹¹ Field et al. (2007, p. 142). The authors cite Perry et al. (2005) for this information.
- ⁹² Field et al. (2007)
- ⁹³ Papiez. (2009, p. 17) (2009)
- ⁹⁴ Peterson, W. & Schwing, F. (2008, p. 45)
- ⁹⁵ Peterson, W. & Schwing, F. (2008, p. 54)
- ⁹⁶ Peterson, W. & Schwing, F. (2008, p. 45)
- ⁹⁷ Hoegh-Guldberg and Bruno. (2010, p. 1526)
- ⁹⁸ Hoegh-Guldberg and Bruno. (2010, p. 1526-1527)
- ⁹⁹ ADB. (2005, p. 7)
- ¹⁰⁰ Gregg et al. (2011, p. 30)
- ¹⁰¹ Gregg et al. (2011, p. 29)
- ¹⁰² Glick et al. (2009, p. 12)
- ¹⁰³ Glick et al. (2009, p. 13); U.S. Fish and Wildlife Service. (2010, Sec1:16)
- ¹⁰⁴ Gregg et al. (2011); Lawler (2009); Glick et al. (2009)
- ¹⁰⁵ Gregg et al. (2011); Lawler (2009); Glick et al. (2009)
- ¹⁰⁶ Gregg et al. (2011); Lawler (2009); Glick et al. (2009)
- ¹⁰⁷ Gregg et al. (2011); Heinz Center. (2008); Littell et al. (2009)
- ¹⁰⁸ U.S. EPA. (2007, p. 332); U.S. EPA. (2009, p. 12)

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- ¹⁰⁹ NOAA. (2010, p. 83)
- ¹¹⁰ NOAA. (2010, p. 85)
- ¹¹¹ Kling and Sanchirico. (2009, p. 46)
- ¹¹² Kling and Sanchirico. (2009, p. 41); U.S. EPA. (2009, p. 16)
- ¹¹³ NOAA. (2010, p. 80)
- ¹¹⁴ U.S. EPA. (2009, p. 17)
- ¹¹⁵ U.S. AID. (2009, p. 98)
- ¹¹⁶ Littell et al. (2009)
- ¹¹⁷ Binder. (2010, p. 355)
- ¹¹⁸ Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); ADB (2005); Pew Center (2009)
- ¹¹⁹ Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); Pew Center (2009)
- ¹²⁰ Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); ADB (2005)
- ¹²¹ Gregg et al. (2011); Glick et al. (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); ADB (2005)
- ¹²² Gregg et al. (2011); Littell et al. (2009)
- ¹²³ Littell et al. (2009)
- ¹²⁴ Glick et al. (2011a)

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List of frequently used acronyms and abbreviations

AOGCM	Atmosphere-Ocean General Circulation Model
AR4	4 th Assessment Report (produced by IPCC)
BC	Province of British Columbia, Canada
CA	State of California, United States
CCE	California Current Ecosystem
CIG	Climate Impacts Group
CO ₂	Carbon Dioxide
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency, United States
GCM	Global Circulation Model
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LCC	Landscape Conservation Cooperative
LEK	Local Ecological Knowledge
LME	Large Marine Ecosystem
MoE	Ministry of Environment, British Columbia
NASA	National Aeronautics and Space Administration, United States
NOAA	National Oceanic and Atmospheric Administration, United States
NPLCC	North Pacific Landscape Conservation Cooperative
O ₂	Oxygen
OCAR	Oregon Climate Assessment Report (produced by OCCRI)
OCCRI	Oregon Climate Change Research Institute
OMZ	Oxygen Minimum Zone
OR	State of Oregon, United States
PCIC	Pacific Climate Impacts Consortium
PDO	Pacific Decadal Oscillation
PNW	Pacific Northwest
SLR	Sea Level Rise
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
TEK	Traditional Ecological Knowledge
WA	State of Washington, United States
WACCIA	Washington Climate Change Impacts Assessment (produced by CIG)

PREFACE

This report is intended as a reference document – a science summary – for the U.S. Fish and Wildlife Service (FWS) Region 1 Science Applications Program. The report compiles findings on climate change impacts and adaptation approaches in marine and coastal ecosystems within the North Pacific Landscape Conservation Cooperative region (NPLCC). The report is intended to make scientific information on climate change impacts within the NPLCC region accessible and useful for natural resource managers and others. It was produced by National Wildlife Federation under a grant from the U.S. FWS (FWS Agreement Number 10170AG200).

A companion report compiling similar information on freshwater aquatic and riparian ecosystems within the NPLCC region was also completed under the same grant. The authors seek funding to complete a third report compiling similar information on terrestrial ecosystems within the NPLCC region. Together, the three reports would provide information on climate change effects and adaptation approaches for the NPLCC region’s three broad ecosystem types: marine, freshwater, and terrestrial.

Production and Methodology

This report draws from peer-reviewed studies, government reports, and publications from non-governmental organizations to summarize climate change and ecological literature on historical baselines, observed trends, future projections, policy and management options, knowledge gaps, and the implications of climate change for species, habitats, and ecosystems in the marine and coastal environment. Because the report strives to reflect the state of knowledge as represented in the literature, in most cases language is drawn directly from cited sources. By compiling and representing verbatim material from relevant studies rather than attempting to paraphrase or interpret information from these sources, the authors sought to reduce inaccuracies and possible mis-characterizations by presenting data and findings in their original form. The content herein does not, therefore, necessarily reflect the views of National Wildlife Federation or the sponsors of this report. Given the extensive use of verbatim material, in order to improve readability while providing appropriate source attributions, citation footnotes include the phrase “Verbatim or nearly verbatim from” when the passages are drawn verbatim, or near verbatim, from the cited source. For figures and tables, the phrases “Reproduced from” and “Modified from” are used when the figure or table is drawn completely or largely from the cited source. In general, verbatim and near verbatim material is found in the main body of the report, while the Executive Summary, Boxes, and Case Studies reflect the report authors’ synthesis of multiple sources.

To produce this report, the authors worked with the University of Washington Climate Impacts Group (CIG) and reviewers from federal, state, tribal, non-governmental, and university sectors. CIG provided expert scientific review throughout the production process, as well as assistance in the design and organization of the report. Reviewers provided access to local data and publications, verified the accuracy of content, and helped ensure the report is organized to be relevant and useful for management needs. In addition, the authors engaged early with stakeholders throughout the NPLCC region for assistance and input in the production of this report. More than 100 people provided input or review of this document.

Description of Synthesis Documents Utilized

This report draws from primary sources as well as synthesis reports. In synthesis reports, the authors accepted information as it was presented. Readers are encouraged to refer to the primary sources utilized in those synthesis reports for more information. In most cases, the page number is included for reference.

In cases where a primary source is referenced in a secondary source, it is indicated in the footnote. The global, regional, state, and provincial level synthesis reports drawn from include:

- *Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4): Climate Change 2007.*
- *Global Climate Change Impacts in the United States.* (2009).
- *Alive and Inseparable: British Columbia's Coastal Environment* (2006).
- *Environmental Trends in British Columbia: 2007.*
- *Taking Nature's Pulse: The Status of Biodiversity in British Columbia* (2009).
- *Climatic Change*, Volume 102, Numbers 1-2 (September 2010). This volume published the findings of the Washington Climate Change Impacts Assessment (WACCIA).
- *Washington Climate Change Impacts Assessment (WACCIA)* (2009).
- *Oregon Climate Assessment Report (OCAR)* (2010).
- *2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008.*
- *Synthesis of Adaptation Options for Coastal Areas.* (2009).
- *The State of Marine and Coastal Adaptation in North America: A Synthesis of Emerging Ideas.* (2011).
- *Strategies for Managing the Effects of Climate Change on Wildlife and Ecosystems.* (2008).

How to Use This Document

We encourage the reader to focus on the general magnitude and direction of projections, their implications, and on the range of options available to address climate change impacts. It is our hope that this document will provide useful information to North Pacific LCC members and stakeholders, and help facilitate effective conservation that accounts for climate change and its impacts in the region.

Acknowledgements

We thank our partner, the U.S. Fish and Wildlife Service, for funding and support throughout the production of this report, with special thanks to the Region 1 Science Applications Program.

We are grateful to our partner, the University of Washington Climate Impacts Group, for their expertise and insight, and for the many improvements that came through their guidance.

We are indebted to the 100+ individuals who gave generously of their time and knowledge to inform the development of this report. With the expertise of reviewers and interviewees, we were able to acquire and incorporate additional peer-reviewed reports and publications evaluating climate change impacts on relatively small geographic scales. This allowed us to add nuance to the general picture of climate change impacts throughout the NPLCC geography. Further, this report benefitted tremendously from the resources, thoughtfulness, expertise, and suggestions of our 29 reviewers. Thank you for your time and effort throughout the review process. Reviewers and people interviewed are listed in Appendix 6. List of Reviewers and Interviewees.

We also thank Ashley Quackenbush, Matt Stevenson, and Dan Uthman for GIS support.

Suggested Citation

Tillmann, Patricia. and Dan Siemann. *Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature. Final Report.* National Wildlife Federation – Pacific Region, Seattle, WA. December 2011.

I. INTRODUCTION

This report compiles existing knowledge on known and potential climate change effects on marine and coastal ecosystems within the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). The report also includes a menu of policy and management responses, culled from published science and grey literature, to adapt to climate change in marine and coastal environments. The NPLCC was established by the U.S. Department of Interior and is one of twenty-two Landscape Conservation Cooperatives (LCCs) planned for the United States, Canada, and Mexico. LCCs are member-directed conservation partnerships among State and Federal agencies, Tribes, nongovernmental organizations, universities, existing partnership efforts, and other conservation entities.¹ Other key partners of the NPLCC will be the three regional Climate Science Centers (CSCs) within the geographic area of the NPLCC – the Alaska, Northwest, and Southwest CSCs.² The CSCs will deliver basic climate change impact science for their region, prioritizing fundamental science, data and decision-support activities based principally on the needs of the LCCs.³ LCCs will link the science with conservation delivery.⁴ Thus, LCCs are management-science partnerships that inform resource management actions and provide needed tools.⁵ They provide a forum for identifying common science questions and needs for the defined landscapes, across organization lines.⁶ More specifically, LCCs generate applied science to inform conservation actions related to climate change, habitat fragmentation, and other landscape-level stressors and resource issues.⁷ For further information, please see <http://www.fws.gov/science/shc/lcc.html> (accessed March 14, 2011).

Description of NPLCC

The NPLCC region comprises approximately 204,000 square miles (530,000 square kilometers, km²) in six western U.S. states and Canadian provinces (see Figure 3 on page 4).⁸ Public lands make up approximately 78 percent, or 159,000 square miles (412,000 km²) of the NPLCC, with 82,000 square miles (212,000 km²) of Federal lands in the U.S. portion of the NPLCC and 77,000 square miles (200,000 km²) of Crown lands in the Canadian portion of the NPLCC.⁹ The total amount of coastline is approximately 38,200 miles (~ 61,500 km)¹⁰ and extends from Kenai Peninsula in southcentral Alaska to Bodega Bay in northern California. The inland extent of the NPLCC is delineated according to the Pacific

¹ Verbatim or nearly verbatim from USFWS. *North Pacific Landscape Conservation Cooperative*. (August 2010, p. 1)

² USFWS. *North Pacific Landscape Conservation Cooperative (pdf, website)*. (December 2010, p. 2). A total of eight CSCs are being established to support the 22 LCCs. They consist mainly of university-based consortiums.

³ Verbatim or nearly verbatim from U.S. Department of the Interior. *Interior's plan for a coordinated, science-based response to climate change impacts on our land, water, and wildlife resources (pdf, website)*. (n.d., p. 2)

⁴ Verbatim or nearly verbatim from U.S. Department of the Interior. (n.d., p. 5)

⁵ Verbatim or nearly verbatim from USFWS. (August 2010, p. 1)

⁶ Verbatim or nearly verbatim from USFWS. (August 2010, p. 1)

⁷ Verbatim or nearly verbatim from USFWS. (August 2010, p. 1)

⁸ USFWS. *North Pacific Landscape Conservation Cooperative High Resolution Map*. (2010). Within the Yukon Territory (YT; 186,272 mi², 482,443 km²), the only land within the NPLCC region is that covered by the Kluane National Park and Preserve (8,487 miles², 21, 980 km²; ~4.6% of total area in YT), located in the southwest corner of the Territory. While information on climate change adaptation planning in Kluane National Park and Preserve was limited, information for the Government of Yukon was available. Please see Chapter VIII.8 for further information.

⁹ USFWS. *North Pacific Landscape Conservation Cooperative High Resolution Map*. (2010)

¹⁰ USFWS. *North Pacific Landscape Conservation Cooperative High Resolution Map*. (2010)

Flyway, ecoregions, and the crests of several mountain ranges and, from the coast, stretches inland up to 150 miles (~240 km); therefore only the lower extent of many of the larger river watersheds are included within the area. This area encompasses a variety of water forms including bays, estuaries, inlets, and lagoons. Land types include deltas, coastal dunes and beaches, rocky shores, salt marshes, and mudflats. A wide variety of fish, wildlife, and other organisms populate this region.

Organization of Report

Key findings begin in Chapter II, which describes observed trends and future projections, both globally and within the NPLCC geography, for carbon dioxide (CO₂) concentrations, temperature, and precipitation. Chapter III describes the primary effects of changes in greenhouse gas concentrations, temperature, and precipitation on ocean acidification, sea surface temperature, hydrology, ocean currents, storms, sea level, coastal upwelling, and hypoxia and anoxia in the NPLCC region. The report then describes how the changes presented in Chapter II and the effects presented in Chapter III impact marine and coastal ecosystem processes (Chapter IV), the geomorphology of coastal nearshore systems (Chapter V), species behavior and community-level responses (Chapter VI), and specific fish, wildlife, plants, plankton, and shellfish (Chapter VII) in the NPLCC region. Chapter VIII provides a menu of policy and management responses to address the impacts described in Chapters IV-VII. These responses are based on the general tenets of climate change adaptation for natural systems and are culled from published scientific literature, grey literature, and interviews with experts throughout the NPLCC region. Chapter IX briefly describes future work in the NPLCC region. Six appendices provide key terms and definitions, an explanation of climate modeling and emissions scenarios, an explanation of long-term climate variability, a discussion of the Sea Level Affecting Marshes Model (SLAMM), resources for adaptation principles and responses to climate change, and a list of reviewers and interviewees.

Definitions for Marine and Coastal Environments

In this report, we use definitions for marine and coastal areas based on oceanography and law (Figure 1 and Figure 2).¹¹ **Nearshore** areas extend from the farthest reach inland of tidally influenced water to the depth of light penetration in the ocean (usually about 10 meters).¹² **Coastal waters** are described often as extending to the edge of the continental shelf. The **open ocean** is described often as the area beyond the edge of the continental shelf.

¹¹ NOAA. *Federal Geographic Data Committee's (FCDG) Marine Boundary Working Group Shoreline Boundaries Diagram*. (2010). The mean higher high water (MHHW) is the average of the higher high water height of each tidal day. The mean lower low water (MLLW) is the average of the lower low water height of each tidal day. The mean high water (MHW) is the average of all high water heights.

¹² Puget Sound Nearshore Project (website). (2003); Puget Sound Nearshore Ecosystem Restoration Partnership (website).(2010).

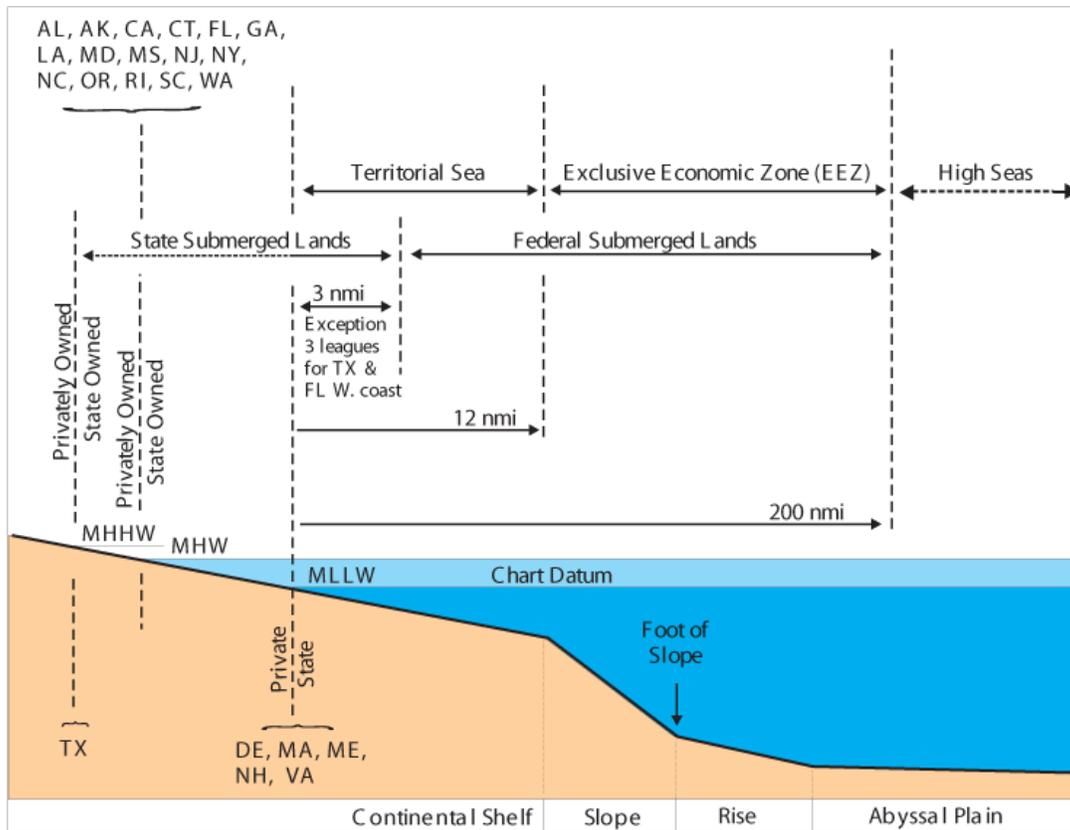


Figure 1. This diagram illustrates shoreline boundaries as defined by different states as well as seaward boundaries (state and federal submerged lands, contiguous zone, territorial seas, exclusive economic zone, etc.).
 Source: *Reproduced from NOAA. Federal Geographic Data Committee's (FCDG) Marine Boundary Working Group Shoreline Boundaries Diagram. (2010) by authors of this report.*

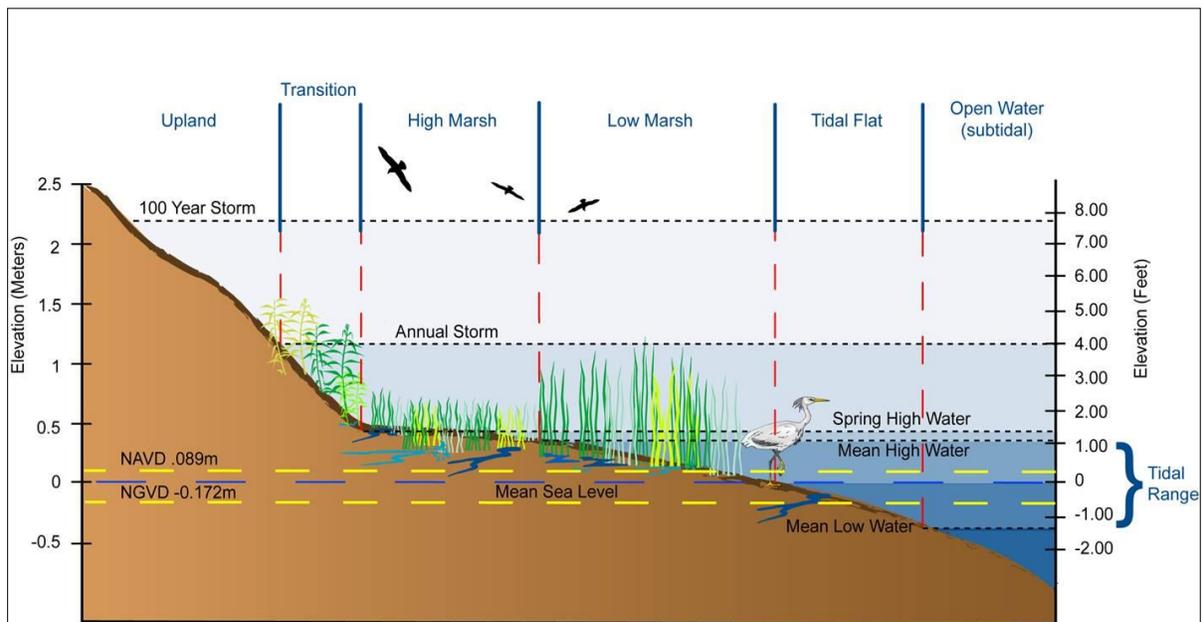


Figure 2. General marine habitat types and associated tidal influence.
 Source: http://maps.risingsea.net/wetland_loss/tides_wetlands_elevation.jpg (accessed 2.11.2011)

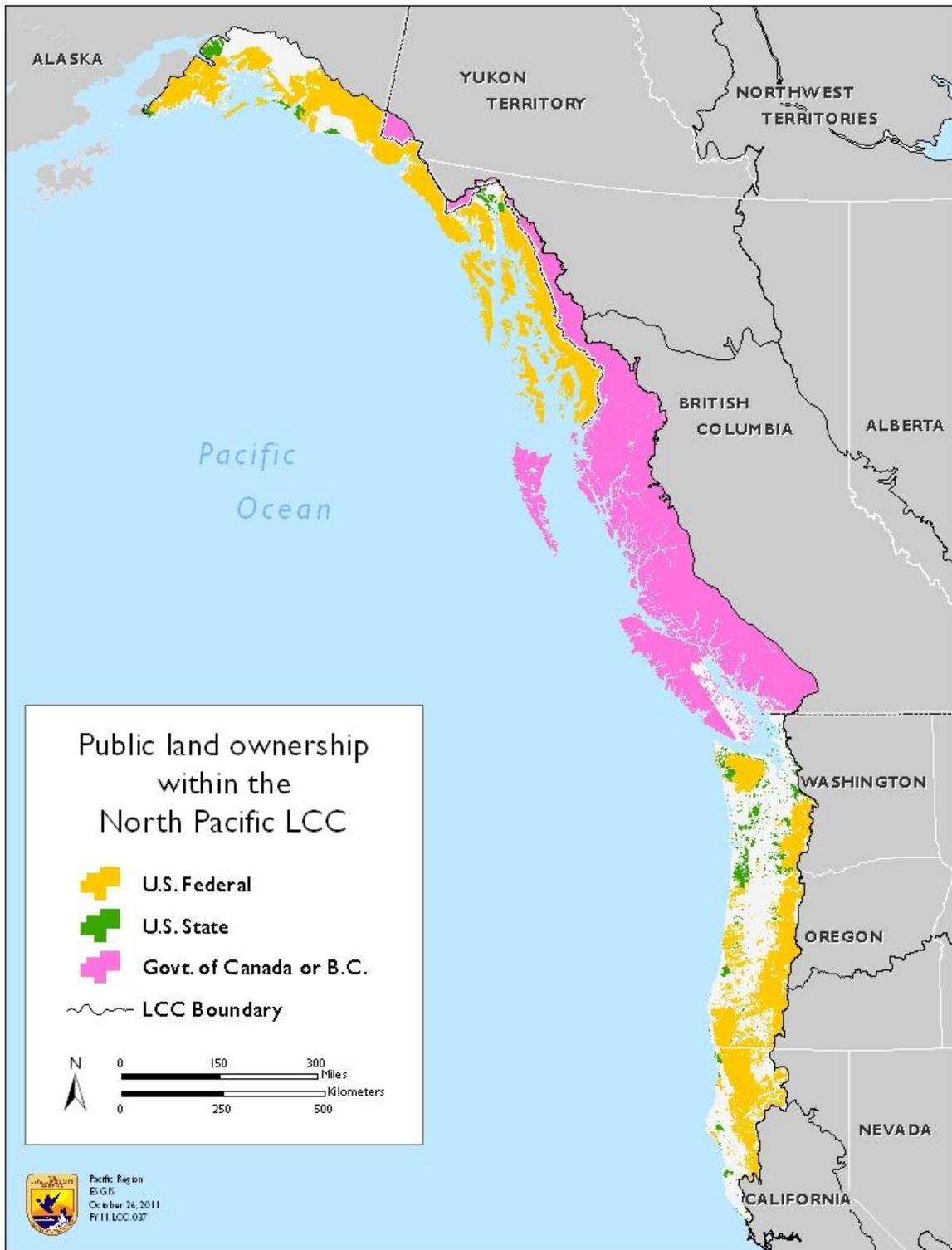


Figure 3. Public land ownership within the North Pacific Landscape Conservation Cooperative (NPLCC). Source: U.S. Fish and Wildlife Service (2011). This is a preliminary land ownership map, including only federal, state, and provincial lands. At a later date, the map will be updated to include Native Alaskan, First Nations, and Tribal lands. Lands owned by other entities (e.g. NGOs, private property) may be included as well.

II. CO₂ CONCENTRATIONS, TEMPERATURE, & PRECIPITATION

Box 1. Summary of observed trends and future projections for greenhouse gas concentrations, temperature, and precipitation

Observed Trends

- Atmospheric CO₂ concentrations in March 2011 were approximately 392 parts per million (ppm),¹³ higher than any level in the past 650,000 years¹⁴ and 41% higher than the pre-industrial value (278 ppm).¹⁵ From 2000-2004, the emissions growth rate (>3%/yr) exceeded that of the highest-emissions IPCC scenario (A1F1), and the actual emissions trajectory was close to that of the A1F1 scenario.¹⁶
- Annual average temperatures in the NPLCC region increased, in general, 1-2°F (~0.6-1°C) over the 20th century.¹⁷ Alaska is an exception – a 3.4°F (~1.9°C) increase was observed from 1949-2009.¹⁸
- In the 20th century and early 21st century, the largest increase in seasonal temperature occurred in winter: +3.3°F (+1.83°C) in western BC, OR, and WA¹⁹ and +1.8-2.0°F (+1.0-1.1°C) in northwestern CA.²⁰ These increases tend to drive the annual trends, particularly in AK (+6.2°F or 3.4°C from 1949-2009 near Juneau).²¹
- In the 20th century and early 21st century, average annual precipitation trends are highly variable, with increases of 2 to approximately 7 inches (~5-18 cm) observed in WA, OR,²² and northwestern CA,²³ and both small increases and decreases (±1 inch or ± 2.54 cm) observed in BC's Georgia Basin and coastal areas, depending on the time period studied.²⁴ Precipitation trends in Alaska were not available. However, precipitation was 32-39 inches (80-100 cm) in southcentral Alaska and at least 39 inches (100 cm) in southeast Alaska from 1949-1998.²⁵
- In the 20th century and early 21st century, seasonal precipitation trends are highly variable, with increases in winter and spring precipitation observed in WA, OR,²⁶ and northwestern CA,²⁷ and both increases and decreases observed in BC, depending on location and time period.²⁸ Specifically, in WA and OR, spring precipitation increased +2.87 inches (7.29 cm) and winter precipitation increased 2.47 inches (6.27 cm) from 1920 to 2000.²⁹

A summary of future projections can be found on the next page.

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

¹³ NOAA. *Trends in Atmospheric Carbon Dioxide: Global 2011 (website)*. (2011)

¹⁴ CIG. *Climate Change: Future Climate Change in the Pacific Northwest (website)*. (2008)

¹⁵ Forster et al. (2007, p. 141)

¹⁶ Raupach et al. *Global and regional drivers of accelerating CO₂ emissions*.

¹⁷ Mote (2003, p. 276); Butz and Safford (Butz and Safford 2010, 1). Butz and Safford refer the reader to Figures 1 & 2 in the cited report.

¹⁸ Karl, Melillo and Peterson. (2009, p. 139). The authors cite Fitzpatrick et al. (2008) for this information.

¹⁹ Mote (2003, p. 276)

²⁰ Butz and Safford (Butz and Safford 2010, 1). The authors refer the reader to Figures 1 & 2 in the cited report.

²¹ Alaska Climate Research Center. *Temperature Change in Alaska (website)*. (2009)

²² Mote (2003, p. 279)

²³ Killam et al. (2010, p. 2)

²⁴ Pike et al. (2010, Table 19.1, p. 701)

²⁵ Stafford, Wendler and Curtis. (2000, p. 41). Information obtained from Figure 7.

²⁶ Mote (2003, p. 279)

²⁷ Killam et al. (2010, p. 4)

²⁸ Pike et al. (2010, Table 19.1, p. 701)

²⁹ Mote (2003, p. 279)

Future projections

- Projected atmospheric CO₂ concentrations in 2100 range from a low of about 600 ppm under the A1T, B1, and B2 scenarios to a high of about 1000 ppm in the A1F1 scenario.³⁰ Recent emissions trajectories are close to that of the A1F1 scenario.³¹
- By 2100, average annual temperatures in the NPLCC region are projected to increase 3.1-6.1°F (1.7-3.4°C) (excluding AK & BC, where temperatures are projected to increase 2.5-2.7°F (1.4-1.5°C) by 2050 and 5-13°F (2.8-7.2°C) after 2050, respectively).³² The range of projected increases varies from 2.7 to 13°F (1.5-7.2°C), with the largest increases projected in AK.³³ Baselines for projections vary by study location: 1960s-1970s in AK, 1961-1990 in BC, 1970-1999 in the Pacific Northwest (PNW), and 1971-2000 in northwest CA.
- By 2100, seasonal temperatures are projected to increase the most in summer (region-wide: 2.7-9.0°F, 1.5-5°C): in BC, 2.7°F to 5.4°F (1.5-3°C) along the North Coast and 2.7°F to 9.0°F (1.5-5°C) along the South Coast. In WA and OR, 5.4-8.1°F (3.0-4.5°C).³⁴ The exception is AK, where seasonal temperatures are projected to increase the most in winter.³⁵ The baseline for projections varies by study location: 1960s-1970s in Alaska, 1961-1990 on the BC coast and northern CA, 1970-1999 in the PNW.
- Precipitation may be more intense, but less frequent, and is more likely to fall as rain than snow.³⁶ Annual precipitation is projected to increase in AK,³⁷ BC (2050s: +6% along the coast, no range provided),³⁸ and WA and OR (2070-2099: +4%, range of -10 to +20%),³⁹ but is projected to decrease in CA (2050: -12 to -35%, further decreases by 2100).⁴⁰ Increases in winter and fall precipitation drive the trend (+6 to +11% [-10 to +25% in winter] in BC and +8% [small decrease to +42%] in WA and OR), while decreases in summer precipitation mitigate the upward trend (-8 to -13% in BC [-50 to +5%] and -14% [some models project -20 to -40%] in WA and OR).⁴¹ In southeast AK, however, a 5.7% increase in precipitation during the growing season is projected (no range or baseline provided).⁴² Baselines for BC, WA, OR, and CA are the same as those listed in the previous bullet.

³⁰ Meehl et al. (2007, p. 803). This information was extrapolated from Figure 10.26 by the authors of this report.

³¹ Raupach et al. *Global and regional drivers of accelerating CO₂ emissions*. (2007)

³² For BC, Pike et al. (2010, Table 19.3, p. 711). For AK, Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. *Climate Change (website)*. (2008, Table 3) and Mote et al. (2010, p. 21). For CA, California Natural Resources Agency (NRA). (2009, p. 16-17), Port Reyes Bird Observatory (PRBO). (2011, p. 8), and Ackerly et al. (2010, Fig. S2, p. 9).

³³ For AK, Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. *Climate Change (website)*. (2008, Table 3) and Mote et al. (2010, p. 21). For CA, CA NRA.. (2009, p. 16-17) and PRBO. (2011, p. 8).

³⁴ For BC, BC Ministry of Environment (MoE). (2006, Table 10, p. 113). For OR and WA, Mote and Salathé, Jr. (2010, Fig. 9, p. 42). For CA, PRBO. (2011, p. 8).

³⁵ Karl, Melillo and Peterson. (2009)

³⁶ Karl, Melillo and Peterson. (2009)

³⁷ Karl, Melillo and Peterson. (2009, p. 139).

³⁸ Pike et al. (2010, Table 19.3, p. 711)

³⁹ The precipitation range was obtained from the Climate Impacts Group. It can be found in *Summary of Projected Changes in Major Drivers of Pacific Northwest Climate Change Impacts*, available in draft form from http://www.ecy.wa.gov/climatechange/2010TAGdocs/20100521_projecteddrrivers.pdf (accessed 1.5.2011).

⁴⁰ California Natural Resources Agency. (2009, p. 16-17)

⁴¹ For BC, BC MoE. (2006, Table 10, p. 113). For OR & WA, Mote & Salathé, Jr. (2010, 42-44)

⁴² Alaska Center for Climate Assessment and Policy. (2009, p. 31)

1. CARBON DIOXIDE (CO₂) CONCENTRATIONS – GLOBAL OBSERVED TRENDS AND FUTURE PROJECTIONS

Observed Trends

- Overall change: Atmospheric CO₂ concentrations in March 2011 were approximately 392 parts per million (ppm),⁴³ higher than any level in the past 650,000 years⁴⁴ and 41% higher than the pre-industrial value (278 ppm).⁴⁵ Current CO₂ concentrations are about 3.4 percent higher than the 2005 concentration reported by the IPCC's Fourth Assessment Report (AR4: 379 ± 0.65 ppm).⁴⁶ From 2000-2004, the actual emissions trajectory was close to that of the high-emissions A1F1 scenario.⁴⁷ See Box 2 for more information on emissions scenarios.
- Annual growth rates
 - 1960-2005: CO₂ concentrations grew 1.4 ppm per year, on average.⁴⁸
 - 1995-2005: CO₂ concentrations grew 1.9 ppm per year, on average.⁴⁹ This is the most rapid rate of growth since the beginning of continuous direct atmospheric measurements, although there is year-to-year variability in growth rates.⁵⁰
 - 2000-2004: the emissions growth rate (>3%/yr) exceeded that of the highest-emissions IPCC scenario (A1F1).⁵¹
 - 2010: the annual mean rate of growth of CO₂ concentrations was 2.68 ppm.⁵²

⁴³ NOAA. *Trends in Atmospheric Carbon Dioxide (website)*. (2011)

⁴⁴ CIG. *Climate Change: Future Climate Change in the Pacific Northwest (website)*. (2008).

⁴⁵ Forster et al. (2007, p. 141)

⁴⁶ Forster et al. (2007, p. 141)

⁴⁷ Raupach et al. *Global and regional drivers of accelerating CO₂ emissions*. (2007)

⁴⁸ IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. (2007f, p. 2)

⁴⁹ IPCC. (2007f, p. 2)

⁵⁰ Verbatim or nearly verbatim from IPCC. (2007f, p. 2)

⁵¹ Raupach et al. (2007)

⁵² NOAA. *Trends in Atmospheric Carbon Dioxide: Global (website)*. (2011)

Box 2. The Special Report on Emissions Scenarios (SRES).

Changes in greenhouse gas (GHG, e.g. carbon dioxide, CO₂) and sulfate aerosol emissions are based on different assumptions about future population growth, socio-economic development, energy sources, and technological progress. Because we do not have the advantage of perfect foresight, a range of assumptions about each of these factors are made to bracket the range of possible futures, i.e. scenarios. Individual scenarios, collectively referred to as the IPCC Special Report on Emissions Scenarios or SRES scenarios, are grouped into scenario “families” for modeling purposes. Forty individual emissions scenarios are grouped into six families: A1F1, A1B, A1T, A2, B1, and B2. The “A” families are more economic in focus than the “B” families, which are more environmentally focused. The A1 and B1 families are more global in focus compared to the more regional A2 and B2. All scenarios are assumed to be equally valid, with no assigned probabilities of occurrence. While the scenarios cover multiple GHGs and multiple drivers are used to project changes, this report focuses on CO₂ because it is the major driver of ocean acidification, as well as other climate change impacts, and is tightly coupled with many ecological processes.

- The A1 scenarios (A1F1, A1B, and A1T) assume rapid economic growth, a global population that peaks in mid-century, and rapid introduction of new and more efficient technologies. They are differentiated by assumptions about the dominant type of energy source: the fossil-intensive A1F1, non-fossil intensive A1T, and mixed energy source A1B scenarios. Cumulative CO₂ emissions from 1990 to 2100 for the A1T, A1B, and A1F1 scenarios are 1061.3 Gigatons of carbon (GtC), 1492.1 GtC, and 2182.3 GtC, respectively. These correspond to a low-, medium-high, and high-emissions scenario, respectively.
- The B1 scenario assumes the same population as A1, but with more rapid changes toward a service and information economy. This is a low-emissions scenario: cumulative CO₂ emissions from 1990 to 2100 are 975.9 GtC.
- The B2 scenario describes a world with intermediate population and economic growth, emphasizing local solutions to sustainability. Energy systems differ by region, depending on natural resource availability. This is a medium-low emissions scenario: cumulative CO₂ emissions from 1990 to 2100 are 1156.7 GtC.
- The A2 scenario assumes high population growth, slow economic development, and slow technological change. Resource availability primarily determines the fuel mix in different regions. This is a high-emissions scenario: cumulative CO₂ emissions from 1990 to 2100 are 1855.3 GtC.

Scenario	Cumulative CO ₂ emissions (GtC), 1990-2100	Population Growth Rate	Economic Development Rate	Fuels used
A1F1	2182.3	Peaks in mid-21 st century	Rapid	Fossil fuel intensive
A1B	1492.1	Peaks in mid-21 st century	Rapid	Mixed energy sources
A1T	1061.3	Peaks in mid-21 st century	Rapid	Non-fossil fuel intensive
A2	1855.3	High	Slow	Determined by resource availability
B2	1156.7	Intermediate	Intermediate	Determined by resource availability
B1	975.9	Peaks in mid-21 st century	Rapid – toward service & information economy	Non-fossil fuel intensive

Source: IPCC. *Climate Change 2007: Synthesis Report*. (2007); IPCC. *The SRES Emissions Scenarios (website)*. (2010); IPCC. *IPCC Special Report on Emissions Scenarios: Chapters 4.3 & 5.1 (website)*. (2010); IPCC. *SRES Final Data (version 1.1) Breakdown (website)*. (2000); CIG. *Climate Change (website)*. (2008).

Future Projections

- Compared to the concentration in 2005 (~379 ppm), atmospheric CO₂ concentrations are projected to increase over the period 2000-2100 across all six SRES scenarios,⁵³ from a low of about 600 ppm under the A1T, B1, and B2 scenarios to a high of about 1000 ppm in the A1F1 scenario.⁵⁴
- *Note: Most projections in this chapter are based on climate modeling and a number of emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES, see Box 2 and Appendix 3. Major Climate Patterns in the NPLCC: ENSO and PDO for further information).*⁵⁵

Box 3. Why are CO₂ concentrations, air temperature, and precipitation important?

- Increasing carbon dioxide concentrations in the atmosphere contribute to the greenhouse effect, leading to increases in global average air temperature. Increased carbon dioxide levels in the atmosphere also drive the acidification of the ocean.
- Air temperature is important because increases in air temperature are reflected in increasing sea surface temperature, drive sea level rise, and because warmer air holds more water vapor. Air temperature affects wind patterns, which affect ocean currents, storm patterns, upwelling, and sea level rise.
- Precipitation is important because its type (e.g. rain vs. snow), amount, frequency, duration, and intensity affects other hydrologic processes such as the amount and timing of freshwater inflow into coastal regions, which in turn affects the incidence and severity of hypoxic events.
- Together, temperature, precipitation, and CO₂ concentrations affect the land (e.g. coastal erosion), coastal environment (e.g. inundation due to sea level rise), open ocean (e.g. storm frequency and intensity) and the habitats and biological communities dependent on each.

Sources: see, for example, Pew (2011); Trenberth et al. (2007); Grantham et al. (2004); Hauri et al. (2009); Nicholls and Cazenave (2010); Feely, Doney, and Cooley (2009); Glick, Clough, and Nunley (2007)

⁵³ Meehl et al. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (2007, p. 803). This information has been extrapolated from Figure 10.26 by the authors of this report.

⁵⁴ Meehl et al. (2007, p. 803). This information has been extrapolated from Figure 10.26 by the authors of this report.

⁵⁵ IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 44)

2. TEMPERATURE – global and regional observed trends and future projections

Observed Trends

Globally

- In 2010, the combined land and ocean global surface temperature was 58.12°F (14.52°C; NCDC dataset).⁵⁶ This is tied with 2005 as the warmest year on record, at 1.12°F (0.62°C) above the 20th century average of 57.0°F (13.9°C; NCDC dataset).⁵⁷ The range associated with this value is plus or minus 0.13°F (0.07°C; NCDC dataset).⁵⁸
 - From 1850 through 2006, 11 of the 12 warmest years on record occurred from 1995 to 2006.⁵⁹
 - In 2010, Northern Hemisphere combined land and ocean surface temperature was the warmest on record: 1.31°F (0.73°C) above the 20th century average (NCDC dataset).⁶⁰
- From 1906 to 2005, global average surface temperature increased ~1.34°F ± 0.33°F (0.74°C ± 0.18°C).⁶¹
 - From the 1910s to 1940s, an increase of 0.63°F (0.35°C) was observed.⁶² Then, about a 0.2°F (0.1°C) decrease was observed over the 1950s and 1960s, followed by a 0.99°F (0.55°C) increase between the 1970s and the end of 2006 (Figure 4).⁶³
- The 2001-2010 decadal land and ocean average temperature trend was the warmest decade on record for the globe: 1.01°F (0.56°C) above the 20th century average (NCDC dataset).⁶⁴
 - From 1906-2005, the decadal trend increased ~0.13°F ± 0.04°F (0.07°C ± 0.02°C) per decade.⁶⁵ From 1955-2005, the decadal trend increased ~0.24°F ± 0.05°F (0.13°C ± 0.03°C) per decade.⁶⁶
- Warming has been slightly greater in the winter months from 1906 to 2005 (December to March in the northern hemisphere; June through August in the southern hemisphere).⁶⁷ Analysis of long-term changes in daily temperature extremes show that, especially since the 1950s, the number of very cold days and nights has decreased and the number of extremely hot days and warm nights has increased.⁶⁸

⁵⁶ NOAA. *State of the Climate Global Analysis 2010 (website)*. (2011)

⁵⁷ NOAA. (2011)

⁵⁸ NOAA. (2011)

⁵⁹ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report: Summary for Policymakers*. (2007, p. 2)

⁶⁰ NOAA. (2011)

⁶¹ Verbatim or nearly verbatim from Trenberth et al. *Climate Change 2007: The Physical Science Basis*. (2007, p. 252). Note: Trenberth et al. comprise Working Group 1 of the IPCC 4th Assessment Report.

⁶² Trenberth et al. (2007, p. 252)

⁶³ Trenberth et al. (2007, p. 252)

⁶⁴ NOAA. (2011)

⁶⁵ Trenberth et al. (2007, p. 237)

⁶⁶ Trenberth et al. (2007, p. 237)

⁶⁷ Verbatim or nearly verbatim from Trenberth et al. (2007, p. 252)

⁶⁸ Verbatim or nearly verbatim from Trenberth et al. (2007, p. 252)

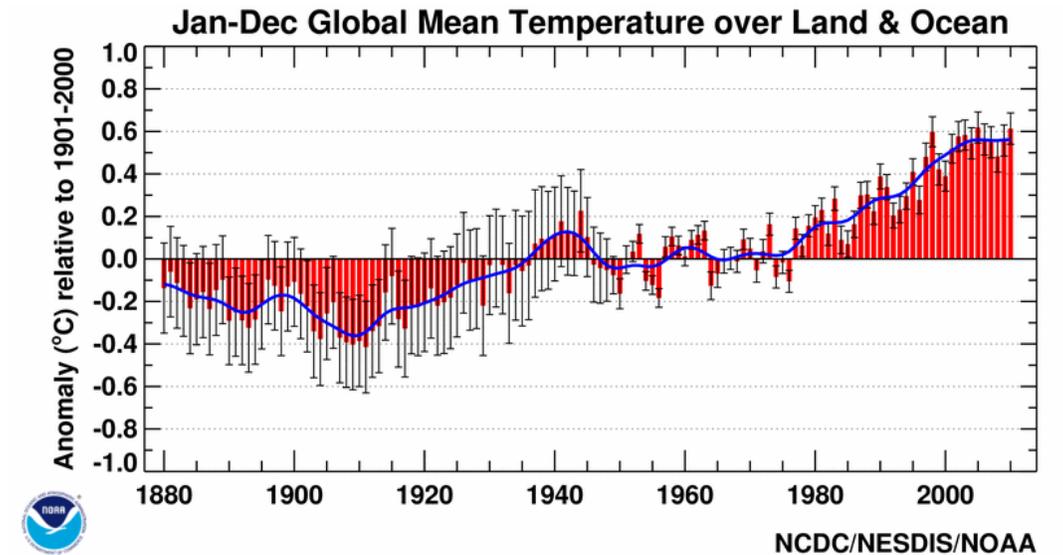


Figure 4. Jan-Dec Global Mean Temperature over Land & Ocean. *Source: NCDC/NESDIS/NOAA. Downloaded from <http://www.ncdc.noaa.gov/sotc/service/global/global-land-ocean-mntp-anom/201001-201012.gif> (7.27.2011).*

Southcentral and Southeast Alaska

- Annual average temperature has increased 3.4°F (~1.9°C) over the last fifty years, while winters have warmed even more, by 6.3°F (3.5°C).⁶⁹ The time period over which trends are computed is not provided. However, compared to a 1960s-1970s baseline, the average temperature from 1993 to 2007 was more than 2°F (1.1°C) higher.⁷⁰
 - Annual average temperature increased 3.2°F (1.8°C) in Juneau over 1949-2009.⁷¹
From 1971 to 2000, temperatures in Anchorage increased by 2.26°F (1.27°C).⁷²
- From 1949 to 2009, winter temperatures increased the most, followed by spring, summer, and autumn temperatures.⁷³ For example, in Juneau, winter temperatures increased by 6.2°F (3.4°C), spring temperatures increased by 2.9°F (1.6°C), summer temperatures increased by 2.2°F (1.2°C), and autumn temperatures increased 1.4°F (0.8°C).⁷⁴

⁶⁹ Verbatim or nearly verbatim from Karl, Melillo and Peterson. *Global Climate Change Impacts in the United States*. (2009, p. 139). The report does not provide a year range for this information. The authors cite Fitzpatrick et al. (2008) for this information.

⁷⁰ Karl, Melillo and Peterson. (2009, p. 139). See the figure entitled *Observed and Projected Temperature Rise*.

⁷¹ Alaska Climate Research Center. *Temperature Change in Alaska (website)*. (2009)

⁷² Alaska Center for Climate Assessment and Policy. *Climate Change Impacts on Water Availability in Alaska (presentation)*. (2009, p. 4)

⁷³ Alaska Climate Research Center. (2009)

⁷⁴ Alaska Climate Research Center. (2009)

- A comparison of official data from the National Climatic Data Center (NCDC) for 1971-2000 and unofficial National Weather Service (NWS) data for 1981-2010 for Juneau, Alaska indicates average annual, warm season (April – September), and cold season (October – March) temperatures have increased from 1971-2000 to 1981-2010 (Table 1):⁷⁵
 - Annual: +0.6°F (+0.33°C), from 41.5°F (5.28°C) to 42.1°F (5.61°C).⁷⁶
 - April-September: +0.2°F (+0.1°C), from 50.9°F (10.5°C) to 51.1°F (10.6°C).⁷⁷
 - October-March: +0.8°F (+0.444°C), from 32.1°F (0.0556°C) to 32.9°F (0.500°C).⁷⁸

Table 1. Annual and seasonal temperature trends for Juneau, AK over two thirty-year time periods.

		1971-2000*	1981-2010*	Absolute Change °F (°C)	Percent Change [†]
Annual	Average	41.5 (5.28)	42.1 (5.61)	+0.6 (+0.33)	+1.45
	Average maximum	47.6 (8.67)	48.1 (8.94)	+0.5 (+0.27)	+1.05
	Average minimum	35.3 (1.83)	36.1 (2.28)	+0.8 (+0.45)	+2.27
Warm season (April – Sept)	Average	50.9 (10.5)	51.1 (10.6)	+0.2 (+0.1)	+0.393
	Average maximum	58.2 (14.6)	58.3 (14.6)	+0.1 (0.06)	+0.172
	Average minimum	43.5 (6.39)	44.0 (6.67)	+0.5 (+0.28)	+1.15
Cold season (Oct – March)	Average	32.1 (0.0556)	32.9 (0.500)	+0.8 (+0.444)	+2.49
	Average maximum	37.0 (2.78)	37.7 (3.17)	+0.7 (+0.39)	+1.89
	Average minimum	27.2 (-2.67)	28.1 (-2.17)	+0.9 (+0.50)	+3.31

*Data for 1971-2000 are official data from the National Climatic Data Center (NCDC). Data for 1981-2010 are preliminary, unofficial data acquired from Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The official data for 1981-2010 are scheduled for release by NCDC in July 2011. The table was created by the authors of this report and approved by Tom Ainsworth and Rick Fritsch on June 10, 2011.

[†]Percent change reflects the relative increase or decrease from 1971-2000 to 1981-2010.

Western British Columbia

- Observed trends in the annually averaged daily minimum, mean, and maximum temperatures from 1950 to 2006 are available for four stations along the BC coast (Table 2).⁷⁹

⁷⁵ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁷⁶ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁷⁷ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁷⁸ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

⁷⁹ BC Ministry of Environment (MoE). *Environmental Trends in British Columbia: 2007: Climate Change*. (2007, p. 7)

Table 2. Trends in the average daily minimum, mean, and maximum temperatures per decade in °F (°C) in southern coastal British Columbia, 1950-2006.

	Temperature	Annual	Winter	Spring	Summer	Autumn
Abbotsford Airport, near Vancouver	Minimum	0.72 (0.40)	1.58 (0.88)	0.86 (0.48)	0.58 (0.32)	0.23 (0.13)
	Average	0.59 (0.33)*	0.52 (0.29)*	0.68 (0.38)*	0.74 (0.41)*	0.27 (0.15)*
	Maximum	0.20 (0.11)	1.13 (0.63)	-0.41 (-0.23)	1.21 (0.67)	-0.76 (-0.42)
Comox Airport, east Vancouver Island	Minimum	0.58 (0.32)*	0.40 (0.22)*	0.79 (0.44)*	0.65 (0.36)*	0.38 (0.21)*
	Average	0.41 (0.23)*	0.40 (0.22)*	0.50 (0.28)*	0.45 (0.25)*	0.22 (0.12)*
	Maximum	0.23 (0.13)*	0.31 (0.17)*	0.23 (0.13)	0.27 (0.15)	0.11 (0.06)
Port Hardy Airport, NE Vancouver Island	Minimum	0.38 (0.21)*	0.43 (0.24)*	0.50 (0.28)*	0.45 (0.25)*	0.04 (0.02)
	Average	0.34 (0.19)*	0.49 (0.27)*	0.36 (0.20)	0.31 (0.17)	0.07 (0.04)
	Maximum	0.27 (0.15)*	0.52 (0.29)*	0.41 (0.23)*	0.14 (0.08)	0.05 (0.03)
Victoria Airport, near Victoria	Minimum	0.40 (0.22)*	0.36 (0.20)*	0.63 (0.35)*	0.45 (0.25)*	0.20 (0.11)*
	Average	0.45 (0.25)*	0.40 (0.22)*	0.58(0.32)*	0.52 (0.29)*	0.22 (0.12)*
	Maximum	0.43 (0.24)*	0.52 (0.29)*	0.43 (0.24)*	0.49 (0.27)*	0.18 (0.10)

Note: Asterisks indicate a statistically significant difference, meaning there is at least a 95% probability that the trend is not due to chance.

Source: Modified from B.C. MoE. (2007, Table 1, p. 7-8) by authors of this report.

Pacific Northwest (Figure 5)

- Average 20th century warming was 1.64°F (0.91°C; the linear trend over the 1920-2000 period, expressed in degrees per century).⁸⁰
- Warming over the 20th century varied seasonally, with average warming in winter being the largest (+3.3°F, +1.83°C), followed by summer (+1.93°F, +1.07°C), spring (+1.03°F, +0.57°C), and autumn (+0.32°F, +0.18°C).⁸¹ Data reflect the linear trend over the 1920-2000 period, expressed in degrees per century; data for summer are significant at the 0.05 level.⁸²
- Increases in maximum and minimum temperatures in the cool (October-March) and warm (April-September) seasons from 1916 to 2003 and from 1947 to 2003 were observed (Table 3).⁸³

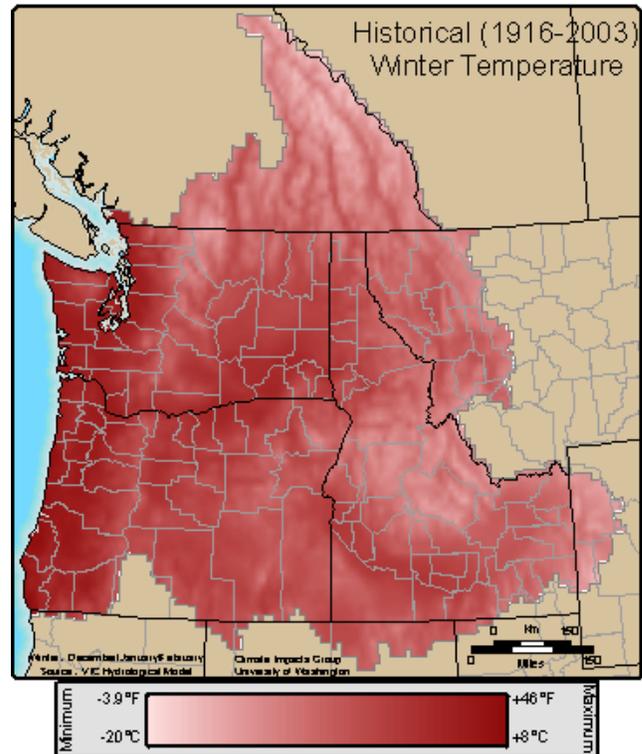


Figure 5. Historical average (1916-2003) winter temperature in the Pacific Northwest.
Source: Downloaded with permission from Center for Science in the Earth System August 13, 2011.
(<http://cses.washington.edu/cig/maps/index.shtml>).

- When comparing the 1981-2010 climate normals (i.e., the 30-year average) to the 1971-2000 climate normals, both maximum and minimum temperatures are about 0.5°F (~0.3°C) warmer on average in the new normals across the United States.⁸⁴ The averaged annual statewide increases in maximum and minimum temperatures observed over this period are:
 - **Maximum:** +0.3 to +0.5°F (~+0.2-0.3°C) in Washington and Oregon.⁸⁵
 - **Minimum:** +0.3 to +0.5°F (~+0.2-0.3°C) in Washington and +0.1 to +0.3°F (~+0.06-0.3°C) in Oregon.⁸⁶

⁸⁰ Mote (2003, Fig. 6, p. 276)

⁸¹ Mote (2003, Fig. 6, p. 276)

⁸² Mote (2003, Fig. 6, p. 276)

⁸³ Hamlet et al. *Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States*. (2007, Table 1, p. 1475).

⁸⁴ Verbatim or nearly verbatim from NOAA. *NOAA Satellite and Information Service: NOAA's 1981-2010 Climate Normals (website)*. (2011)

⁸⁵ Verbatim or nearly verbatim from NOAA. (2011, Fig. 1)

⁸⁶ Verbatim or nearly verbatim from NOAA. (2011, Fig. 2)

Table 3. Regional-scale maximum and minimum temperature trends during 1916-2003 and 1947-2003 for the cool season (October-March) and warm season (April-September) in the Pacific Northwest. (*°F per century with °C per century in parentheses; trends extrapolated from 1916-2003 and 1947-2003 data records*)

Source: Modified from Hamlet et al. (2007, Table 1, p. 1475) by authors of this report.

Maximum temperature	October-March	1916-2003 1947-2003	1.82 (1.01) 3.47 (1.93)
	April-September	1916-2003 1947-2003	0.40 (0.22) 2.68 (1.49)
Minimum temperature	October-March	1916-2003 1947-2003	3.01 (1.67) 4.09 (2.27)
	April-September	1916-2003 1947-2003	2.43 (1.35) 3.47 (1.93)

Northwest California

- PRISM data (a climate-mapping system) suggest that most of the Six Rivers National Forest area, located in northwestern California, experienced increases in mean annual temperature of about 1.8°F (1°C) between the 1930s and 2000s, although some coastal areas have seen a slight decrease in temperature.⁸⁷ Average temperatures at the Orleans station increased approximately 2°F (1.1°C) in the period from 1931 to 2009 (1931 baseline: ~56.2°F, or ~13 °C).⁸⁸ The trend is driven by a highly significant increase in mean minimum (i.e., nighttime) temperature, which rose by almost 4°F (2.2°C) between 1931 and 2009 (1931 baseline: ~42°F, or ~5.5°C).⁸⁹ *Note: For a figure showing mean annual temperature and annual temperature seasonality from 1971 to 2000, please see Figure S1 in the link included in the footnote.*⁹⁰

⁸⁷ Verbatim or nearly verbatim from Butz and Safford. *A summary of current trends and probable future trends in climate and climate-driven processes for the Six Rivers National Forest and surrounding lands (pdf)*. (2010, p. 1). Butz and Safford refer the reader to Figure 1 in the cited report.

⁸⁸ Verbatim or nearly verbatim from Butz and Safford. (2010, p. 1). Butz and Safford refer the reader to Figure 1 in the cited report. For the 1931 baseline, please see Figure 2 in the cited report.

⁸⁹ Verbatim or nearly verbatim from Butz and Safford. (2010, p. 1). Butz and Safford refer the reader to Figure 2 in the cited report.

⁹⁰ Ackerly et al. *The geography of climate change: implications for conservation biogeography (Supplemental Information)*. (2010). http://onlinelibrary.wiley.com/store/10.1111/j.1472-4642.2010.00654.x/asset/supinfo/DDI_654_sm_Data_S1andFig_S1-S8.pdf?v=1&s=93f8310b31bb81d495bae87579a8d7f4d710ca3e (accessed 6.8.2011).

- When comparing the 1981-2010 climate normals (i.e., the 30-year average) to the 1971-2000 climate normals, both maximum and minimum temperatures are about 0.5°F (~0.3°C) warmer on average in the new normals across the United States.⁹¹ The averaged annual increase in maximum and minimum temperatures in California observed over this period are:
 - **Maximum:** +0.3 to +0.5°F (~+0.2-0.3°C).⁹²
 - **Minimum:** +0.3 to +0.5°F (~+0.2-0.3°C).⁹³

Future Projections

Note: The studies presented here differ in the baseline used for projections. Baselines include 1980-1999 (IPCC), 1961-1990 (BC, CA), 1970-1999 (WA, OR), 1971-2000 (CA) and 1960-1970s (AK).

Globally (1980 – 1999 baseline)

- Even if greenhouse gas (GHG) concentrations were stabilized at year 2000 levels (not currently the case), an increase in global average temperature would still occur: 0.67°F (0.37°C) by 2011-2030, 0.85°F (0.47°C) by 2046-2065, 1.01°F (0.56°C) by 2080-2099, and 1.1°F (0.6°C) by 2090-2099 (all compared to a 1980-1999 baseline).^{94,95}
- Global average temperatures are projected to increase at least 3.2°F (1.8°C) under the B1 scenario and up to 7.2°F (4.0°C) under the A1F1 scenario by 2090-2099 compared to a 1980-1999 baseline.⁹⁶ The range of projected temperature increases is 2.0°F (1.1°C) to 11.5°F (6.4°C) by 2090-2099, compared to a 1980-1999 baseline (Figure 6).⁹⁷
- A study by Arora et al. (2011) suggests that limiting warming to roughly 3.6°F (2.0°C) by 2100 is unlikely since it requires an immediate ramp down of emissions followed by ongoing carbon sequestration after 2050.⁹⁸

⁹¹ Verbatim or nearly verbatim from NOAA. (2011)

⁹² Verbatim or nearly verbatim from NOAA. (2011, Fig. 1)

⁹³ Verbatim or nearly verbatim from NOAA. (2011, Fig. 2)

⁹⁴ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report: Summary for Policymakers*. (2007f, p. 8). See Figure SPM.1 for the information for 2090-2099.

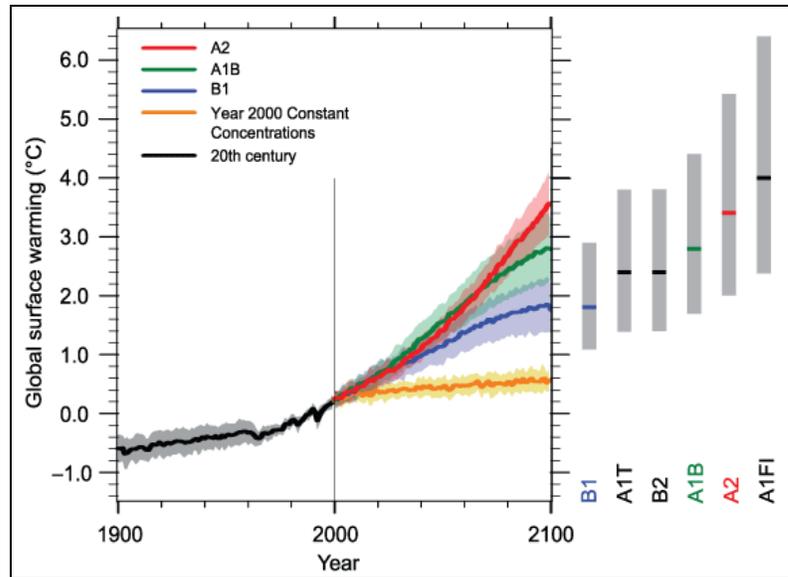
⁹⁵ Meehl et al. *Climate Change 2007: The Physical Science Basis*. (2007). Data for 2011-2030, 2046-2065, 2080-2099, and 2180-2199 were reproduced from Table 10.5 on p. 763. Data for 2090-2099 were obtained from p. 749.

⁹⁶ IPCC. *Climate Change 2007: Synthesis Report: Summary for Policymakers*. (2007f, p. 8). See Figure SPM.1.

⁹⁷ IPCC. *Climate Change 2007: Synthesis Report: Summary for Policymakers*. (2007f, Table SPM.3, p. 13). AOGCMs are Atmosphere Ocean General Circulation Models.

⁹⁸ Verbatim or nearly verbatim from Arora et al. *Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases*. (2011)

Figure 6. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ± 1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the **likely** range assessed for the six SRES marker scenarios. The assessment of the best estimate and **likely** ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29} Source: Reproduced from IPCC. (2007f, Fig. SPM.5, p. 14) by authors of this report.



Southcentral and Southeast Alaska (1960s-1970s baseline)

- By 2020, compared to a 1960-1970s baseline, average annual temperatures in Alaska are projected to rise 2.0°F to 4.0°F (1.1-2.2°C) under both the low-emissions B1 scenarios and higher-emissions A2 scenario.⁹⁹
- By 2050, average annual temperatures in Alaska are projected to rise 3.5°F to 6°F (1.9-3.3°C) under the B1 scenario, and 4°F to 7°F (2.2-3.9°C) under the A2 scenario (1960-1970s baseline).¹⁰⁰ Later in the century, increases of 5°F to 8°F (2.8-4.4°C) are projected under the B1 scenario, and increases of 8°F to 13°F (4.4-7.2°C) are projected under the A2 scenario (1960-1970s baseline).¹⁰¹
- On a seasonal basis, Alaska is projected to experience far more warming in winter than summer, whereas most of the United States is projected to experience greater warming in summer than in winter.¹⁰²
- No data were found for mean temperatures associated with the ranges reported here.

Western British Columbia (1961-1990 baseline)

- Along the North Coast by the 2050s, annual air temperature is projected to increase 2.5°F (1.4°C) compared to a 1961-1990 baseline (multi-model average; scenarios not provided).¹⁰³ Along the

⁹⁹ Karl, Melillo and Peterson. (2009, p. 139). See the figure titled *Observed and Projected Temperature Rise* (section on Regional Impacts: Alaska).

¹⁰⁰ Karl, Melillo and Peterson. (2009, p. 139)

¹⁰¹ Karl, Melillo and Peterson. (2009, p. 139)

¹⁰² Verbatim or nearly verbatim from Karl, Melillo and Peterson. (2009)

¹⁰³ Pike et al. *Compendium of forest hydrology and geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia*. (2010, Table 19.3, p. 711).

South Coast, annual air temperature is projected to increase 2.7°F (1.5°C) compared to a 1961-1990 baseline (multi-model average; scenarios not provided).¹⁰⁴ The North Coast extends from the border with Alaska to just north of Vancouver Island; the South Coast extends to the Washington border.¹⁰⁵

- Along the North Coast by 2050, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, temperatures are projected to increase 0°F to 6.3°F (0-3.5°C), and
 - In summer, temperatures are projected to increase 2.7°F to 5.4°F (1.5-3°C).¹⁰⁶
- Along the South Coast by 2050, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, temperatures are projected to increase 0°F to 5.4°F (0-3°C), and
 - In summer, temperatures are projected to increase 2.7°F to 9.0°F (1.5-5°C).¹⁰⁷

Pacific Northwest (1970-1999 baseline)

- Average annual temperature could increase beyond the range of year-to-year variability observed during the 20th century as early as the 2020s.¹⁰⁸ Annual temperatures, averaged across all climate models under the A1B and B1 scenarios, are projected to increase as follows (1970-1999 baseline):
 - By the 2020s: 2.0°F (1.1°C), with a range of 1.1°F to 3.4°F (0.61-1.9°C),
 - By the 2040s: 3.2°F (1.8°C), with a range of 1.6°F to 5.2°F (0.89-2.89°C), and
 - By the 2080s: 5.3°F (~3.0°C), with a range of 2.8°F to 9.7°F (1.56-5.4°C).¹⁰⁹
- Seasonal temperatures, averaged across all models under the B1 and A1B scenarios, are projected to increase as described in Table 4 (compared to a 1970-1999 baseline).

Table 4. Projected multi-model average temperature increases, relative to the 1970-1999 mean. (°F with °C in parentheses) *Source: Modified from Mote and Salathé, Jr. (2010, Fig. 9, p. 42) by authors of this report. Please see Figure 9 in the cited report for the range of each average shown below.*

	2020s		2040s		2080s	
	B1	A1B	B1	A1B	B1	A1B
Winter (Dec-Feb)	2.0 (1.1)	2.2 (1.2)	2.9 (1.6)	3.4 (1.9)	4.9 (2.7)	5.9 (3.3)
Spring (March-May)	1.8 (1.0)	1.8 (1.0)	2.5 (1.4)	3.1 (1.7)	3.8 (2.1)	5.0 (2.8)
Summer (June-Aug)	2.3 (1.3)	3.1 (1.7)	3.4 (1.9)	4.9 (2.7)	5.4 (3.0)	8.1 (4.5)
Fall (Sept-Nov)	1.8 (1.0)	2.0 (1.1)	2.7 (1.5)	3.6 (2.0)	4.3 (2.4)	6.1 (3.4)

¹⁰⁴ Pike et al. (2010, Table 19.3, p. 711)

¹⁰⁵ Please see the map available at <http://pacificclimate.org/resources/publications/mapview> (accessed 3.16.2011).

¹⁰⁶ B.C. Ministry of Environment. *Alive and Inseparable: British Columbia's Coastal Environment: 2006*. (2006, Table 10, p. 113). The authors make the following note: From data in the Canadian Institute for Climate Studies, University of Victoria (www.cics.uvic.ca) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000).

¹⁰⁷ B.C. Ministry of Environment. (2006, Table 10, p. 113). The authors make the following note: From data in the Canadian Institute for Climate Studies, University of Victoria (www.cics.uvic.ca) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000).

¹⁰⁸ Verbatim or nearly verbatim from CIG. *Climate Change Scenarios: Future Northwest Climate (website)*. (2008)

¹⁰⁹ CIG. *Climate Change: Future Climate Change in the Pacific Northwest (website)*. (2008, Table 3)

- In another look at the Pacific Northwest by the 2080s, temperatures are projected to increase 2.7 to 10.4 °F (1.5-5.8 °C), with a multi-model average increase of 4.5°F (2.5°C) under the B1 scenario and 6.1°F (3.4°C) under the A1B scenario (1970-1999 baseline).¹¹⁰

Northwest California (1961-1990 and 1971-2000 baselines)

- Compared to a 1961-1990 baseline under the B1 and A2 scenarios, California-wide annual average temperatures are projected to increase as follows:
 - By 2050: 1.8 to 5.4 °F (1-3 °C), and
 - By 2100: 3.6 to 9 °F (2-5 °C).¹¹¹
- In northwestern California, regional climate models project mean annual temperature increases of 3.1 to 3.4°F (1.7-1.9°C) by 2070 (no baseline provided).¹¹² In contrast, Ackerly et al. (2010) project a mean annual temperature increase of more than 3.6°F (2°C) but less than 5.4°F (3°C) by 2070-2099 (Figure 7; 1971-2000 baseline).¹¹³
 - By 2070, mean diurnal (i.e., daily) temperature range is projected to increase by 0.18 to 0.36°F (0.1-0.2°C) based on two regional climate models.¹¹⁴ No baseline was provided.
- In northern California, Cayan et al. (2008) project average annual temperature increases of 2.7°F (1.5°C) or 4.9°F (2.7°C) under the B1 scenario (PCM and GFDL models, respectively) and 4.7°F (2.6°C) or 8.1°F (4.5°C) (PCM and GFDL models, respectively) under the A2 scenario by 2070-2099 (1961-1990 baseline).¹¹⁵
- Seasonally, the projected impacts of climate change on thermal conditions in northwestern California will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures.¹¹⁶ Average seasonal temperature projections in northern California are as follows (1961-1990 baseline):¹¹⁷
 - Winter projections:
 - 2005-2034: at least ~0.18°F (0.1°C; A2, PCM model) and up to 2.5°F (1.4°C; A2, GFDL model).
 - 2035-2064: at least 1.6°F (0.9°C; A2, PCM model) and up to 4.3°F (2.4°C; B1, PCM model).
 - 2070-2099: at least 3.1°F (1.7°C; B1, PCM model) and up to 6.1°F (3.4°C; A2, GFDL model).

¹¹⁰ Mote, Gavin and Huyer. *Climate change in Oregon's land and marine environment*. (2010, p. 21)

¹¹¹ California Natural Resources Agency. *2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008*. (2009, p. 16-17). Figure 5 (p. 17) indicates projections are compared to a 1961-1990 baseline.

¹¹² Verbatim or nearly verbatim from Port Reyes Bird Observatory. *Projected effects of climate change in California: Ecoregional summaries emphasizing consequences for wildlife. Version 1.0 (pdf)*. (2011, p. 8)

¹¹³ Ackerly et al. (2010, Fig. S2, p. 9). Ackerly et al. use bias-corrected and spatially downscaled future climate projections from the CMIP-3 multi-model dataset. Data are downscaled to 1/8th degree spatial resolution (see p. 2).

¹¹⁴ Verbatim or nearly verbatim from Port Reyes Bird Observatory. *Projected effects of climate change in California: Ecoregional summaries emphasizing consequences for wildlife. Version 1.0 (pdf)*. (2011, p. 8). This data was based on two regional climate models presented in Stralberg et al. (2009).

¹¹⁵ Cayan et al. *Climate change scenarios for the California region*. (2008, Table 1, p. S25)

¹¹⁶ Verbatim or nearly verbatim from Port Reyes Bird Observatory. (2011, p. 8)

¹¹⁷ Cayan et al. (2008, Table 1, p. S25)

- Summer projections:
 - 2005-2034: at least ~1°F (0.6°C; B1, PCM model) and up to 3.8°F (2.1°C; A2, GFDL model).
 - 2035-2064: at least ~2.0°F (1.1°C; B1, PCM model) and up to 6.1°F (3.4°C; A2, GFDL model).
 - 2070-2099: at least 2.9°F (1.6°C; B1, PCM model) and up to ~12°F (6.4°C; A1, GFDL model).
- Coastal regions are likely to experience less pronounced warming than inland regions.¹¹⁸

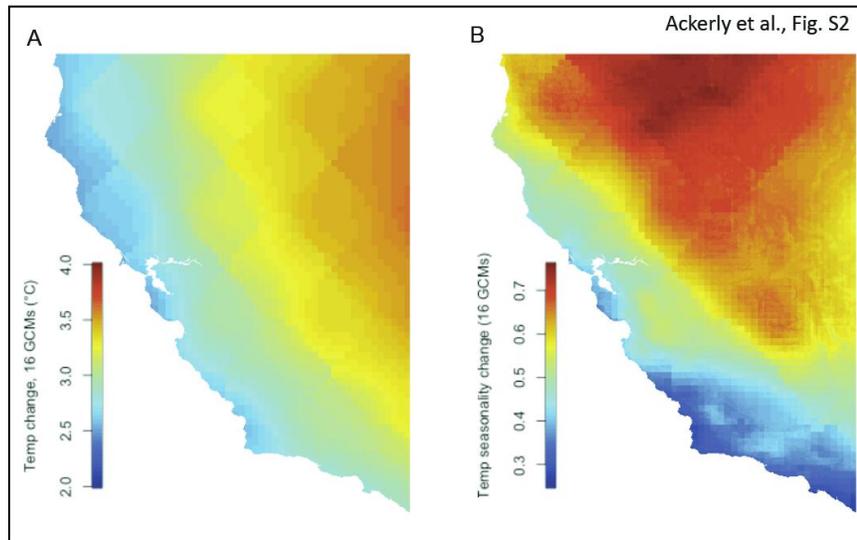


Figure 7. Changes in (A) mean annual temperature and (B) temperature seasonality, averaged over 16 GCMs, A1B scenario, for 2070-2099 (1971-2000 baseline).

Source: Reproduced from Ackerly et al. (2010, Fig. S2, p. 9) by authors of this report.

Note: Temperature seasonality is the standard deviation of monthly means. Lower values indicate temperature varies less throughout the year, i.e. temperature is more constant throughout the year in blue areas than in yellow and red areas.

¹¹⁸ Verbatim or nearly verbatim from California Natural Resources Agency. 2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008. (2009, p. 17)

3. PRECIPITATION – global and regional observed trends and future projections

Observed Trends

Note: Please see Box 4 for information on extreme precipitation in the NPLCC region.

Global (see also: projections below)

- Atmospheric moisture amounts are generally observed to be increasing after about 1973 (prior to which reliable atmospheric moisture measurements, i.e. moisture soundings, are mostly not available).¹¹⁹
- Most of the increase is related to temperature and hence to atmospheric water-holding capacity,¹²⁰ i.e. warmer air holds more moisture.

Southcentral and Southeast Alaska

- In southeast Alaska from 1949 to 1998, mean total annual precipitation was at least 39 inches (1000 mm).¹²¹ The maximum annual precipitation over this period was 219 inches (5577 mm) at the Little Port Walter station on the southeast side of Baranof Island about 110 miles (177 km) south of Juneau.¹²²
- In southcentral Alaska from 1949 to 1998, mean total annual precipitation was at least 32 inches (800 mm) and up to 39 inches (1000 mm).¹²³
- A comparison of official data from the National Climatic Data Center (NCDC) for 1971-2000 and unofficial National Weather Service (NWS) data for 1981-2010 for Juneau, Alaska indicates annual, warm season, and cold season precipitation increased.¹²⁴ The official NCDC record indicates average snowfall increased from 1971-2000 to 1981-2010, but the local NWS database indicates average snowfall decreased over the same time periods (Table 5, see notes).¹²⁵ In addition:
 - The date of first freeze occurred, on average, one day earlier over 1981 to 2010 than over 1971 to 2000, on October 3 instead of October 4.¹²⁶
 - The date of last freeze occurred two days earlier, on average, over 1981 to 2010 than over 1971 to 2000, on May 6 instead of May 8.¹²⁷

¹¹⁹ Verbatim or nearly verbatim from Trenberth et al. *The changing character of precipitation*. (2003, p. 1211). The authors cite Ross and Elliott (2001) for this information.

¹²⁰ Verbatim or nearly verbatim from Trenberth et al. (2003, p. 1211)

¹²¹ Stafford, Wendler and Curtis. *Temperature and precipitation of Alaska: 50 year trend analysis*. (2000, Fig. 7, p. 41).

¹²² Stafford, Wendler and Curtis. (2000, Fig. 7, p. 41)

¹²³ Stafford, Wendler and Curtis. (2000, Fig. 7, p. 41)

¹²⁴ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

¹²⁵ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

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¹²⁷ This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

Table 5. Annual and seasonal precipitation and date of freeze trends for Juneau, AK over two thirty-year time periods.

		1971-2000* inches (cm)	1981-2010* inches (cm)	Absolute Change inches (cm)	Percent Change [†]
Annual and date of freeze trends	Total annual precipitation (including melted snow)	58.33 (148.2)	62.17 (157.9)	+3.84 (+9.75)	+6.58
	Average snowfall (Jan-Dec, NWS/Juneau)	93.0 [#] (236)	86.8 (220)	-6.2 (-16)	-6.7
	Average snowfall (Jan-Dec, NCDC/Asheville)	84.1 [#] (214)	N/A*	N/A	N/A
	Date of first freeze, on average	October 4	October 3	One day earlier	N/A
	Date of last freeze, on average	May 8	May 6	Two days earlier	N/A
Warm season (April – Sept)	Average seasonal precipitation (mostly rain)	26.85 (68.20)	28.52 (72.44)	+1.67 (+4.24)	+6.22
	Average snowfall (NWS/Juneau)	1.0 (2.5)	1.1 (2.8)	+0.1 (+0.3)	+10
	Average snowfall (NCDC/Asheville)	1.0 (2.5)	N/A*	N/A	N/A
Cold season (Oct – March)	Average seasonal precipitation	31.48 (79.96)	33.65 (85.47)	+2.17 (+5.51)	+6.89
	Average snowfall (NWS/Juneau)	92.0 [#] (234)	85.7 (218)	-6.3 (-16)	-6.8
	Average snowfall (NCDC/Asheville)	83.1 [#] (211)	N/A*	N/A	N/A

*Data for 1971-2000 are official data from the National Climatic Data Center (NCDC). Data for 1981-2010 are preliminary, unofficial data acquired from Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The official data for 1981-2010 are scheduled for release by NCDC in July 2011. The table was created by the authors of this report and approved by Tom Ainsworth and Rick Fritsch on June 10, 2011.

[†]Percent change reflects the relative increase or decrease from 1971-2000 to 1981-2010.

[#]Two values for average snowfall for 1971-2000 are reported due to differences between the locally held National Weather Service (NWS) database in Juneau and the official NWS database in Asheville, North Carolina. Differences represent the quality assurance processing and filtering that occurs at the National Climatic Data Center (NCDC) in Asheville (the source of official U.S. climate data) as well as missing data in the NCDC record. The Juneau office of the NWS is investigating the discrepancy.

Western British Columbia

- Annual and seasonal precipitation trends over thirty, fifty, and 100-year time periods in the Georgia Basin and remaining coastal regions of B.C. within the NPLCC region are summarized in Table 6.¹²⁸ The Georgia Basin includes eastern Vancouver Island and a small portion of the mainland east of Vancouver Island; the coastal region includes all remaining areas in B.C. within the NPLCC region.¹²⁹

¹²⁸ Pike et al. (2010, Table 19.1, p. 701)

¹²⁹ Pike et al. (2010, Fig. 19.1, p. 702)

Table 6. Historical trends precipitation in 30-, 50-, and 100-year periods, calculated from mean daily values as seasonal and annual averages.
(inches per month per decade, with millimeters per month per decade in parentheses)
Source: Modified from Pike et al. (2010, Table 19.1, p. 701) by authors of this report.

	<i>Time period</i>	<i>Coastal B.C.</i>	<i>Georgia Basin</i>
Annual	30-year: 1971-2004	0.064 (1.63)	-0.017 (-0.42)
	50-year: 1951-2004	0.040 (1.01)	-0.017 (-0.43)
	100-year: 1901-2004	0.089 (2.25)	0.047 (1.20)
Winter (Dec-Feb)	30-year: 1971-2004	-0.24 (-6.08)	-0.32 (-8.06)
	50-year: 1951-2004	-0.12 (-3.06)	-0.21 (-5.35)
	100-year: 1901-2004	0.13 (3.39)	0.070 (1.78)
Summer (June-Aug)	30-year: 1971-2004	0.14 (3.50)	-0.071 (-1.80)
	50-year: 1951-2004	0.083 (2.11)	-0.011 (-0.27)
	100-year: 1901-2004	0.036 (0.91)	0.034 (0.93)

Pacific Northwest

- Annual precipitation increased 12.9% (6.99"; 17.76 cm) from 1920 to 2000.¹³⁰
- Observed relative increases were largest in the spring (+37%; +2.87"; 7.29 cm), followed by winter (+12.4%; 2.47"; 6.27 cm), summer (+8.9%; +0.39"; 0.99 cm), and autumn (+5.8%; +1.27"; 3.22 cm) from 1920 to 2000.¹³¹ The spring trend (April-June) is significant at the p < 0.05 level.¹³²
- *Note: For the reader interested in trends in mean temperature, maximum temperature, minimum temperature, and precipitation annually, seasonally, and monthly, an online mapping tool produced by the Office of the Washington State Climatologist is available at <http://www.climate.washington.edu/trendanalysis/> (accessed 6.8.2011).*

¹³⁰ Mote. *Trends in temperature and precipitation in the Pacific Northwest during the Twentieth Century.* (2003, p. 279)

¹³¹ Mote. (2003, p. 279)

¹³² Mote. (2003, p. 279)

Northwest California

- A preliminary study found annual precipitation increased 2 to 6 inches (~5-15cm) from 1925 to 2008.¹³⁹ There also appears to be a shift in seasonality of precipitation: an increase in winter and early spring precipitation and a decrease in fall precipitation from 1925 to 2008.¹⁴⁰
- From 1925 to 2008, the daily rainfall totals show a shift from light rains to more moderate and heavy rains that is especially evident in northern regions.¹⁴¹ The increase in precipitation intensity over this time period is similar to results from other regions of the United States.¹⁴²

Future Projections

Note: The studies presented here differ in the baseline used for projections. Baselines include 1961-1990 (BC, CA) and 1970-1999 (WA, OR).

Note: Please see Box 4 for information on extreme precipitation in the NPLCC region.

Global

- Global precipitation patterns are projected to follow observed recent trends, increasing in high latitudes and decreasing in most subtropical land regions.¹⁴³ Overall, precipitation may be more intense, but less frequent, and is more likely to fall as rain than snow.¹⁴⁴
- *Note: There is greater confidence overall in*

Box 4. Trends and projections for extreme precipitation in the NPLCC region.

Trends. In the Pacific Northwest, trends in extreme precipitation are ambiguous.¹³³ Groisman et al. (2004) find no statistical significance in any season in the Pacific Northwest (1908-2000).¹³⁴ Madsen and Figdor (2007) find a statistically significant increase of 18% (13-23%) in the Pacific states (WA, OR, CA), a statistically significant increase of 30% (19-41%) in Washington, and a statistically significant decrease of 14% (-4 to -24%) in Oregon (1948-2006).¹³⁵ In southern British Columbia and along the North Coast, Vincent and Mekis (2006) report some stations showed significant increases in very wet days (the number of days with precipitation greater than the 95th percentile) and heavy precipitation days ($\geq 0.39''$, 1.0cm).¹³⁶ A limited number of stations also showed significant decreases.

Projections. Precipitation patterns in the Northwest are expected to become more variable, resulting in increased risk of extreme precipitation events, including droughts.¹³⁷ In northern California, daily extreme precipitation occurrences (99.9 percentile) are projected to increase from 12 occurrences (1961-1990) to 25 (+108%) or 30 (+150%) occurrences by 2070-2099 under A2 simulations in the PCM and GFDL models, respectively.¹³⁸

¹³³ Mote et al. (2010, p. 17)

¹³⁴ Groisman et al. (2004, Fig. 8, p. 71)

¹³⁵ Madsen and Figdor. (2007, App. A & B, p. 35-37)

¹³⁶ Vincent and Mekis. (2006, Fig. 5, p. 186)

¹³⁷ Capalbo et al. (2010, p. 374)

¹³⁸ Cayan et al. (2008, Table 4, p. S30). For the 99 percentile, the occurrence of extreme precipitation is projected to increase from 111 (1961-1990) to 161 (45%) or 127 (~14%) occurrences by 2070-2099 under A2 simulations in the PCM and GFDL models, respectively.

¹³⁹ Killam et al. *California rainfall is becoming greater, with heavier storms.* (2010, p. 2)

¹⁴⁰ Verbatim or nearly verbatim from Killam et al. (2010, p. 4)

¹⁴¹ Verbatim or nearly verbatim from Killam et al. (2010, p. 3)

¹⁴² Verbatim or nearly verbatim from Killam et al. (2010, p. 3)

¹⁴³ Verbatim or nearly verbatim from IPCC. (2007f, p. 8)

¹⁴⁴ Verbatim or nearly verbatim from Karl, Melillo and Peterson. (2009).

projected temperature changes than projected changes in precipitation given the difficulties in modeling precipitation¹⁴⁵ and the relatively large variability in precipitation (both historically and between climate model scenarios) compared with temperature.

Southcentral and Southeast Alaska (1961-1990 and 2000 baseline)

- Climate models project increases in precipitation over Alaska.¹⁴⁶ Simultaneous increases in evaporation due to higher air temperatures, however, are expected to lead to drier conditions overall, with reduced soil moisture.¹⁴⁷
 - Using a composite of five Global Circulation Models (GCMs) under the A1B scenario,¹⁴⁸ one study projects an average increase of 0.59 inches (15 mm) by 2090-2099 (1961-1990 baseline), from a mean of 3.1 inches (78 mm) in the 1961-1990 period to a mean of 3.7 inches (93 mm) in the 2090-2099 period, an approximately 19% increase from the 1961-1990 mean at the rate of approximately 0.059 inches per decade (+1.5 mm/decade).¹⁴⁹
- In the coastal rainforests of southcentral and southeast Alaska, precipitation during the growing season (time period between last spring freeze and first fall frost) is projected to increase approximately four inches (~100 mm, or 5.7%) from 2000 to 2099, from approximately 69 inches (~1750 mm) in 2000 to approximately 73 inches (1850 mm) in 2099 using a GCM composite (scenario not provided).¹⁵⁰
- The University of Alaska – Fairbanks Scenarios Network for Alaska Planning (SNAP) has web-based mapping tools for viewing current and future precipitation under the B1, A1B, and A2 scenarios for the 2000-2009, 2030-2039, 2060-2069, and 2090-2099 decades (baseline not provided). Tools are available at <http://www.snap.uaf.edu/web-based-maps> (accessed 3.16.2011).¹⁵¹

Western British Columbia (1961-1990 baseline)

- By the 2050s, annual precipitation is projected to increase 6% (range not provided) along the B.C. coast compared to a 1961-1990 baseline (multi-model average; scenarios not provided).¹⁵²
- Along the North Coast by the 2050s, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, precipitation is projected to increase 6%¹⁵³ (0 to +25%).¹⁵⁴

¹⁴⁵ CIG. *Climate Change: Future Climate Change in the Pacific Northwest (website)*. (2008) The authors cite the IPCC AR4, Chapter 8 of the Working Group I report, for this information.

¹⁴⁶ Karl, Melillo and Peterson. (2009, p. 139)

¹⁴⁷ Verbatim or nearly verbatim from Karl, Melillo and Peterson. (2009, p. 139). The authors cite Meehl et al. (2007) for this information.

¹⁴⁸ Alaska Center for Climate Assessment and Policy. *Climate Change Impacts on Water Availability in Alaska (presentation)*. (2009, p. 10-11)

¹⁴⁹ Alaska Center for Climate Assessment and Policy. (2009, p. 13)

¹⁵⁰ Alaska Center for Climate Assessment and Policy. (2009, p. 31)

¹⁵¹ Maps are also available for current and future mean annual temperature, date of thaw, date of freeze up, and length of growing season. The scenario and decadal options are the same as those described for precipitation.

¹⁵² Pike et al. (2010, Table 19.3, p. 711)

¹⁵³ Pike et al. (2010, Table 19.3, p. 711)

¹⁵⁴ B.C. Ministry of Environment. (2006, Table 10, p. 113). B.C. Ministry of Environment makes the following note: “From data in the Canadian Institute for Climate Studies, University of Victoria (www.cics.uvic.ca) study of model

- In spring, precipitation is projected to increase 7% (range not provided).¹⁵⁵
- In summer, precipitation is projected to decrease 8%¹⁵⁶ (-25 to +5%).¹⁵⁷
- In fall, precipitation is projected to increase 11% (range not provided).¹⁵⁸
- Along the South Coast by the 2050s, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
 - In winter, precipitation is projected to increase 6%¹⁵⁹ (-10 to +25%).¹⁶⁰
 - In spring, precipitation is projected to increase 7% (range not provided).¹⁶¹
 - In summer, precipitation is projected to decrease 13%¹⁶² (-50 to 0%).¹⁶³
 - In fall, precipitation is projected to increase 9% (range not provided).¹⁶⁴

Pacific Northwest (1970-1999 baseline)

- Annual average precipitation is projected to increase as follows (1970-1999 baseline):
 - By 2010-2039, precipitation is projected to increase 1% (-9 to +12%),
 - By 2030-2059, precipitation is projected to increase increase 2% (-11 to +12%), and
 - By 2070-2099, precipitation is projected to increase 4% (-10 to +20%).¹⁶⁵
- Winter projections are as follows (1970-1999 baseline):
 - In 2010-2039 and 2030-2059, 58 to 90% of models project increases in precipitation.¹⁶⁶
 - In 2070-2099, an 8% increase in precipitation is projected (small decrease to +42%; 1.2 inches; ~3cm).¹⁶⁷
- Summer precipitation is projected to decrease 14% by the 2080s, although some models project decreases of 20 to 40% (1.2-2.4 inches; 3-6cm) compared to a 1970-1999 baseline.¹⁶⁸
- These regionally averaged precipitation projections reflect all B1 and A1B simulations, along with the weighted reliability ensemble average (REA, an average that gives more weight to models that perform well in simulating 20th century climate).¹⁶⁹

results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000).”

¹⁵⁵ Pike et al. (2010, Table 19.3, p. 711)

¹⁵⁶ Pike et al. (2010, Table 19.3, p. 711)

¹⁵⁷ B.C. Ministry of Environment. (2006, Table 10, p. 113)

¹⁵⁸ Pike et al. (2010, Table 19.3, p. 711)

¹⁵⁹ Pike et al. (2010, Table 19.3, p. 711)

¹⁶⁰ B.C. Ministry of Environment. (2006, Table 10, p. 113)

¹⁶¹ Pike et al. (2010, Table 19.3, p. 711)

¹⁶² Pike et al. (2010, Table 19.3, p. 711)

¹⁶³ B.C. Ministry of Environment. (2006, Table 10, p. 113).

¹⁶⁴ Pike et al. (2010, Table 19.3, p. 711)

¹⁶⁵ The range of precipitation reported here was obtained from the Climate Impacts Group. It can be found in a document titled *Summary of Projected Changes in Major Drivers of Pacific Northwest Climate Change Impacts*. A draft version is available online at

http://www.ecy.wa.gov/climatechange/2010TAGdocs/20100521_projecteddrrivers.pdf (last accessed 1.5.2011).

¹⁶⁶ Mote and Salathé Jr. *Future climate in the Pacific Northwest*. (2010, p. 43-44)

¹⁶⁷ Mote and Salathé Jr. (2010, p. 43-44)

¹⁶⁸ Mote and Salathé Jr. (2010, p. 42)

¹⁶⁹ Mote and Salathé Jr. (2010, p. 39)

Northwest California (1961-1990 baseline)

- Annual average precipitation is projected to decrease 12 to 35% by mid-century, with further decreases expected by 2070-2099 compared to a 1961-1990 baseline.¹⁷⁰ Over 2005-2034, small to moderate decreases are projected compared to a 1961-1990 baseline.¹⁷¹ These projections are based on six climate models using the A2 and B1 emissions scenarios.¹⁷²

Information Gaps

- Information on seasonal temperature projections in California is needed.
- One reviewer suggested updated regional runs could be made for Oregon and Washington.
- Peterson and Schwing (2008) identify four categories of information needs for the California Current region (south of Vancouver, B.C.) – climate data, monitoring, models, and climate products and forecasts:
 - Climate data are needed to provide the climate forcing and environmental context for climate impacts on the CCE, for developing science-based operational indicators, and to provide continuity of satellite data and products.¹⁷³
 - Monitoring needs include large-scale monitoring to provide information on gyre-scale circulation, monitoring in the coastal region, and maintaining NDBC monitoring and data archives.¹⁷⁴
 - Modeling of climate and atmospheric and oceanic physics needs to be linked with similar work being carried out by NOAA and its partners.¹⁷⁵
 - Climate product and forecasting needs include indicators and indices of climate variability, seasonal and longer-term forecasts and projections, and additional research to understand the mechanisms linking equatorial ENSO processes and teleconnections with California Current conditions and their populations.¹⁷⁶

¹⁷⁰ Verbatim or nearly verbatim from California Natural Resources Agency. (2009, p. 17-18)

¹⁷¹ Verbatim or nearly verbatim from California Natural Resources Agency. (2009, p. 17-18)

¹⁷² California Natural Resources Agency. (2009, p. 17-18)

¹⁷³ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (authors). Osgood (Ed.). *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs: California Current Ecosystem*. (2008, p. 49)

¹⁷⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (authors). Osgood (Ed.). (2008, p. 49)

¹⁷⁵ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (authors). Osgood (Ed.). (2008, p. 49)

¹⁷⁶ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (authors). Osgood (Ed.). (2008, p. 50)

III. MAJOR CLIMATE IMPACTS ON MARINE & COASTAL ENVIRONMENTS

Coastal and marine ecosystems are tightly coupled to both the adjacent land and open ocean ecosystems and are thus affected by climate in multiple ways.¹⁷⁷ Coastal and near-shore ecosystems are vulnerable to a host of climate change-related effects, including increasing air and water temperatures, ocean acidification, altered terrestrial runoff patterns, altered currents, sea level rise, and altered human pressures due to these and other related changes (such as developing, shipping, pollution, and anthropogenic adaptation strategy implementation).¹⁷⁸ Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations including global and regional synthesis reports (see PREFACE), the following major climate-driven impacts on coastal and marine environments in the NPLCC region have been identified:

1. Ocean acidification
2. Increasing sea surface temperature
3. Altered hydrology
4. Altered ocean currents
5. Increased frequency and severity of storms
6. Sea level rise
7. Coastal upwelling
8. Coastal hypoxia and anoxia

These eight impacts will be discussed in the order listed. The first three impacts – ocean acidification, increasing sea surface temperature, and altered hydrology – are primarily affected by changes in CO₂ concentrations, temperature, and precipitation, as discussed in the previous chapter (Chapter II). The remaining five impacts – altered ocean currents, increased frequency and severity of storms, sea level rise, coastal upwelling, and coastal hypoxia and anoxia – are primarily affected by other climate impacts (Figure 8). The following structure will be used to discuss all impacts, with the exception of altered hydrology, for which effects on the marine environment are discussed briefly and the reader is referred to a forthcoming report for further detail:

- **Section summary box** – summary of the section’s key points
- **Definition and causes of impact** – definition and description of physical, chemical, and/or biological dynamics and processes contributing to each impact
- **Observed trends** – observed changes, compared to the historical baseline, at the global level and for each jurisdiction (Alaska, British Columbia, Washington, Oregon, California)
- **Future projections** – projected direction and/or magnitude of future change at the global level and for each jurisdiction (Alaska, British Columbia, Washington, Oregon, California)
- **Information gaps** – information and research needs identified by reviewers and literature searches.

¹⁷⁷ Verbatim or nearly verbatim from Janetos et al. *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States*. (2008, p. 159)

¹⁷⁸ Verbatim or nearly verbatim from Janetos et al. (2008, p. 159)

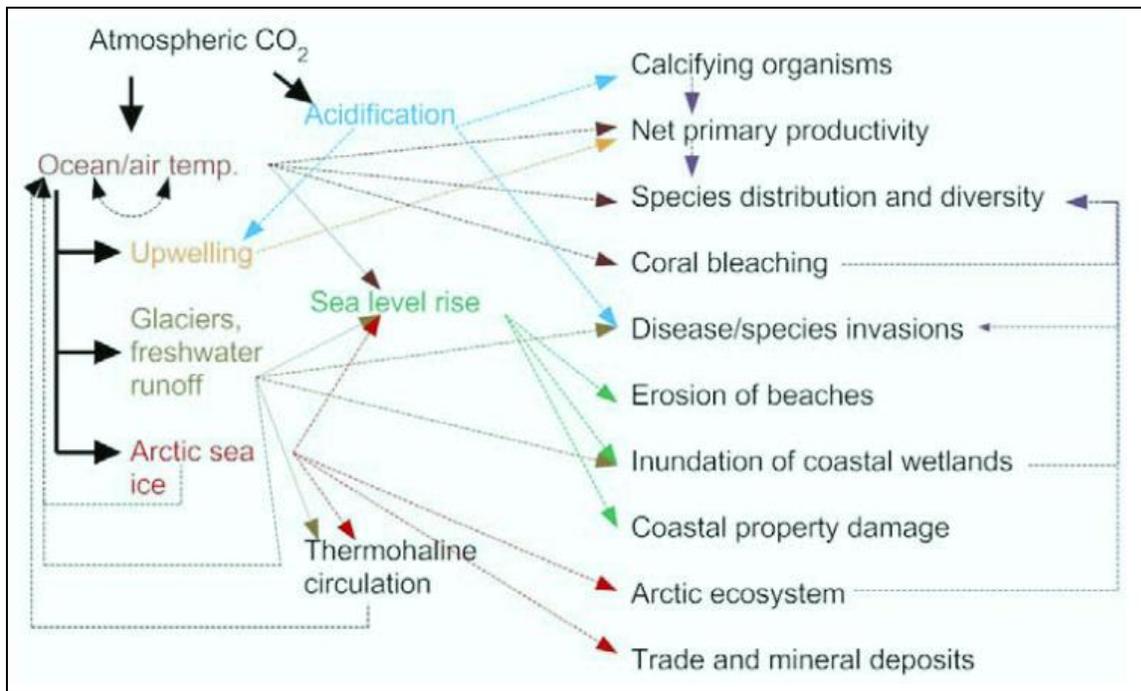


Figure 8. A sample of the impacts and potential feedbacks in oceans and coastal systems from greenhouse gas emissions. *Source: Reproduced from Kling and Sanchirico. An Adaptation Portfolio for the United States Coastal and Marine Environment. (2009, Fig. 3, p. 9) by authors of this report.*

1. OCEAN ACIDIFICATION

Box 5. Summary of observed trends and future projections in ocean acidification

Observed Trends

- By the early 21st century, global ocean pH had declined from 8.2 to 8.1 compared to pre-industrial times (~1765), increasing the ocean's acidity by approximately 26%.¹⁷⁹ pH declines in the NPLCC region are consistent with those observed globally.¹⁸⁰
- In the early 21st century, the fraction of total anthropogenic CO₂ emissions stored in the ocean was approximately one-third of the long-term potential.¹⁸¹
- In May and June 2007, ocean water detrimental to shell-making was observed in shallow waters off the Pacific coast (Queen Charlotte Sound in B.C. south to Baja California), a condition that was not predicted to occur in open ocean surface waters until 2050.¹⁸²

Future Projections

- Surface water pH will drop to approximately 7.8 by 2100, increasing the ocean's acidity by about 150% relative to the beginning of the industrial era (~1750; A2 scenario).¹⁸³ For the NPLCC region, pH is projected to decline by 0.14 and 0.15 in the subpolar and North Pacific Ocean (>50°N), respectively (with doubling of atmospheric CO₂ compared to ~1750, ~550ppm).¹⁸⁴
- In the NPLCC region, the concentration of carbonate ion, and saturation states of aragonite and calcite are projected to decrease 24.7% in the subpolar Pacific Ocean and 26.5% in the North Pacific Ocean north of 50°N (compared to a projected 25% decrease globally¹⁸⁵).¹⁸⁶ Specifically, with a doubling of atmospheric CO₂ (~550 ppm) compared to pre-industrial levels (~280 ppm):¹⁸⁷
 - *The mean concentration of carbonate ion* decreases 33.2 μmol/kg, from 134.5 to 101.3 μmol/kg in the subpolar Pacific Ocean and 4.5 μmol/kg, from 92.3 to 67.8 μmol/kg in the North Pacific Ocean.
 - *The saturation state of aragonite* decreases by 0.51, from 2.06 to 1.55, in the subpolar Pacific Ocean and 0.37, from 1.4 to 1.03 in the North Pacific Ocean.
 - *The saturation state of calcite* decreases by 0.80, from 3.24 to 2.44, in the subpolar Pacific Ocean and 0.59, from 2.24 to 1.65 in the North Pacific Ocean.

As a note to the reader, the oxidation of organic matter, which is mediated by microorganisms, also lowers seawater pH by adding CO₂ into solution (i.e. seawater).¹⁸⁸ However, these biological processes take place naturally and we focus in this report on changes to ocean chemistry as a result of anthropogenic emissions of carbon dioxide, otherwise known as ocean acidification.

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

¹⁷⁹ Orr et al. (2005); Feely et al. (2009)

¹⁸⁰ Feely et al. (2009); Hauri et al. (2009)

¹⁸¹ Verbatim or nearly verbatim from Sabine et al. (2004, p. 367)

¹⁸² Verbatim or nearly verbatim from Feely et al. (2008, p. 1491)

¹⁸³ Feely et al. (2009, p. 37)

¹⁸⁴ Feely et al. (2009, Table 2, p. 46)

¹⁸⁵ Cooley et al. (2009, p. 172-173) The authors cite Cooley and Doney (2009) for this information. This projection corresponds to CO₂ concentrations reaching 467 to 555 ppm by 2050.

¹⁸⁶ Feely et al. (2009, Table 2, p. 46)

¹⁸⁷ Feely et al. (2009, Table 2, p. 46)

¹⁸⁸ Byrne et al. (2010, p. 1). The authors cite Millerio (2007) for this information.

Definition and Causes of Ocean Acidification

Ocean acidification (Figure 9) is a process that occurs when anthropogenic carbon dioxide is absorbed by seawater, initiating chemical reactions that reduce seawater pH, carbonate ion concentration, and saturation states of the biologically important calcium carbonate minerals calcite and aragonite:¹⁸⁹

- **Reduced seawater pH:** pH is a measure of the concentration of hydrogen ions in a solution;¹⁹⁰ the more acidic a solution, the higher the concentration of hydrogen ions. The reaction of dissolved carbon dioxide and seawater forms carbonic acid, which dissociates to form hydrogen ions and bicarbonate.¹⁹¹ The increased concentration of hydrogen ions is reflected in reduced seawater pH.
- **Reduced carbonate ion concentration:** Most of the hydrogen ions formed in the dissociation described above react with carbonate ions to produce additional bicarbonate, thereby decreasing carbonate ion concentrations.¹⁹²
- **Reduced saturation state of biologically important calcium carbonate minerals, aragonite and calcite:** The decrease in carbonate ions described above reduces the saturation state of calcium carbonate, which directly affects the ability of some organisms (e.g. mollusks, corals) to produce their shells or skeletons.¹⁹³ It may also enhance dissolution of nutrients and carbonate minerals in sediments.¹⁹⁴ Seawater is supersaturated with respect to aragonite and calcite when the saturation state (Ω) is greater than 1 ($\Omega > 1$) and calcification (i.e., shell-building) is favored over dissolution (i.e., shell dissolution).¹⁹⁵ For most open ocean surface waters, undersaturation ($\Omega < 1$) occurs when the concentration of aragonite and calcite falls below ~66 and ~42 micromoles per kilogram ($\mu\text{mol/kg}$), respectively.¹⁹⁶ Further, calcium carbonate becomes more soluble (i.e., dissolves more easily) with decreasing temperature and increasing pressure, and hence with ocean depth.¹⁹⁷ As a

Understanding pH

pH is measured on a 0 to 14 scale. A pH less than 7 is acidic (e.g. lemon juice), a pH of 7 is neutral (e.g. pure water), and a pH greater than 7 is basic (e.g. ammonia). The scale itself is logarithmic, such that a solution with a pH of 6 is ten times more acidic than a solution with a pH of 7. Any decrease in pH makes the solution more acidic, while any increase in pH makes a solution more basic. Thus, a decline in pH from 9 to 8 makes the solution more acidic, even though it is still basic.

¹⁸⁹ Verbatim or nearly verbatim from Feely et al. *Ocean acidification: present conditions and future changes in a high CO₂ world*. (2009, p. 37)

¹⁹⁰ More precisely, pH is calculated as the \log_{10} of the concentration of hydrogen cations $[\text{H}^+]$ in solution: $\text{pH} = \log_{10}[\text{H}^+]$.

¹⁹¹ Verbatim or nearly verbatim from Feely et al. (2009, p. 38)

¹⁹² Verbatim or nearly verbatim from Feely et al. (2009, p. 39)

¹⁹³ Verbatim or nearly verbatim from Feely et al. (2009, p. 39)

¹⁹⁴ Nicholls et al. (2007, p. 328). The authors cite Mackenzie et al. (2001) and Caldeira and Wickett (2005) for information on seawater pH and carbonate saturation. The authors cite Andersson et al. (2003), Royal Society (2005), and Turley et al. (2006) for information on the consequences of decreased seawater pH and carbonate saturation.

¹⁹⁵ Verbatim or nearly verbatim from Feely et al. (2009, p. 39)

¹⁹⁶ Verbatim or nearly verbatim from Feely et al. (2009, p. 42). Note that these are not absolute values, and may be affected by temperature, salinity, pressure, and the interactive effects of the three.

¹⁹⁷ Verbatim or nearly verbatim from United Kingdom Royal Society. *Ocean acidification due to increasing atmospheric carbon dioxide*. (2005, p. 10)

result, a natural boundary develops in seawater.¹⁹⁸ This is known as the “saturation horizon” (where $\Omega_{\text{aragonite}}$ or $\Omega_{\text{calcite}} = 1$) and it identifies a clear depth of seawater above which calcium carbonate can form, but below it calcium carbonate can dissolve.¹⁹⁹ One reviewer noted that since many of these processes are often biologically mediated, the saturation state when dissolution actually begins can vary from species to species.²⁰⁰

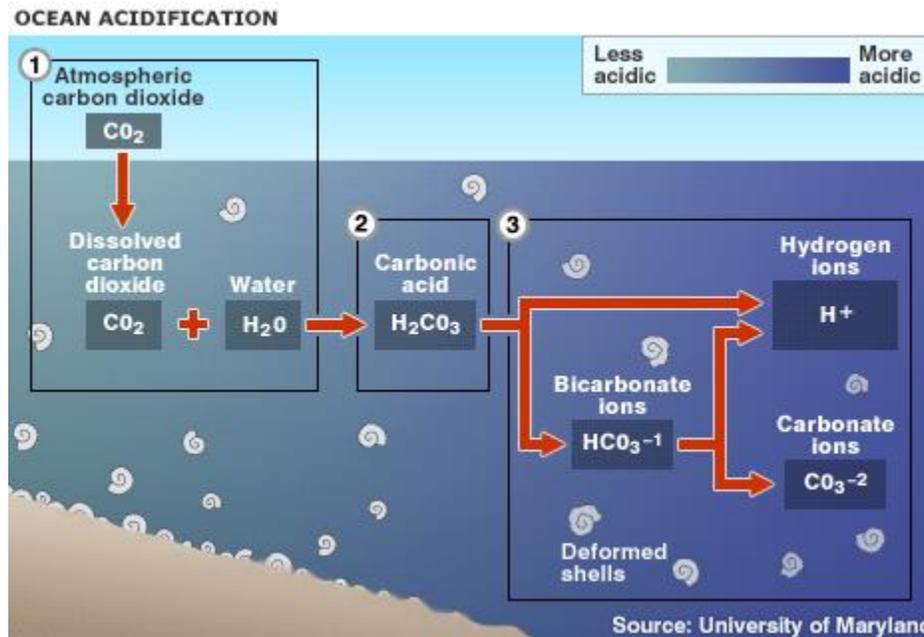


Figure 9. Ocean acidification.

Source: Reproduced from <http://news.bbc.co.uk/2/hi/science/nature/7933589.stm> by authors of this report.²⁰¹

Observed Trends

Global

At the end of the Pleistocene (~10,000 years ago), ocean pH was basically stable at 8.2 – a value that persisted until the beginning of the Industrial Revolution.²⁰² Since the Industrial Revolution, the oceans have absorbed about 540 billion metric tonnes of carbon dioxide from the atmosphere – this is 22 million

¹⁹⁸ Verbatim or nearly verbatim from U.K. Royal Society. (2005, p. 10)

¹⁹⁹ Verbatim or nearly verbatim from U.K. Royal Society. (2005, p. 10)

²⁰⁰ Comment from reviewer, April 2011.

²⁰¹ BBC News. *The key effects of climate change* (website accessed June 8, 2011). (2009).

²⁰² Fierstein. *Scientists and decision-makers discuss the fate of the ocean* (Illustration of the ecosystem effects of ocean acidification) (website). (2007)

metric tonnes per day, or about 30% of anthropogenic carbon emissions.²⁰³ Global ocean pH has declined 0.1 unit relative to its pre-industrial value.²⁰⁴

Because anthropogenic CO₂ enters the ocean by gas exchange across the air-sea interface, the highest concentrations of anthropogenic CO₂ are found in near-surface waters.²⁰⁵ About thirty percent of the anthropogenic CO₂ is found at depths shallower than 656 feet (200 meters) and nearly fifty percent at depths above 1312 feet (400 meters).²⁰⁶ Waters at these depths are commonly upwelled into nearshore zones, where relatively CO₂ rich waters may inhibit shell formation and maintenance, as described in Section 7 of this Chapter (Altered patterns of coastal upwelling), Chapter VI.2 (Altered phenology and development), and Chapter VII.4 (Shellfish). One reviewer noted that upwelling originates from a depth range of 492 to 656 feet (150-250 meters) on the West Coast.²⁰⁷

North Pacific Ocean²⁰⁸

Between 1991 and 2006 in the North Pacific Ocean between Oahu, Hawaii and Kodiak, Alaska (22 – 56 °N) along the 156 °W meridian, Byrne et al. (2010) observed significant upper ocean acidification, roughly keeping pace with rising atmospheric carbon dioxide.²⁰⁹ Estimation of how much of the observed pH change was attributable to naturally-created as opposed to human-generated CO₂ inputs indicates the human “signal” extends to depths of approximately 492 feet (150 m) and up to 1,640 feet (500 m) throughout the study region.²¹⁰ In the surface mixed layer (depths to ~328 feet or 100 m), the extent of pH change is consistent with that expected under conditions of seawater-atmosphere equilibration, with an average rate of change of -0.0017/yr.²¹¹

Southern British Columbia, Washington, Oregon, and northwest California

In the California Current System (CCS) off the west coast of North America, high variability in ocean carbonate chemistry, largely driven by seasonal upwelling of waters with low pH and saturation states, and subsequent interactions of transport and biological production has been found.²¹²

- Model simulations confirm that the pH of CCS waters has decreased by about 0.1 pH unit and by 0.5 in saturation state since pre-industrial times.²¹³

²⁰³ The total uptake since the Industrial Revolution is cited in Sabine et al. (2004, p. 367). The conversion to units of billion metric tonnes of CO₂ is provided by an expert reviewer, who refers the reader to Sabine et al. (2011). The global ocean carbon cycle. In *State of the Climate in 2010. 3. Global Oceans. Bulletin of Am. Meteor. Soc.* [Submitted].; The daily uptake is cited in Feely et al. (2008, p. 1490).

²⁰⁴ Verbatim or nearly verbatim from Orr et al. *Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms.* (2005).

²⁰⁵ Verbatim or nearly verbatim from Sabine et al. *The oceanic sink for anthropogenic CO₂.* (2004, p. 368)

²⁰⁶ Verbatim or nearly verbatim from Sabine et al. (2004, p. 368)

²⁰⁷ Comment from reviewer, April 2011.

²⁰⁸ The North Pacific is defined here as the Pacific Ocean, north of the equator.

²⁰⁹ Verbatim or nearly verbatim from Byrne et al. *Direct observations of basin-wide acidification of the North Pacific Ocean.* (2010, p. 4),

²¹⁰ Verbatim or nearly verbatim from Byrne et al. (2010, p. 2-3). The anthropogenic influence is observed to more than 500 m between the 22nd and 38th parallels. The 38th parallel intersects the Port Reyes National Seashore (CA), just south of the southern extent of the NPLCC. The northern extent of the NPLCC falls at approximately the 61st parallel, near Anchorage, AK.

²¹¹ Verbatim or nearly verbatim from Byrne et al. (2010, p. 1)

²¹² Verbatim or nearly verbatim from Hauri et al. *Ocean acidification in the California Current System.* (2009, p. 61)

²¹³ Verbatim or nearly verbatim from Hauri et al. (2009, p. 61)

- Water masses acidic enough to be detrimental to shell-making have risen 164 to 328 feet (50-100 m) since pre-industrial times.²¹⁴ These water masses are now within the density layers that are currently being upwelled along the west coast of North America.²¹⁵ For example:
 - In May and June 2007, Feely et al. (2008) observed the entire water column shoreward of the 164 foot (50 m) bottom contour was undersaturated with respect to aragonite, a condition that was not predicted to occur in open ocean surface waters until 2050.²¹⁶
 - Feely et al. (2008) also estimated the contribution of anthropogenic CO₂ to these upwelled waters, concluding without the anthropogenic signal, the equilibrium aragonite saturation level ($\Omega_{\text{aragonite}} = 1$) would be deeper by about 164 feet (50 m) across the shelf, and no undersaturated waters would reach the surface.²¹⁷

***Upwelling** is the replacement of surface ocean water by colder, saltier, nutrient and CO₂-rich but oxygen-poor, intermediate-depth ocean water. Upwelling occurs when alongshore winds blow toward the equator along the western margin of continents, pushing surface water offshore. The surface water is replaced by intermediate-depth water moving up the continental shelf toward shore. For more information on coastal upwelling and climate change interactions in the NPLCC region, please see the section “Altered patterns of coastal upwelling.” Source: Hauri et al. (2009); Feely et al. (2008).*

Further, in May and June 2007, Feely et al. (2008) gathered information on the location and depth of corrosive waters ($\Omega_{\text{aragonite}} < 1$; pH < 7.75) in the California Current System, which extends from southern British Columbia south to the Baja Peninsula in Mexico.²¹⁸ Results for the NPLCC region include:

- At the northern end of the study region, from Queen Charlotte Sound to northern Vancouver Island (BC), corrosive waters were observed at a depth of 459 feet (140 m) in most areas, with corrosive waters reaching shallower depths in a few areas (~394 feet; 120 m).²¹⁹
- Corrosive waters reached mid-shelf depths (~131-394 ft; ~40-120 m) off the coast of central Vancouver Island south to the central Oregon coast.²²⁰ Corrosive waters were, in general, found in the top 262 feet (80 m) of the water column along the coastline, with shallower depths observed off the coast of northern Oregon (<197 feet; < 60 m).²²¹
- Corrosive waters were found in the top 131 feet (40 m) of the water column along the coast from central Oregon to the southern boundary of the NPLCC region, and reached the surface near Crescent City (CA).²²²

²¹⁴ Verbatim or nearly verbatim from Feely et al. *Evidence for upwelling of corrosive "acidified" water onto the continental shelf.* (2008)

²¹⁵ Verbatim or nearly verbatim from Feely et al. (2008, p. 1491)

²¹⁶ Verbatim or nearly verbatim from Feely et al. (2008, p. 1491)

²¹⁷ Verbatim or nearly verbatim from Feely et al. (2008, p. 1492)

²¹⁸ Feely et al. (2008)

²¹⁹ Feely et al. (2008, Fig. 1, p. 1490) The authors of this report extrapolated this information from Figure 1.

²²⁰ Feely et al. (2008, p. 1491) The authors refer to Figure 1, p. 1490.

²²¹ Feely et al. (2008, p. 1491) The authors refer to Figure 1, p. 1490.

²²² Feely et al. (2008, p. 1491). The authors refer to Figure 1, p. 1490.

In Puget Sound (a large estuary complex in the Pacific Northwest), observed values for pH and aragonite saturation state in surface and subsurface waters were substantially lower in parts of Puget Sound than would be expected from anthropogenic carbon dioxide uptake alone.²²³ For example, in the deep waters of the Hood Canal sub-basin (> ~66 feet, 20 m):

- pH decreased from an estimated pre-industrial winter value of 7.60 to 7.56 ± 0.06 in February 2008, and aragonite saturation decreased from 0.66 to 0.61 ± 0.06 .²²⁴
- pH declined from an estimated pre-industrial summer value of 7.41 to 7.39 ± 0.05 in August 2008, and aragonite saturation decreased from 1.73 to 1.50 ± 0.66 .²²⁵
- Feely et al. (2010) estimate that ocean acidification can account for twenty-four to forty-nine percent of the observed decline in pH.²²⁶ The remaining change in pH between when seawater enters the sound and when it reaches Hood Canal results from remineralization of organic matter due to natural or anthropogenically stimulated respiration processes within Puget Sound.²²⁷

Researchers at Tatoosh Island on the northwestern tip of Washington State (near Neah Bay) observed that pH declined with increasing atmospheric CO₂ levels and varied substantially in response to biological processes and physical conditions that fluctuate over multiple time scales.²²⁸ Examination of 24,519 measurements of coastal ocean pH spanning eight years (2000-2007) revealed several patterns:²²⁹

- pH exhibited a pronounced 24-hour cycle, spanning 0.24 units during a typical day.²³⁰ This diurnal oscillation is readily explained by daily variation in photosynthesis and background respiration: water pH increases as CO₂ is taken up, via photosynthesis, over the course of the day, and then declines as respiration and diffusion from the atmosphere replenish CO₂ overnight.²³¹
- pH fluctuated substantially among days and years, ranging across a unit or more within any given year and 1.5 units over the study period.²³²
- When the entire temporal span of the data was considered, a general declining trend in pH became apparent.²³³ The decline is significant ($P < 0.05$).²³⁴

A model of mechanistic drivers underlying changes in pH captured 70.7% of the variance in the data.²³⁵ All parameters differed significantly from zero.²³⁶ The generalized R² value (the reduction in explained

²²³ Verbatim or nearly verbatim from Feely et al. *The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary*. (2010, p. 442).

²²⁴ Feely et al. (2010, Table 1, p. 446).

²²⁵ Feely et al. (2010, Table 1, p. 446).

²²⁶ Verbatim or nearly verbatim from Feely et al. (2010, p. 442)

²²⁷ Verbatim or nearly verbatim from Feely et al. (2010, p. 442)

²²⁸ Verbatim or nearly verbatim from Wootton, Pfister and Forester.. *Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset*. (2008, p. 18848)

²²⁹ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18848). The authors refer the reader to Fig. 1 in the cited report.

²³⁰ Verbatim or nearly verbatim from Wootton, Pfister and Forester.. (2008, p. 18848). The authors refer the reader to Fig. 1A in the cited report.

²³¹ Verbatim or nearly verbatim from Wootton, Pfister and Forester.. (2008, p. 18848). The authors cite Bensoussan and Gattuso (2007) for this information.

²³² Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18848)

²³³ Verbatim or nearly verbatim from Wootton, Pfister and Forester.. (2008, p. 18848). The authors refer the reader to Fig. 1B in the cited report.

²³⁴ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, Fig. 1, p. 18849)

²³⁵ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18848)

variance when a given variable is removed from the full model²³⁷) for the change in pH with atmospheric CO₂ (pH/ppm CO₂) was the largest of all model parameters: 29.8.²³⁸ Comparison of Wootton et al.'s empirical results to previous model predictions emphasizing rates of change over time (completed by fitting Wootton et al.'s pH data to a model with a linear temporal trend) revealed the linear decline explained 23.9% of the variation in the data and generated an estimated annual trend of -0.045 (95% Confidence Interval: -0.039 to -0.054 after accounting for temporal autocorrelation).²³⁹ This rate of decline is more than an order of magnitude higher than predicted by simulation models (-0.0019), suggesting that ocean acidification may be a more urgent issue than previously predicted, at least in some ocean areas.²⁴⁰

In conclusion, Wootton et al. state their model includes all variables that are currently suggested to have a large impact on ocean pH.²⁴¹ Of these, only atmospheric CO₂ exhibits a consistent change that can explain the persistent decline in pH.²⁴² Thus, their results agree qualitatively with predictions that ocean pH will decline with increases in atmospheric CO₂, but the rate of decline observed is substantially faster than predicted by current models and exhibited by the limited data that exist on ocean pH change through time.²⁴³

²³⁶ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18848)

²³⁷ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18852)

²³⁸ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, Table 1, p. 18849)

²³⁹ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18849). The authors cite Orr et al. (2005) for information on previous model predictions.

²⁴⁰ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18849). The authors cite Orr et al. (2005) for the value of -0.0019.

²⁴¹ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18851). The authors cite Solomon et al. (2007), Dore et al. (2003), Pelejero et al. (2005), and Feely et al. (2008) for this information.

²⁴² Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18851)

²⁴³ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18851). The authors cite Solomon et al. (2007) and Santana-Casiano et al. (2007) for this information.

Future Projections

Global

Anthropogenic CO₂ in seawater should steadily increase as atmospheric levels continue to rise.²⁴⁴ Under the A2 scenario, biogeochemical models for the ocean indicate that surface water pH will drop from a pre-industrial value of about 8.2 to about 7.8 by the end of this century, increasing the ocean's acidity by about 150% relative to the beginning of the industrial era (see Figure 10 for projections under a range of scenarios).²⁴⁵ The total volume of water in the ocean that is undersaturated with regard to calcite or aragonite increases substantially as atmospheric CO₂ concentrations continue to rise.²⁴⁶ For example:

- If atmospheric CO₂ concentrations reach 467-555 ppm by 2050 (a condition likely to occur given current emissions), global mean surface saturation of aragonite and calcite is projected to decrease by about twenty-five percent relative to current values.²⁴⁷
- Southern Ocean surface water is projected to become undersaturated with respect to aragonite at a CO₂ concentration of approximately 600 ppm.²⁴⁸ This concentration threshold is largely independent of emission scenarios.²⁴⁹

By the end of the 21st century, distinctions between total pH change and pH change attributable to anthropogenic CO₂ will become increasingly subtle.²⁵⁰ On multidecadal timescales, pH changes attributable to anthropogenic CO₂ can be expected to eventually dominate the overall signal.²⁵¹

North Pacific (> 50°N) and Subpolar Pacific Ocean

Projected changes in pH, carbonate ion, and aragonite and calcite saturation states in the North Pacific and subpolar Pacific Ocean are summarized in Table 7.²⁵² This data is based on National Center for Atmospheric Research Community Climate System Model 3.1 results.²⁵³ For visual depictions of projected changes by 2050 and 2095 compared to 1875 and 1995, please see Figures 3, 4, 5, and 7 in Feely et al. (2009). These figures were not accompanied by explanatory text specific to this geography, and are therefore not summarized here.

²⁴⁴ Verbatim or nearly verbatim from Byrne et al. *Direct observations of basin-wide acidification of the North Pacific Ocean*. (2010, p. 3)

²⁴⁵ Verbatim or nearly verbatim from Feely et al. *Ocean acidification: present conditions and future changes in a high CO₂ world*. (2009, p. 37)

²⁴⁶ Verbatim or nearly verbatim from Meehl et al. *Climate Change 2007: The Physical Science Basis: Global Climate Projections*. (2007, p. 793)

²⁴⁷ Verbatim or nearly verbatim from Cooley et al. *Ocean acidification's potential to alter global marine ecosystem services*. (2009, p. 172-173). The authors cite Cooley and Doney (2009) for this information.

²⁴⁸ Verbatim or nearly verbatim from Meehl et al. (2007, p. 793)

²⁴⁹ Verbatim or nearly verbatim from Meehl et al. (2007, p. 793)

²⁵⁰ Verbatim or nearly verbatim from Byrne et al. (2010, p. 3)

²⁵¹ Verbatim or nearly verbatim from Byrne et al. (2010, p. 3)

²⁵² Feely et al. (2009, Table 2, p. 46)

²⁵³ Feely et al. (2009, Table 2, p. 46)

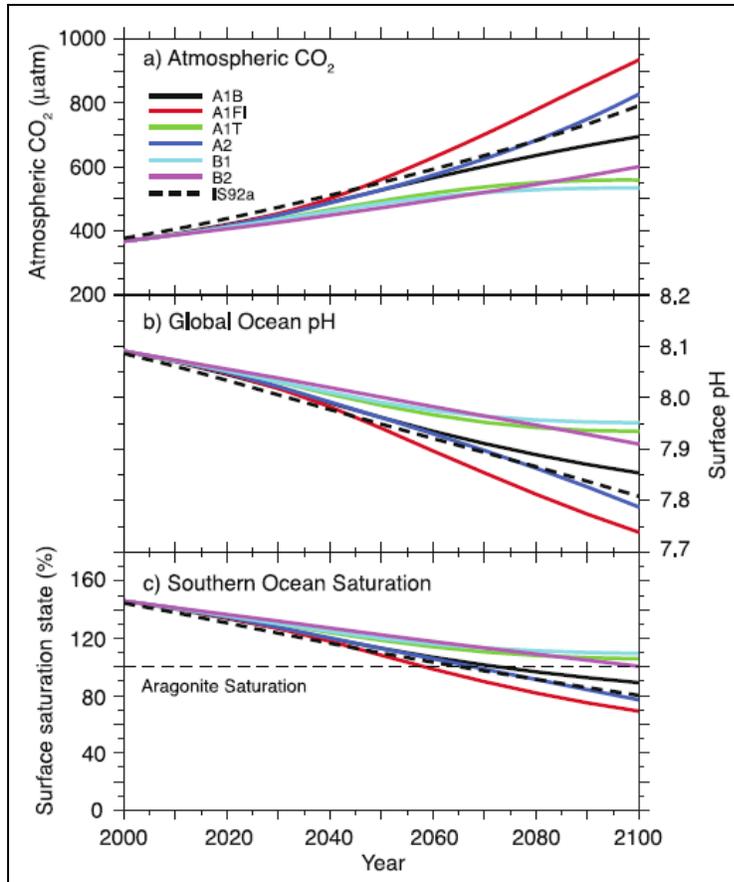


Figure 10. Changes in global average surface pH and saturation state with respect to aragonite in the Southern Ocean under various SRES scenarios. Time series of (a) atmospheric CO₂ for the six illustrative SRES scenarios, (b) projected global average surface pH and (c) projected average saturation state in the Southern Ocean from the BERN2.5D EMIC (Plattner et al., 2001). The results for the SRES scenarios A1T and A2 are similar to those for the non-SRES scenarios S650 and IS92a, respectively. Modified from Orr et al. (2005).

Source: Reproduced from Meehl et al. (2007, Fig. 10.24, p. 195) by authors of this report.

Table 7. Absolute and relative changes in pH, carbonate ion, and aragonite (Ω_{arag}) and calcite (Ω_{calc}) saturation states for three CO₂ levels (2005, and 2X and 3X pre-industrial* levels) in the North Pacific and Subpolar Pacific Oceans.

* One reviewer suggested using ppm for CO₂ values. Feely, Doney and Cooley do not provide ppm values for CO₂. However, using the IPCC value of 278 ppm for pre-industrial CO₂, 2X would be 2*278=556 ppm CO₂ and 3X would be 3*278=834 ppm CO₂.

Ocean	CO ₂	pH	Δ pH	Carbonate ion (μ mol/kg)	Δ Carbonate	Ω_{arag}	$\Delta \Omega_{arag}$	Ω_{calc}	$\Delta \Omega_{calc}$
North Pacific (>50°N)	2005	8.1		92.3		1.4		2.24	
	2X	7.885	-0.15	67.8	-24.5 (-26.5%)	1.03	-0.37 (-26.5%)	1.65	-0.59 (-26.5%)
	3X	7.719	-0.31	47.5	-44.8 (-48.5%)	0.72	-0.68 (-48.5%)	1.15	-1.09 (-48.5%)
Subpolar Pacific	2005	8.0		134.5		2.06		3.24	
	2X	7.913	-0.14	101.3	-33.2 (-24.7%)	1.55	-0.51 (-24.7%)	2.44	-0.80 (-24.7%)
	3X	7.756	-0.30	72.5	-62.0 (-46.1%)	1.11	-0.95 (-46.1%)	1.75	-1.49 (-46.1%)

Source: Modified from Feely, Doney and Cooley (2009, Table 2, p. 46) by authors of this report.

Information Gaps

Information is needed on regional trends in ocean pH and other indicators of ocean acidification for British Columbia. More specific projections throughout the geographic extent of the NPLCC are also needed. For the Gulf of Alaska, Sigler et al. (2008) state surface and vertical ocean pH and carbon species measurements, especially over the continental shelf and slope where fish, shellfish and marine mammal species are concentrated, are needed.²⁵⁴

²⁵⁴ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (authors). Osgood (Ed.). *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs: Alaskan Ecosystem Complex*. (2008, p. 69, 73).

2. INCREASING SEA SURFACE TEMPERATURE (SST)

Box 6. Summary of observed trends and future projections for sea surface temperature

Observed Trends

- By the early 21st century, global mean sea surface temperatures were approximately 1.1°F (0.6°C) higher than the value in 1950.²⁵⁵ Since 1961, the ocean has taken up over 80% of the heat being added to the climate system and the average temperature of the global ocean increased to depths of at least 9842 feet (3000 m).²⁵⁶
- Approximately 98 miles (~160 km) west of Newport, Oregon from 1997 to 2005, SST increased approximately 1.8°F (1°C; range 0-2.6°F or 0-2°C) compared to 1961 to 1971.²⁵⁷
- Off the British Columbia coast, statistically significant increases in SST of 0.52 to 1.7°F (0.29-0.94 °C) were observed from 1915 to 2003.²⁵⁸

Future Projections

- Global sea surface temperatures are projected to rise by 1.8-5.4°F (1.0-3.0°C) in the 21st century compared to a 1980-1999 baseline, e.g. 4.7°F (2.6°C) under the A2 scenario.²⁵⁹
- In the northern Pacific Ocean, increases in winter SST of 1.8 to 2.9°F (1.0-1.6°C) are projected by 2040-2049 (1980-1999 baseline; A1B).²⁶⁰ These increases in SST will be accompanied by warmer maximum and minimum temperatures overall.²⁶¹
- SST is projected to increase approximately 2.2°F (1.2°C) in the nearshore and offshore waters of Washington and northern Oregon by 2030-2059 (1970-1999 baseline).²⁶² These projections are compatible with the projected change for the northern Pacific Ocean.

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

Definition and Causes of Increasing Sea Surface Temperature

The world's oceans are the main storage reservoir for excess solar and heat energy initially retained within Earth's atmosphere.²⁶³

²⁵⁵ Nicholls et al. (2007, p. 320). The authors cite Bindoff et al. (2007) for this information.

²⁵⁶ Intergovernmental Panel on Climate Change. *Climate Change 2007: Synthesis Report*. (2007c, p. 30)

²⁵⁷ Mote et al. (2010, p. 32).

²⁵⁸ B.C. Ministry of Environment. *Environmental Trends in British Columbia: 2007: Climate Change*. (2007, Table 3, p. 14).

²⁵⁹ IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (2007e); Nicholls et al. (2007, Table 6.3, p. 323)

²⁶⁰ Overland and Wang. *Future climate of the North Pacific Ocean*. (2007, Fig. 2b, p. 7)

²⁶¹ Overland and Wang. (2007)

²⁶² Mote and Salathé, Jr. (2010, p. 44). See also OCCRI. (2010, p. 32-33).

²⁶³ Verbatim or nearly verbatim from Hansen et al. *Earth's energy imbalance: confirmation and implications*. (2005)

As global air temperatures continue to rise, ocean water temperatures are also expected to rise.²⁶⁴ Increases in SST as a result of global climate change occur simultaneously with natural cycles in ocean temperature, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (see Box 7). For example, the PDO naturally shifts heat across regions of the Pacific Ocean over periods

What are Watts per meter squared (W/m²) and Joules per year (J/yr)?

- A **Joule** is a measure of energy, work, or quantity of heat.
- A **Watt** is a measure of power (the rate at which work is performed or energy is converted) or radiant flux (the rate of flow of electromagnetic waves).
- One Watt is equivalent to one Joule per second ($W = J/s$).
- Thus, **W/m²** is a measure of power over a given surface area (an area measuring one meter by one meter) while **J/yr** is a measure of energy, work, or heat quantity over a given time period (one year).

Source: National Institute for Standards and Technology (NIST)(website).

of twenty to seventy years.²⁶⁵ Research studies therefore attempt to distinguish the precise contributions of natural variation and climate change.²⁶⁶ The rate of flow of surface heat (i.e. surface heat fluxes) in the oceans is reported with two primary units of measurement: Watts per meter squared (W/m^2) and Joules per year (J/yr).

Increases in the heat content of the ocean have driven other changes in the physical marine environment:²⁶⁷

- Thermal expansion of the oceans as well as increased meltwater and discharged ice from terrestrial glaciers and ice sheets have increased ocean volume and hence sea level (see Section 6 in this Chapter).²⁶⁸
- Warmer oceans drive more intense storm systems and other changes to the hydrological cycle.²⁶⁹ The warming of the upper layers of the ocean also drives greater stratification of the water column, reducing mixing in some parts of the ocean and consequently affecting nutrient availability and primary production [see Sections 3 (Altered Hydrology) and 4 (Altered ocean currents) in this Chapter; see also, Chapter IV Sections 1 and 2 (Altered nutrient cycling and Altered ocean productivity, respectively)].²⁷⁰

Changes in sea (and land) temperature may contribute to changing wind patterns, which can alter upwelling and nutrient cycling in coastal waters [see Sections 7 (Altered patterns of coastal upwelling) and 8 (Altered patterns of coastal hypoxia and anoxia) in this Chapter].²⁷¹

²⁶⁴ Verbatim or nearly verbatim from California Natural Resources Agency. *California Climate Adaptation Strategy*. (2009)

²⁶⁵ Verbatim or nearly verbatim from National Aeronautics and Space Administration. *Moody Pacific Unleashes Another Climate Mystery (website)*. (2004); See also Dawe and Thompson. *PDO-related heat and temperature changes in a model of the North Pacific*. (2007) and Mantua and Hare. *The Pacific Decadal Oscillation*. (2002).

²⁶⁶ Snover et al. *Uncertain Future: Climate change and its effects on Puget Sound*. (2005)

²⁶⁷ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. *The impact of climate change on the world's marine ecosystems*. (2010, p. 1524)

²⁶⁸ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524). The authors cite Rahmstorf et al. (2007) for this information.

²⁶⁹ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524). The authors cite Knutson et al. (2010) for information on intense storm systems and Trenberth et al. (2007) for information on the hydrological cycle.

²⁷⁰ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524)

²⁷¹ Verbatim or nearly verbatim from California Natural Resources Agency. *California Climate Adaptation Strategy*. (2009)

There is also an inverse relationship between oxygen content and water temperature: warmer water holds less dissolved oxygen than cooler water.²⁷² Further, water temperature regulates oxygen and carbonate solubility, viral pestilence, pH and conductivity, and photosynthesis and respiration rates of estuarine macrophytes (i.e., aquatic plants visible to the naked eye).²⁷³ While temperature is important in regulating physiological processes in estuaries, predicting the ecological outcome is complicated by the feedbacks and interactions among temperature change and independent physical and biogeochemical processes such as eutrophication.²⁷⁴ Nonetheless, there is high confidence, based on substantial new evidence, that observed changes in marine biological systems are associated with rising water temperatures, as well as related changes in ice cover, salinity, oxygen levels, and circulation.²⁷⁵ These include:

- Shifts in ranges and changes in algal, plankton and fish abundance in high-latitude oceans, and
- Range changes and earlier migrations of fish in rivers.²⁷⁶

Increases in water temperature could also affect:

- Algal production and the availability of light, oxygen and carbon for other estuarine species.²⁷⁷ The propensity for harmful algal blooms is further enhanced by the fertilization effect of increasing dissolved CO₂ levels.²⁷⁸
- Microbial processes such as nitrogen fixation and denitrification in estuaries.²⁷⁹

Observed Trends

Global

Global mean sea surface temperatures have risen about 1.1°F (0.6°C) since 1950, with associated atmospheric warming in coastal areas.²⁸⁰ Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 9842 feet (3000 m) and that the ocean has been taking up over eighty percent of the heat being added to the climate system.²⁸¹ In an analysis of 93.4% of the ocean by Willis et al. (2004), the observed annual mean rate of ocean heat gain between 1993 and mid-2003 was 0.86 ± 0.12 W/m² per year.²⁸²

²⁷² Verbatim or nearly verbatim from California Natural Resources Agency. *California Climate Adaptation Strategy*. (2009)

²⁷³ Nicholls et al. (2007, p. 328)

²⁷⁴ Nicholls et al. (2007, p. 328). The authors cite Lomas et al. (2002) for information on the role of temperature in regulating physiological processes in estuaries.

²⁷⁵ IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Summary for Policymakers*. (2007e, p. 8)

²⁷⁶ IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Summary for Policymakers*. (2007e, p. 8)

²⁷⁷ Nicholls et al. (2007, p. 328). The authors cite Short and Neckles (1999) for this information.

²⁷⁸ Nicholls et al. (2007, p. 328)

²⁷⁹ Nicholls et al. (2007, p. 328). The authors cite Lomas et al. (2002) for this information.

²⁸⁰ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 320). The authors cite Bindoff et al. (2007) for this information.

²⁸¹ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 30)

²⁸² Verbatim or nearly verbatim from Hansen et al. *Earth's energy imbalance: confirmation and implications*. (2005, p. 1432)

Most of the heat is stored in the upper reaches of the ocean:

- On average across five simulations run from 1993 to mid-2003, eighty-five percent of the ocean heat storage occurred above 2460 feet (750 m), with the range from seventy-eight to ninety-one percent.²⁸³
- From 1961 to 2003, the global oceans showed a linear increase in heat content of $\sim 0.38 \times 10^{22}$ Joules per year (J/yr) in the top 2297 feet (700 m) of the water column, with approximately ninety-one percent stored in the upper 984 feet (300 m) of the water column.²⁸⁴
- From 1969 to 2008, a linear average increase in heat content of 4.0×10^{21} J/yr (± 0.05 J/yr; the 95% confidence interval) in the top 2297 feet (700 m) of the water column was found (reference period 1957-1990; based on yearly mean heat content values determined as the average of the four seasons).²⁸⁵ Globally from 1969 to 2008, eighty-five percent of the variance in yearly ocean heat content is accounted for by the linear trend (reference period 1955-2006).²⁸⁶

Decadal trends also show an increase in SST from 1850 to 2005, 1901 to 2005, and 1979 to 2005, as shown in Table 8. However, the general warming trend may be mediated by alternating years of warmer and cooler ocean temperatures because changes in winter storm tracks and storm intensity brought on by climate change are likely to increase the interannual variability of winds that modify ocean temperatures.²⁸⁷ For example:

- From 1950 to 1960, trends in globally averaged ocean heat content and sea surface temperature (SST) show a slight increase, followed by a 15-year period to the mid-1970s of zero or slightly negative trend and, after the 1976-1977 climate shift (a rapid change in relatively stable physical ocean properties that affects biota and ecosystems), a steady rise to 2003.²⁸⁸

Finally, since the IPCC's Fourth Assessment Report, the discovery of a time-varying bias in a device for measuring temperature at various depths (XBT, or expendable bathythermograph) has prompted re-evaluations of the rate of upper ocean warming.²⁸⁹ Research on this topic is still relatively new, but at least one study has been conducted. Consistent with the other studies reported here, a statistically significant increase in ocean heat content of 0.64 W/m^2 was reported by Lyman et al. (2010) from 1993 to 2008, even after correcting for the XBT bias (calculated for the Earth's entire surface area; the 90-percent confidence interval is $0.53\text{--}0.75 \text{ W/m}^2$).²⁹⁰

North Pacific Ocean

In the North Pacific from 1969 to 2008, sixty-nine percent of the variance in yearly ocean heat content is accounted for by the linear trend (reference period 1955-2006).²⁹¹

²⁸³ Verbatim or nearly verbatim from Hansen et al. (2005, p. 1432)

²⁸⁴ Verbatim or nearly verbatim from Domingues et al. *Improved estimates of upper-ocean warming and multi-decadal sea level rise*. (2008)

²⁸⁵ Levitus et al. *Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems*. (2009, Fig. 1, p. 2, 20)

²⁸⁶ Levitus et al. (2009, Fig. S11, p. 4, 15)

²⁸⁷ Living Oceans Society. *Climate and Oceans Think Tank – Proceedings, Day 1*. (2009)

²⁸⁸ Verbatim or nearly verbatim from Domingues et al. (2008, p. 1090)

²⁸⁹ Verbatim or nearly verbatim from Lyman et al. *Robust warming of the global upper ocean*. (2010, p. 337)

²⁹⁰ Lyman et al. (2010, p. 334)

²⁹¹ Verbatim or nearly verbatim from Levitus et al. (2009, Fig. S11, p. 4, 15).

Table 8. Linear decadal trends in SST in the Northern Hemisphere and Globally. (°F with °C in parentheses; *significant at the < 1% level, †significant at the 1-5% level)

	Temperature Trend Per Decade		
	1850-2005	1901-2005	1979-2005
Northern Hemisphere	0.076 ± 0.029* (0.042 ± 0.016)	0.13 ± 0.052* (0.071 ± 0.029)	0.342 ± 0.241† (0.190 ± 0.134)
Globe	0.068 ± 0.020* (0.038 ± 0.011)	0.12 ± 0.027* (0.067 ± 0.015)	0.239 ± 0.085* (0.133 ± 0.047)

Source: Modified from Trenberth et al. (2007, Table 3.2, p. 243) by authors of this report.

*Notes: SST are those produced by the United Kingdom Meteorological Office (UKMO) under the HadSST2 (Rayner et al. 2006). Annual averages, with estimates of uncertainties for HadSST2, were used to estimate trends. Trends with 5 to 95% confidence intervals and levels of significance (**bold: <1%;** *italic, 1-5%*) were estimated by Restricted Maximum Likelihood (REML), which allows for serial correlation (first order autoregression AR1) in the residuals of the data about the linear trend. The Durbin Watson D-statistic (not shown) for the residuals, after allowing for first-order serial correlation, never indicates significant positive correlation.*

Southeast and Southcentral Alaska

Information needed.

British Columbia

Increasing SST, ranging from 0.52 to 1.7°F (0.29-0.94 °C), has been observed at nine stations along the coast from 1915 to 2003 (Table 9).²⁹² The largest and most significant increase was a warming of 1.7°F (0.94°C; fifty-year trend) for Langara Island at the northwest tip of the Queen Charlotte Islands from 1941 to 2003 (annual mean ± standard deviation: 15.8 ± 0.94°F or 8.8 ± 0.52°C).²⁹³ A more detailed analysis reported by the B.C. Ministry of Environment (MoE) (2006) showed three of the nine stations had statistically significant increases ($\alpha < 5\%$) in either the annual maximum or annual minimum temperature.²⁹⁴

- The most statistically significant trend was an increase in mean annual maximum temperature at Entrance Island, 3.1°F (1.7°C) from 1936 to 2004.²⁹⁵ This may reflect increased summer warming in the Strait of Georgia.²⁹⁶
- A statistically significant increase in mean annual maximum temperature was also observed at Nootka Point, (1.1°C) from 1938 to 2004.²⁹⁷
- It is unclear whether the final station with statistically significant data is Pine Island or Langara Island because B.C. MoE provides somewhat contradictory information. They state the largest increase in the mean annual minimum temperature is at Langara Island, 3.1°F (1.7°C) from 1937

²⁹² B.C. Ministry of Environment (MoE). *Environmental Trends in British Columbia: 2007: Climate Change*. (2007, Table 3, p. 14)

²⁹³ Verbatim or nearly verbatim from B.C. MoE. (2007, p. 14)

²⁹⁴ Verbatim or nearly verbatim from B.C. MoE. (2007, p. 14). The authors cite *British Columbia Coastal Environment* for this information.

²⁹⁵ Verbatim or nearly verbatim from B.C. MoE. (2006, p. 91)

²⁹⁶ Verbatim or nearly verbatim from B.C. MoE. (2007, p. 14)

²⁹⁷ B.C. MoE. (2006, Table 7, p. 92)

to 2004, but this is only weakly significant.²⁹⁸ In Table 8 of the cited report, however, only data from Pine Island are indicated as statistically significant, +1.2°F (+ 0.68°C) from 1939 to 2004.²⁹⁹

A warming trend in the ocean along the southern B.C. coast is also evident in the deeper waters of five inlets on the mainland coast and two on Vancouver Island.³⁰⁰ Consistent with the temperature trends shown in the sea surface indicator, all seven inlets showed a warming of 0.9 to 1.8°F (0.5 to 1.0°C) over a fifty-year period of record.³⁰¹ A more specific period of record is not provided; however, the graph in the cited report has a time axis from 1950 to 2000.³⁰²

Washington

Information needed.

Table 9. Mean annual sea surface temperature at nine stations on the B.C. coast. (°F with °C in parentheses)			
<i>Station</i>	<i>Period of record</i>	<i>Annual Mean ± Standard Deviation</i>	<i>Trend: °F/50yrs (°C/50yrs)</i>
Langara Island (NC)	1941-2003	15.8 ± 0.94 (8.8 ± 0.52)	1.69 (0.94)*
McInnes Island (CC)	1955-2003	17.3 ± 0.86 (9.6 ± 0.48)	1.2 (0.65)
Pine Island (CC)	1937-2003	15.7 ± 0.92 (8.7 ± 0.51)	1.3 (0.71)*
Kains Island (west VI)	1935-2003	18.4 ± 0.99 (10.2 ± 0.55)	0.77 (0.43)
Nootka Point (west VI)	1935-2003	19.6 ± 0.92 (10.9 ± 0.51)	0.99 (0.55)
Amphitrite Point (west VI)	1935-2003	18.7 ± 0.94 (10.4 ± 0.52)	0.9 (0.50)*
Departure Bay (east VI)	1915-2003	20.0 ± 0.9 (11.1 ± 0.50)	0.52 (0.29)
Entrance Island (SoG)	1937-2002	20.2 ± 0.92 (11.2 ± 0.51)	1.5 (0.82)*
Race Rocks (JFS)	1922-2003	16.4 ± 0.79 (9.1 ± 0.44)	0.54 (0.30)*

NC = North Coast; CC = Central Coast; VI = Vancouver Island; SoG = Strait of Georgia; JFS = Juan de Fuca Strait;
*statistically significant, probability or chance that there is no trend (α): < 5%

Source: Modified from B.C. Ministry of Environment (MoE). Environmental Trends in British Columbia: 2007: Climate Change. (2007, Table 3, p. 14) by authors of this report. BC MoE cites Fisheries and Oceans Canada, www.sci.pac.dfo-mpo.gc.ca/osap/data as their source.

²⁹⁸ Verbatim or nearly verbatim from B.C. MoE. (2006, p. 91-92)

²⁹⁹ B.C. MoE. (2006, Table 8, p. 94)

³⁰⁰ Verbatim or nearly verbatim from B.C. MoE. (2007, p. 14)

³⁰¹ B.C. MoE. (2007, Fig. 7, p. 15). The same figure is also available in B.C. MoE. (2006, Fig. 5, p. 95)

³⁰² Verbatim or nearly verbatim from B.C. MoE. (2007, p. 14)

Box 7. The role of the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) in regional climate.

ENSO and PDO are major sources of climate variability in the NPLCC region. The PDO is often described as a long-lived, El Niño-like pattern of climate variability in the Pacific. Two main characteristics distinguish the Pacific Decadal Oscillations (PDO) from El Niño/Southern Oscillation (ENSO). First, 20th century PDO "events" persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months. Second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. The potential for precipitation and temperature extremes is higher when ENSO and PDO are in the same phase.

- **A warm ENSO (i.e. El Niño) is** characterized by December-January-February sea surface temperatures >0.5 standard deviations above the mean and has been associated with:
 - Warmer than average sea surface temperatures in the central and eastern equatorial Pacific Ocean
 - Reduced strength of easterly trade winds in the Tropical Pacific
 - Increased chance for lower quality coastal and near-shore marine habitat in Pacific Northwest
- **A neutral ENSO is** neither warm nor cool. There are no statistically significant deviations from average conditions at the equator.
- **A cool ENSO (i.e., La Niña) is** characterized by December-January-February mean sea surface temperatures <-0.5 standard deviations and has been associated with:
 - Cooler than average sea surface temperatures in the central and eastern equatorial Pacific Ocean
 - Stronger than normal easterly trade winds in the Tropical Pacific
 - Increased chance for higher quality coastal and near-shore marine habitat in Pacific Northwest
- **A warm PDO is** characterized by sea surface temperatures >0.5 standard deviations above the mean for the October-November-December-January-February-March mean and has been associated with:
 - Negative upwelling in winter-spring
 - Warm and fresh continental shelf water
 - Enhanced coastal ocean biological productivity in Alaska and inhibited productivity off the west coast of the contiguous United States
- **A neutral PDO is** neither warm nor cool.
- **A cool PDO is** characterized by sea surface temperatures <-0.5 standard deviations for the October-November-December-January-February-March mean and has been associated with:
 - Positive upwelling in winter-spring
 - Cold and salty continental shelf water
 - Enhanced coastal ocean productivity off the west coast of the contiguous United States and inhibited productivity in Alaska

Source: CIG. <http://ces.washington.edu/cig/pnnc/ci.shtml#anchor2> (accessed 8.14.2011); Hamlet & Lettenmaier. (2007, Table 1, p. 6); Independent Scientific Advisory Board. (2007, Table 4, p. 61); Mantua. (2000). <http://www.jisao.washington.edu/pdo/> (accessed 8.14.2011).

Oregon

Limited information on SST trends in Oregon was available. Figure 11 below, reproduced from OCAR, shows an increase in SST at one location off the coast of Newport (1997-2005 compared to 1961-1971).³⁰³

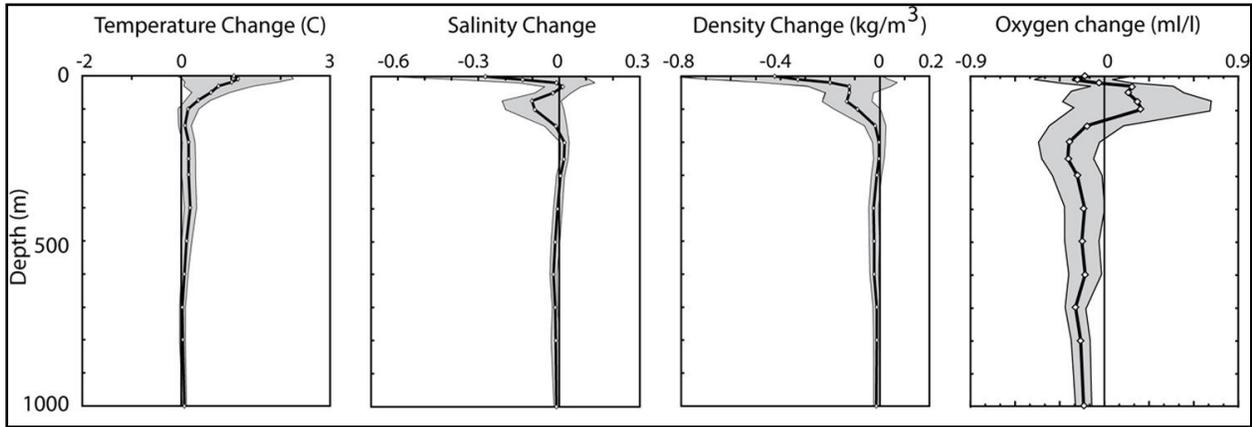


Figure 11. Differences between average temperature, salinity (part per thousand), density, and dissolved oxygen profiles at NH-85 (85 nm, 157 km, off Newport) for two periods: 1997-2005 (~38 samples) minus 1961-1971 (~75 samples), with 95% confidence limits. *Source: Reproduced from Mote, Gavin and Huyer. (2010, p. 32) by authors of this report.*

Northwest California

Information needed.

Future Projections

Global

Global sea surface temperatures are projected to rise 2.7°F (1.5°C) under the B1 scenario, approximately 4.0°F (2.2°C) under the A1B scenario, and 4.7°F (2.6°C) under the A2 scenario by 2100 (relative to 1980-1999).³⁰⁴ Similarly, global average air temperatures are projected to increase at least 3.2°F to 7.2°F (1.8-4.0°C) by 2090-2099 compared to a 1980-1999 baseline (the full range for projected air temperature increases is 2.0-11.5°F or 1.1-6.4°C³⁰⁵).³⁰⁶

North Pacific Ocean

Projected mid-century (2040-2049) winter SST for the northern Pacific Ocean compared to a 1980-1999 baseline under the A1B scenario generally lies between 1.8 and 2.9°F (1.0-1.6°C).³⁰⁷ These increases in

³⁰³ Mote, Gavin and Huyer. (2010, p. 32)

³⁰⁴ Nicholls et al. (2007, Table 6.3, p. 323)

³⁰⁵ IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers.* (2007f, Table SPM.3, p. 13).

³⁰⁶ IPCC. *Climate Change 2007: Synthesis Report: Summary for Policymakers.* (2007, Fig. SPM.1, p. 8)

³⁰⁷ Overland and Wang. *Future climate of the North Pacific Ocean.* (2007, Fig. 2b, p. 7)

SST will be accompanied by warmer maximum and minimum temperatures overall, and the observed decadal pattern of SST in the 20th century is projected to continue nearly the same into the 21st century.³⁰⁸

Southeast and Southcentral Alaska

Information needed.

British Columbia

At the present rate of increase, temperatures at Langara Island, at the extreme northwest point on the B.C. coast, would resemble current conditions at Amphitrite Point, on the southwest coast of Vancouver Island, in less than a hundred years.³⁰⁹ The water around Langara Island is about 2.7°F (1.5°C) colder than that around Amphitrite Point, for both annual mean and average annual extremes.³¹⁰ In other words, at the present rate of increase, Langara Island will be 2.7°F (1.5°C) warmer in less than a hundred years. This includes minimum, mean, and maximum temperatures.

Washington and Northern Oregon

For coastal grid points between 46°N (west of Seaside, OR) and 49°N (west of Vancouver, B.C.) latitude for the mid-century (2030-2059; compared to 1970-1999), the modeled increase in SST is about +2.2°F (1.2°C), somewhat less than for the land areas (+3.6°F, 2.0°C), but a significant change compared to the typical interannual variability of the coastal ocean.³¹¹ The forecast increase of about 2.2°F (1.2°C) is also likely to apply to offshore waters.³¹² This modeled increase is less than the summertime increase observed in recent decades.³¹³ However, the ocean model is still too coarse to represent the complex oceanic processes over the continental margin.³¹⁴

Northwest California

Information needed.

Information Gaps

Information is needed on regional trends for Washington, Oregon, and northern California. Information is needed on regional projections throughout the NPLCC region. For the Gulf of Alaska, Sigler et al. (2008) state fine-scale (both time and space) surface and vertical temperature, salinity, oxygen, and nitrate and chlorophyll fluorescence data are needed.³¹⁵ A significant source of uncertainty in SST may be the uncertainty in trends and projections of vertical ocean currents (including those associated with upwelling). Information is needed on this topic. Sections 4 (Altered ocean currents) and 7 (Altered patterns of coastal upwelling) in this Chapter list additional information gaps on these topics.

³⁰⁸ Overland and Wang. (2007)

³⁰⁹ Verbatim or nearly verbatim from B.C. Ministry of Environment. (2007, p. 14)

³¹⁰ Verbatim or nearly verbatim from B.C. Ministry of Environment. (2007, p. 14)

³¹¹ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 44). See also OCCRI. (2010, p. 32).

³¹² Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 33)

³¹³ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 33)

³¹⁴ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 32)

³¹⁵ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (authors). Osgood (Ed.). (2008, p. 69, 73).

3. ALTERED HYDROLOGY

“Hydrology” refers to the science encompassing the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground.³¹⁶ The hydrologic cycle, or water cycle, describes the existence and movement of water on, in, and above the Earth.³¹⁷ While hydrologic changes such as alterations in spring snowpack and snowmelt, seasonal flows, glacier melt patterns, water temperature, and water quality deal primarily with freshwater, they affect the marine and coastal environment, as described below.

Some of the greatest potential impacts of climate change on estuaries may result from changes in physical mixing characteristics caused by changes in freshwater runoff.³¹⁸ Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity and control of phytoplankton growth rates.³¹⁹ Decreased freshwater inflows increase water residence time and decrease vertical stratification, and vice versa.³²⁰ Observed trends and future projections in streamflow amount in the NPLCC region include:

- **Observed trends in streamflow amount:** In British Columbia’s coastal watersheds, regimes are shifting towards increased winter rainfall, declining snow accumulation, and decreased summer precipitation,³²¹ with subsequent increases in winter flow and decreases in summer flow being observed.³²² Snover et al. (2005) cite that freshwater inflow to Puget Sound from 1948 to 2003 has changed in the following ways:³²³
 - A 13% decline in total inflow due to changes in precipitation
 - An 18% decline in the portion of annual river flow entering Puget Sound during the summer
 - An increase in the likelihood of both low and unusually high daily flow events
- **Future projections in streamflow amount:** As precipitation in southeastern Alaska shifts toward increased rain and less snow, more water will run off the landscape rather than being stored.³²⁴ Mean and mean minimum flows are projected to increase on the Fraser River near Hope in British Columbia (+1.8-5.1% and +14-44%, respectively), while mean peak flows are projected to decrease 18% over the 21st century.³²⁵ The annual average low flow magnitude is

³¹⁶ Verbatim or nearly verbatim from U.S. Geological Survey. *Science in your watershed: general introduction and hydrologic definitions (website)*. (2008). The authors cite the American Society of Civil Engineers Hydrology Handbook (1949, no. 28, pp. 1) for this information.

³¹⁷ Verbatim or nearly verbatim from U.S. Geological Survey. *Summary of the Water Cycle (website)*. (2010)

³¹⁸ Nicholls et al. (2007, p. 328). The authors cite Scavia et al. (2002) for this information.

³¹⁹ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328)

³²⁰ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328). The authors cite Moore et al. (1997) for this information.

³²¹ Verbatim or nearly verbatim from Pike et al. (2010, p. 706)

³²² Verbatim or nearly verbatim from Pike et al. (2010, p. 706, 717)

³²³ Verbatim or nearly verbatim from Snover et al. (2005)

³²⁴ Verbatim or nearly verbatim from Kelly et al. *Climate Change: Predicted impacts on Juneau*. (2007, p. 53)

³²⁵ Verbatim or nearly verbatim from Morrison et al. *Climate change in the Fraser River watershed: flow and temperature projections*. (2002, Table 2, p. 237).

projected to decline up to 50% by the 2080s (A1B & B1 multi-model averages) in the river basins of southwest Washington, the Olympic Peninsula, and Puget Sound.³²⁶

Changes in the timing of freshwater delivery to estuaries could lead to a decoupling of the juvenile phases of many estuarine and marine fishery species from the available nursery habitat.³²⁷ Observed trends and future projections in freshwater runoff timing in the NPLCC region include:

- **Observed trends in freshwater runoff timing:** Widespread and regionally coherent trends toward earlier onsets of springtime snowmelt and streamflow have taken place across most of western North America.³²⁸ In southcentral and southeast Alaska from 1948 to 2002, the timing of the center of mass of annual flow has shifted at least ten days earlier, while the timing of the spring pulse onset has shifted five to fifteen days earlier in some locations and up to five days later in others.³²⁹ Over the last fifteen years (more specific date not provided), the Fraser River (snow-glacial system near Vancouver, B.C.) shows increased peak flows and lower recessional flows, illustrating changes in the associated watersheds, perhaps away from a glacier-dominated regime towards a snow-dominated regime with an earlier freshet and faster recessional period.³³⁰ A twelve day shift toward earlier onset of snowmelt was observed in the Puget Sound (WA) from 1948 to 2003.³³¹
- **Future projections for freshwater runoff timing:** If mean winter minimum temperatures rise, the snow-to-precipitation fraction across the western United States will likely decrease further.³³² An immediate consequence of warmer temperatures and reduced snowfalls would be a regional scale reduction of snowpack.³³³ Assuming that the response to increased warming remains linear, the projections indicate that stream flow timing might shift by 30–40 days by the end of the century.³³⁴

In a study of glacier runoff in freshwater discharge, Neal et al. (2010) suggest changes in timing and magnitude of freshwater delivery to the Gulf of Alaska could impact coastal circulation as well as biogeochemical fluxes in nearshore marine ecosystems and the eastern North Pacific Ocean.³³⁵ Observed trends and future projections in glacial coverage and runoff to coastal systems in the NPLCC region include:

- **Observed trends in glacial coverage and runoff:** In the Gulf of Alaska, discharge from glaciers and icefields accounts for 47% of total annual freshwater discharge, with 10% coming from

³²⁶ Verbatim or nearly verbatim from Mantua et al. *Climate change in the Fraser River watershed: flow and temperature projections*. (2010, p. 204-205)

³²⁷ Nicholls et al. (2007, p. 328)

³²⁸ Verbatim or nearly verbatim from Stewart, Cayan and Dettinger. *Changes toward earlier streamflow timing across western North America*. (2005, p. 1136)

³²⁹ Stewart, Cayan and Dettinger. (2005, Fig. 2, p. 1141)

³³⁰ Verbatim or nearly verbatim from Pike et al. *Climate Change Effects on Watershed Processes in British Columbia*. (2010, p. 706)

³³¹ Snover et al. *Uncertain Future: Climate Change and its Effects on Puget Sound*. (2005)

³³² Verbatim or nearly verbatim from Stewart. *Changes in snowpack and snowmelt runoff for key mountain regions*. (2009, p. 90)

³³³ Verbatim or nearly verbatim from Stewart. (2009, p. 90)

³³⁴ Verbatim or nearly verbatim from Stewart. (2009, p. 90)

³³⁵ Verbatim or nearly verbatim from Neal, Hood and Smikrud. *Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska*. (2010, p. 1)

glacier volume loss associated with rapid thinning and retreat of glaciers along the Gulf of Alaska.³³⁶ Glaciers in British Columbia are out of equilibrium with the current climate, with widespread glacial volume loss and retreat in most regions.³³⁷ Negative trends have been documented for summer streamflow in glacier-fed catchments in British Columbia, with the exception of the northwest, where streamflow has been increasing in glacier-fed catchments.³³⁸

- **Future projections in glacial coverage and runoff:** In British Columbia's glacier-augmented regimes, peak flows would decrease and occur earlier in the year.³³⁹ In southeast Alaska, glacial melt is already occurring, and is likely to continue.³⁴⁰ Neal et al.'s (2010) results indicate the region of the Gulf of Alaska from Prince William Sound to the east, where glacier runoff contributes 371 km³ per year, is vulnerable to future changes in freshwater discharge as a result of glacier thinning and recession.³⁴¹

A fuller discussion of hydrologic changes in the geographic extent of the NPLCC can be found in *Climate Change Effects and Adaptation Approaches in Freshwater Aquatic and Riparian Ecosystems in the North Pacific Landscape Conservation Cooperative: A Compilation of Scientific Literature (Final Report)*, a companion document by the authors of this report.

Information Gaps

Peterson and Schwing (2008) state data and models specific to quantifying and forecasting regional precipitation and streamflow patterns are needed.³⁴² In addition, climate information and predictions for watershed and ocean habitats are needed, including observations and predictions of weather patterns, streamflows, snowpack, and ocean properties.³⁴³ It is important to note that forecasts and predictions can not be made more than a decade or two into the future. Further, forecasts and predictions are distinct from scenarios, which describe a range of plausible futures tied to particular climate models and based on assumptions about future emissions, development patterns, fossil fuel usage, socioeconomic factors, and other factors. Please see Box 2 for information on the IPCC's SRES scenarios.

³³⁶ Verbatim or nearly verbatim from Neal, Hood, and Smikrud. (2010, p. 1)

³³⁷ Verbatim or nearly verbatim from Pike et al. (2010, p. 703)

³³⁸ Verbatim or nearly verbatim from Pike et al. (2010, p. 717)

³³⁹ Verbatim or nearly verbatim from Pike et al. (2010, p. 719).

³⁴⁰ Verbatim or nearly verbatim from AK Department of Environmental Conservation. *Climate Change in Alaska: Adaptation Advisory Group of the Governor's Sub-Cabinet on Climate Change (website)*. (2010, p. 2-3)

³⁴¹ Verbatim or nearly verbatim from Neal, Hood, and Smikrud. (2010, p. 1)

³⁴² Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (authors). Osgood (Ed.). (2008, p. 52)

³⁴³ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (authors). Osgood (Ed.). (2008, p. 52)

4. ALTERED OCEAN CURRENTS

Box 8. Summary of observed trends and future projections for ocean currents

Observed Trends

- The California Current System (CCS) is the dominant current system in the NPLCC region south of northern Vancouver Island (50°N).³⁴⁴
 - Off the California coast from 1950 to 1993, the mean level of the coastal thermocline (i.e., a depth of water separating two layers of different temperature) strengthened and deepened, while the offshore thermocline weakened and decreased in depth in the upper 656 feet (200 m).³⁴⁵
 - Off the Oregon coast, alongshore currents are much stronger than the onshore/offshore currents of the upwelling/downwelling circulation.³⁴⁶
- North of Vancouver Island, the Alaska Current (AC) and Alaska Coastal Current (ACC) are the dominant current systems in the NPLCC region.³⁴⁷
 - Sixty percent of the oxygen in the subsurface waters of the Alaskan Gyre was supplied by subarctic waters; the remaining 40% was supplied by subtropical waters.³⁴⁸

Future Projections

- Projections of future ocean current patterns, both globally and in the NPLCC region, were not found in the scientific and agency literature.
- Some researchers speculate future ocean currents may be similar to or exceed extremes in natural variability observed historically (e.g. of ENSO, PDO).³⁴⁹

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

Definition and Causes of Altered Ocean Currents

Ocean currents are primarily driven by winds, air temperature, and changes in ocean temperature, although regional features such as freshwater influx (e.g. river plumes), the width of the continental shelf, submarine canyons, banks, and coastal promontories can alter flow patterns and modulate the local upwelling response.³⁵⁰ Changes in fluxes of heat and freshwater at the ocean's surface, along with surface wind forcing, play key roles in forming ocean currents, which in turn have a major effect on climate.³⁵¹

³⁴⁴ Whitney, Freeland, and Robert. (2007, Fig. 1, p. 180).

³⁴⁵ Palacios et al. *Long-term and seasonal trends in stratification in the California Current, 1950-1993*. (2004, p. 1)

³⁴⁶ Mote, Gavin and Huyer. (2010, p. 24)

³⁴⁷ Whitney, Freeland, and Robert. (2007, Fig. 1, p. 180).

³⁴⁸ Whitney, Freeland, and Robert. (2007, p. 179)

³⁴⁹ Peterson and Schwing (2008) and Sigler, Napp, and Hollowed (2008). In *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs*. Osgood (Ed.). (2008)

³⁵⁰ Verbatim or nearly verbatim from Hickey and Banas. *Oceanography of the U.S. Pacific Northwest Coastal Ocean and Estuaries with Application to Coastal Ecology*. (2003, p. 1014)

³⁵¹ Verbatim or nearly verbatim from Rahmstorf. *The current climate*. (2003, p. 699)

There are two basic types of ocean circulation:

- *Thermohaline circulation* is defined as currents driven by changes to the rate of flow of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt.³⁵²
- *Wind-driven circulation* is relegated to the upper ocean due to stratification – in unstratified water, wind-driven currents would extend to the bottom.³⁵³

Flux refers to the amount of a substance flowing through an area over a certain period of time. Flux can be used to measure ocean currents by measuring the volume of water that passes a certain point over a certain period of time. For example, if a net were placed in the water, flux would increase as the strength of the current increases (more water passes at once), as the size of the net increases (more water passes at once), and when the net is facing exactly the direction of the current (minimal resistance to the flow of water).

The major currents of the subarctic Pacific (north of the equator) are shown in Figure 12.³⁵⁴ Ocean currents transport nutrients across large distances, at varying ocean depths, and circulate nutrients in gyres (a spiral oceanic surface current moving in a clockwise direction).³⁵⁵ For example, waters in the North Pacific Current (NPC) acquire heat and salt from the subtropics as they cross the ocean.³⁵⁶ They also contain more oxygen than waters within the Alaska Gyre (AG), and are the oxygen source for the interior waters of the eastern subarctic Pacific.³⁵⁷

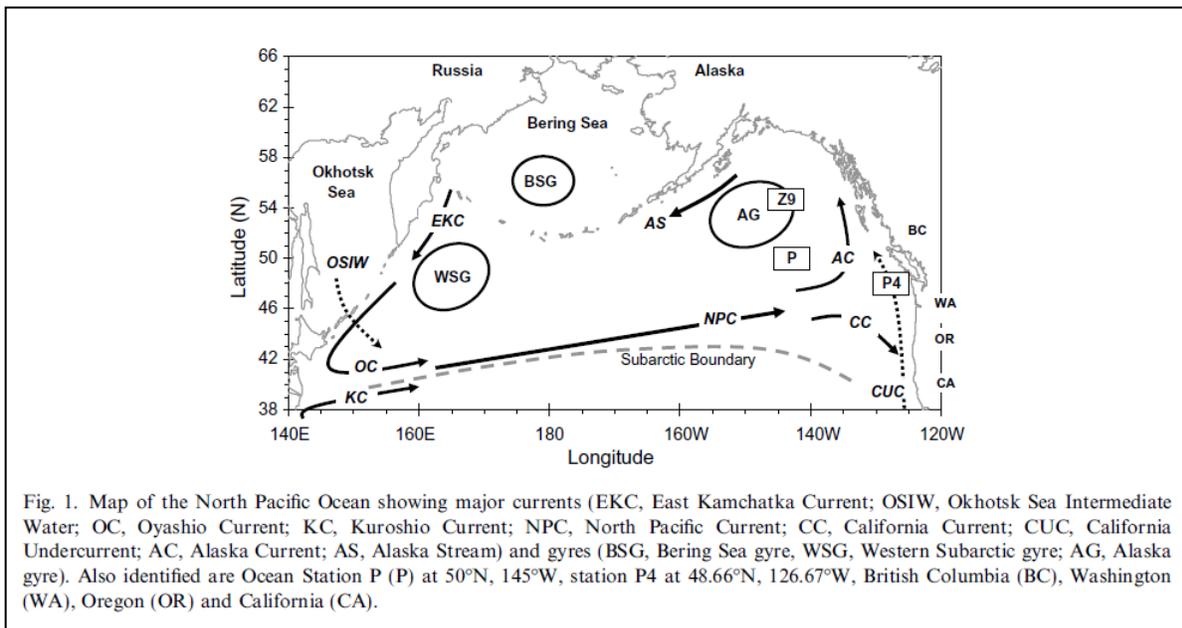


Figure 12. Map of the North Pacific Ocean showing major currents.

Source: Reproduced from Whitney, Freeland, & Robert. (2007, Fig. 1, p. 180) by authors of this report.

³⁵² Verbatim or nearly verbatim from Rahmstorf. (2003, p. 699)

³⁵³ Verbatim or nearly verbatim from Rahmstorf. (2003, p. 699)

³⁵⁴ Whitney, Freeland, and Robert. *Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific*. (2007, Fig. 1, p. 180)

³⁵⁵ Verbatim or nearly verbatim from Whitney, Freeland, and Robert. (2007)

³⁵⁶ Verbatim or nearly verbatim from Whitney, Freeland, and Robert. (2007, p. 182). The authors cite Mecking et al. (2006) for this data.

³⁵⁷ Verbatim or nearly verbatim from Whitney, Freeland, and Robert. (2007, p. 182)

Thermal stratification refers to the layering of water due to differences in temperature and density. As water warms, its density decreases and it rises to the surface. In the oceans, the **mixed layer** is the layer between the ocean surface and a depth usually ranging between 82 and 656 feet (25-200m), where density is almost uniform due to the competition between stratifying and destratifying processes. Stratifying processes include surface heating and freshwater influx, while destratifying forces include wind forcing, surface cooling, evaporation and turbulent mixing. With the exception of polar and sub-polar oceans, the **thermocline** separates the mixed layer from the deep ocean. Its depth ranges from 164 to 3280 feet (50-1000m), and the rate of decrease of temperature with increase of depth is the largest in the ocean. In mid-latitude regions, thermocline depth varies seasonally, where a secondary and much shallower thermocline (<164 ft; <50m) occurs in summer. In high latitudes, a thermocline may only appear seasonally.

Sources: *Earth & Space Research (website) (2004); Sarkar, Royer and Grosch. (2005).*

Changes to ocean currents affect such processes as the upwelling of nutrients, coastal hypoxia and anoxia, local climate, and marine biology:

- In some situations, intensified upwelling resulting from changes in wind strength can lead to a greater flux of organic material into deeper shelf waters, leading to an increase in respiration, hypoxia, and in some cases the eruption of toxic gases such as methane and hydrogen sulfide from deep anoxic sediments.³⁵⁸ One reviewer noted a greater flux of organic material may increase primary productivity as well.³⁵⁹ Changes to wind and ocean currents driven by anthropogenic climate change are consequently likely to interact with overfishing and eutrophication, further increasing the incidence of hypoxic and anoxic events.³⁶⁰
- The uneven distribution of ocean heating also strongly influences the behavior of ocean currents, which play critical roles in the dynamics, local climates, and biology of the ocean.³⁶¹
- Natural variability within the ocean climate system also occurs at various time scales (seasonal to decadal), producing climatic phenomena such as ENSO, the North Atlantic Oscillation (NAO), and the PDO.³⁶² Although how this variability will change over the coming decades is uncertain, the steady increases in heat content of the ocean and atmosphere are likely to have profound influences on the strength, direction, and behavior of the world's major current systems.³⁶³
- Changes in the behavior of ocean currents have the

potential to strongly influence the distribution and abundance of marine ecosystems, as demonstrated by recent impacts of ENSO variability on kelp forests and coral reefs.³⁶⁴

These interactions are discussed further in their respective sections of this report: in this Chapter, see Section 7 for Altered patterns of coastal upwelling and Section 8 for Altered patterns of coastal hypoxia

³⁵⁸ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524). The authors cite Bakun and Weeks (2004) for this information.

³⁵⁹ Comment from reviewer, April 2011.

³⁶⁰ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524)

³⁶¹ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524). The authors cite Alheit and Bakun (2010) for information on the effect of ocean heating on ocean currents.

³⁶² Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524). The authors cite Alheit and Bakun (2010) for this information.

³⁶³ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524). The authors cite Bindoff et al. (2007) for this information.

³⁶⁴ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1524). The authors cite Ling (2008) for information on kelp forests and Hoegh-Guldberg et al. (2007) for information on coral reefs.

and anoxia, Box 7 for an explanation of ENSO and PDO, and Chapters IV through VII for ecosystem, habitat, and species effects. Climate patterns are discussed in Appendix 3. Major Climate Patterns in the NPLCC: ENSO and PDO).

Observed Trends

Southcentral and Southeast Alaska, and British Columbia

Surveys by Whitney, Freeland, and Robert (2007) found that oxygen in the subsurface waters of the Alaskan Gyre was supplied about 60% by subarctic and 40% by subtropical waters.³⁶⁵ At an ocean station off the coast of British Columbia and southeast Alaska (station P in Figure 12), evidence of low nitric oxide waters flowing north from California was observed.³⁶⁶ Cycles of variability off the British Columbia coast were also discerned by this study, including increased ventilation of deeper, constant-density waters on an ~18 year cycle and strong, short term (few month) variability caused by passing eddies of intermediate size.³⁶⁷

Washington

Information needed.

Oregon

In the Oregon Climate Assessment Report, Mote, Gavin, and Huyer (2010) report information on ocean currents for Oregon. After sustained summer upwelling, the resulting density gradients cause a southward current whose speed is greatest at the surface and decreases with depth.³⁶⁸ After sustained winter downwelling, the coastal current is northward; its speed tends to decrease with depth.³⁶⁹ In both seasons, alongshore currents are much stronger than the onshore/offshore currents of the upwelling/downwelling circulation.³⁷⁰ Some interannual variability in shelf currents and temperature can also be explained by local alongshore wind stress: for example, unusually strong northward winds in the El Niño winters of 1983 and 1998 enhanced the northward coastal current; unusually late arrival of northerly winds in the spring of 2005 delayed the onset of upwelling by more than a month.³⁷¹

Northwest California

In a study by Palacios et al. (2004) of thermal stratification in the upper 656 feet (200 m) of the California Current System (CCS) off the California coast from 1950 to 1993, the mean level of the coastal thermocline strengthened and deepened, while the offshore thermocline weakened and shoaled (i.e. decreased in depth).³⁷² These tendencies are likely the result of a natural oceanic process adjusting to

³⁶⁵ Verbatim or nearly verbatim from Whitney, Freeland, and Robert. (2007, p. 179)

³⁶⁶ Verbatim or nearly verbatim from Whitney, Freeland, and Robert. (2007, p. 179)

³⁶⁷ Verbatim or nearly verbatim from Whitney, Freeland, and Robert. (2007, p. 179)

³⁶⁸ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 24)

³⁶⁹ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 24)

³⁷⁰ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 24)

³⁷¹ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 25-26). The authors cite Kosro (2002) for information on northward winds in the El Niño winters of 1983 and 1998 and Pierce et al. (2006) for information on the late arrival of northerly winds in 2005.

³⁷² Verbatim or nearly verbatim from Palacios et al. *Long-term and seasonal trends in stratification in the California Current, 1950-1993*. (2004, p. 1)

changes in ocean basin-scale circulation (i.e. geostrophic adjustment; geostrophic currents result when pressure from the Coriolis force is in balance with pressure due to seawater moving from areas of high to low sea level), as well as to a long-term increase in upper ocean heat content of two to nine percent throughout the study area.³⁷³ Substantial decadal variability superimposed on these linear tendencies may play a role in determining the response of the upper ocean to interannual events such as El Niño.³⁷⁴ Further, it is possible that the net impact of an El Niño event on the CCS will depend greatly on the ambient conditions present at the time of the impact.³⁷⁵ The seasonal component of thermocline depth and strength exhibited a high degree of nonstationarity (i.e. varying with time), with alternating periods of weakened and enhanced annual cycles lasting three to five years, along with changes in phase.³⁷⁶

Future Projections

Information needed. Some researchers speculated that ocean currents of the future may be similar to extremes in natural variability observed historically (e.g. ENSO, PDO) and that the negative consequences observed during extreme phases – for example, large reductions in fish populations, harmful algal blooms, hypoxia, and anoxia – could occur more frequently, or become the norm.³⁷⁷

Information Gaps

Information is needed on global trends and future projections in ocean currents. Information is also needed on regional trends, as results from single studies are presented here. Further, information is needed on regional projections for ocean currents. Sigler et al. (2008) identify climate information needs for understanding changes in ocean circulation in the Gulf of Alaska:

- Downscaled IPCC climate scenarios resolved to drive kilometer and hourly-scale Regional Ocean Circulation Models (ROMS) with ice; and
- Archived runs of ROMS from 1900s to present.³⁷⁸

Peterson and Schwing (2008) identify two additional climate information needs for understanding changes in ocean circulation in the California Current region, which will also inform the impacts of altered ocean circulation on species distribution and community structure in pelagic (open-ocean) habitats:

- Water mass climatology and anomaly fields (using water mass characteristics to distinguish water type and sources in near real-time), and satellite and blended satellite-model reanalysis products to provide the details of water sources and transport patterns in near real-time.³⁷⁹
- Basin-scale ocean circulation observations and models to determine changes in gyre circulation and source and advection of water mass types.³⁸⁰

³⁷³ Verbatim or nearly verbatim from Palacios et al. (2004, p. 1)

³⁷⁴ Verbatim or nearly verbatim from Palacios et al. (2004, p. 1)

³⁷⁵ Verbatim or nearly verbatim from Palacios et al. (2004, p. 6)

³⁷⁶ Verbatim or nearly verbatim from Palacios et al. (2004, p. 1)

³⁷⁷ Verbatim or nearly verbatim from Osgood (Ed.). *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs.* (2008)

³⁷⁸ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 69, 73).

³⁷⁹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 60)

5. ALTERED FREQUENCY AND SEVERITY OF STORMS

Box 9. Summary of observed trends and future projections for storm frequency and severity

Observed Trends

- Coasts are highly vulnerable to extreme events, such as storms.³⁸¹ The coasts of the NPLCC region, particularly Oregon and Washington, are well-known for the severity of their winter storms.
- Wave heights have increased globally since the 1970s.³⁸²

Future Projections

- Under scenarios of future climate change in the 21st century, a poleward shift of storm tracks by several degrees latitude and greater storm activity at high latitudes is projected (baseline not provided).³⁸³
- Over the 21st century in the mid-latitudes, extratropical storms are likely to become more intense, but perhaps less frequent, likely leading to increased extreme wave heights (baseline not provided).³⁸⁴ Increased wind speed is associated with mid-latitude storms, resulting in higher waves produced by these storms.³⁸⁵ Higher sea levels will also increase the height of storm waves and surges, increasing the frequency of extreme events.³⁸⁶
- In determining future beach erosion rates, several recent studies indicate that beach protection strategies and changes in the behavior or frequency of storms can be more important than the projected acceleration of sea level rise.³⁸⁷ One reviewer noted this is especially true of the outer coast, and less important for large estuaries like the Puget Sound.³⁸⁸
- The combined effects of beach erosion and storms can lead to the erosion or inundation of other coastal systems.³⁸⁹

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

Definition and Causes of Altered Frequency and Severity of Storms

Storms develop when a center of low pressure develops with a system of high pressure surrounding it. Cyclones, for example, are a weather system characterized by relatively low surface pressure compared with the surrounding air; this is associated with convergence, and therefore rising motion, cloudiness, and

³⁸⁰ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 61)

³⁸¹ Nicholls et al. (2007, p. 317).

³⁸² Hoffman. *Designing reserves to sustain temperate marine ecosystems in the face of global climate change*. (2003, p. 135)

³⁸³ Meehl et al. (2007, p. 789)

³⁸⁴ Field et al. *Climate Change 2007: Impacts, Adaptation, and Vulnerability: North America*. (2007, p. 627). The authors cite Meehl et al., 2007: Section 10.3.6.4 in the IPCC AR4, for this information.

³⁸⁵ Meehl et al. (2007, p. 789)

³⁸⁶ Hoffman. (2003, p. 135)

³⁸⁷ Nicholls et al. (2007, p. 324). The authors cite Ahrendt (2001) and Leont'yev (2003) for this information.

³⁸⁸ Personal communication with reviewer (January 2011).

³⁸⁹ Nicholls et al. (2007, p. 324).

precipitation.³⁹⁰ One way in which climate change may affect the frequency and severity of storms is via changes to mean sea level pressure: the IPCC AR4 considers projections of the mean sea level pressure for the medium scenario A1B.³⁹¹ Sea level pressure differences show decreases at high latitudes in both seasons in both hemispheres.³⁹² The compensating increases are predominantly over the mid-latitude and subtropical ocean regions.³⁹³ Many of these increases are consistent across the models.³⁹⁴ This pattern of change has been linked to an expansion of the Hadley Circulation and a poleward shift of the mid-latitude storm tracks.³⁹⁵

Observed Trends

Global

Information needed.

Alaska

Information needed.

British Columbia

Extreme sea level events, related to intense storms, can result in sea levels reaching 3.28 feet (1 meter) above the predicted high tide level.³⁹⁶

Washington and Oregon

The Oregon Coastal Management Program (2009) reports that along the Oregon coast, data show that both the frequency and intensity of storms have increased in recent years, and individual storms are producing higher waves and storm surges (no baseline or range provided).³⁹⁷ Along the Oregon and Washington coasts, increased vulnerability to storm surge, high tides, and accelerated coastal erosion are all listed as impacts due to climate change.³⁹⁸ This vulnerability would be compounded by an increase in average wave heights, a physical effect associated with more intense storms.³⁹⁹ The heights of storm waves measured at buoys hundreds of miles off the Oregon and Washington coasts have increased as much as eight feet since the mid-1980s (end-date not provided), and such waves deliver sixty-five percent more force when they come ashore.⁴⁰⁰

³⁹⁰ Verbatim or nearly verbatim from Tokay. *Chapter 13: Mid-latitude cyclones (website)*. (Tokay 2009)

³⁹¹ Meehl et al. (2007, p. 770)

³⁹² Verbatim or nearly verbatim from Meehl et al. (2007, p. 770)

³⁹³ Verbatim or nearly verbatim from Meehl et al. (2007, p. 770)

³⁹⁴ Verbatim or nearly verbatim from Meehl et al. (2007, p. 770)

³⁹⁵ Verbatim or nearly verbatim from Meehl et al. (2007, p. 770). The authors cite Yin (2005) for information on the Hadley Circulation and poleward shifts in mid-latitude storm tracks. The authors refer the reader to Section 10.3.5.3 in the cited report for further discussion of patterns in sea level pressure differences.

³⁹⁶ Verbatim or nearly verbatim from Bornhold. *Projected sea level changes for British Columbia in the 21st century*. (2008, p. 9)

³⁹⁷ Verbatim or nearly verbatim from Oregon Coastal Management Program (OCMP). *Climate Ready Communities: A Strategy for Adapting to Impacts of Climate Change on the Oregon Coast (pdf)*. (2009, p. 12)

³⁹⁸ Verbatim or nearly verbatim from OCMP. (2009, p. 66)

³⁹⁹ Verbatim or nearly verbatim from OCMP. (2009, p. 66)

⁴⁰⁰ Verbatim or nearly verbatim from OCMP. (2009, p. 66)

Northwest California

Information needed.

Northeast Pacific Ocean (Pacific Northwest and British Columbia)

The wave climate of the Pacific Northwest is recognized for its severity, with winter storms commonly generating deep-water significant wave heights (SWHs, the average height from trough to crest of the top third highest waves) greater than 32.8 feet (10 m) (approximately one event of this magnitude per year), with the strongest storms in the region having generated SWHs in the range of 46 to 49 feet (14-15 m).⁴⁰¹ In recent decades increases in wave heights generated by the most intense storms have occurred in the Northeast Pacific Ocean.⁴⁰² Specifically, Ruggiero et al. (2010) note progressive multi-decadal increases in winter (October through April, the dominant season of strongest storms) SWHs have been observed.⁴⁰³ the overall range of measured SWHs has shifted toward higher values between the 1976 to 1990 and 1998 to 2007 decades.⁴⁰⁴

Observed changes in the rate of SWHs include:

- The annual averages of the deep-water SWHs have increased at a rate of approximately 0.049 feet/year (ft/yr; 0.015 meters/yr), while averages for the winter season (October – March) increased at the higher rate of 0.075 ft/yr (0.023 m/yr).⁴⁰⁵
- Averages of the five highest SWHs measured each year have increased at the appreciably greater rate of 0.23 ft/yr (0.071 m/yr), with the rate for the annual maximum SWHs having been 0.31 ft/yr (0.095 m/yr).⁴⁰⁶
- The highest rate of increase in wave heights was identified offshore from the Washington coast, with slightly lower rates of increase offshore from Oregon.⁴⁰⁷ Northern to central California is a zone of transition having still lower rates of SWH increases.⁴⁰⁸

This increase has been documented by measurements from a series of NOAA buoys along the U.S. West Coast, and by analyses of the storm intensities and hindcasts of the generated waves, with the waves having been generated by extratropical storms.⁴⁰⁹ While these increases are most likely due to Earth's changing climate, uncertainty remains as to whether they are the product of human-induced greenhouse

⁴⁰¹ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. *Increasing wave heights and extreme value projections: the wave climate of the U.S. Pacific Northwest*. (2010, p. 2). The authors cite Allan and Komar (2002, 2006) for this information.

⁴⁰² Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 1)

⁴⁰³ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 2). The authors cite Allan and Komar (2000, 2006) for this information.

⁴⁰⁴ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 5)

⁴⁰⁵ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 13)

⁴⁰⁶ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 13)

⁴⁰⁷ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 2). The authors cite Allan and Komar (2000, 2006) for this information.

⁴⁰⁸ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 2). The authors cite Allan and Komar (2006) and Adams et al. (2008) for this information.

⁴⁰⁹ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 1). The authors cite Allan and Komar (2000, 2006), Mendez et al. (2006), Menendez et al. (2008a), and Komar et al. (2009) for information obtained from NOAA buoy measurements. The authors cite Graham and Diaz (2001) for information on analyses of storm intensities and hindcasts.

warming or represent variations related to natural multi-decadal climate cycles.⁴¹⁰ However, Ruggiero et al. (2010) state that measurements of SWHs off the U.S. Pacific Northwest coast represent a clear example for a phenomenon that was suggested by Wigley (1988) in general terms: a gradual change in the mean climate of an environmental variable can result in significant increases in the frequency of extreme events.⁴¹¹

Future Projections

Global

The IPCC reports that the most consistent results from the majority of the current generation of models show, for a future warmer climate, a poleward shift of storm tracks in both hemispheres by several degrees of latitude.⁴¹² Greater storm activity at higher latitudes is also projected.⁴¹³ In the mid-latitudes, extratropical storms are likely to become more intense, but perhaps less frequent, likely leading to increased extreme wave heights.⁴¹⁴ This is related to increased wind speed associated with mid-latitude storms, resulting in higher waves produced by these storms, and is consistent with studies described in the IPCC AR4 that showed decreased numbers of mid-latitude storms but more intense storms.⁴¹⁵

Alaska

Over this century, an increase of sea surface temperatures and a reduction of ice cover are likely to lead to northward shifts in the Pacific storm track and increased impacts on coastal Alaska.⁴¹⁶

British Columbia

Information needed.

Washington

Information needed.

Oregon

In Oregon, projected changes suggest that future winter storms may be similar to recent strong El Niño-influenced storms that accelerated coastal erosion (no baseline or range provided).⁴¹⁷

Northwest California

Information needed.

⁴¹⁰ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 1)

⁴¹¹ Verbatim or nearly verbatim from Ruggiero, Komar, and Allan. (2010, p. 6)

⁴¹² Verbatim or nearly verbatim from Meehl et al. (2007, p. 789)

⁴¹³ Verbatim or nearly verbatim from Meehl et al. (2007, p. 789)

⁴¹⁴ Verbatim or nearly verbatim from Field et al. (2007, p. 627). The authors cite Meehl et al., 2007: Section 10.3.6.4 in the IPCC AR4, for this information.

⁴¹⁵ Verbatim or nearly verbatim from Meehl et al. (2007, p. 789)

⁴¹⁶ Verbatim or nearly verbatim from Karl, Melillo and Peterson. *Global Climate Change Impacts in the United States (pdf)*. (2011, p. 143). The authors cite Yin (2005) and Salathé (2006) for this information.

⁴¹⁷ Verbatim or nearly verbatim from OCMF. (2009, p. 12)

Information Gaps

Information is needed on global trends in the frequency and intensity of storms. In addition, regionally-specific information is needed to expand on the trends and projections for storms throughout the geographic extent of the NPLCC, as the information presented above pertains more closely to wave heights than storms.

6. SEA LEVEL RISE (SLR)

Box 10. Summary of observed trends and future projections for sea level rise

Observed Trends

- Global sea level rose by about 394 feet (120 m) during the several millennia that followed the end of the last ice age (approximately 21,000 years ago), and stabilized between 3,000 and 2,000 years ago.⁴¹⁸
- Sea levels rose approximately 0.56 feet (0.40-0.72 ft; 0.17m ± 0.05) in the 20th century.⁴¹⁹
- The IPCC AR4 reports that from 1961 to 2003, sea levels rose 0.071 inches per year (0.051-0.091 inches/yr; 1.8 ± 0.5 mm/yr), while from 1993 to 2003, sea levels rose 0.12 inches per year (0.094-0.15 inches/yr; 3.1 ± 0.7 mm/yr).⁴²⁰
- In the NPLCC region, sea level rise is less than the 1961-2003 global average at most stations.⁴²¹
 - In fact, a relative *decline* in sea level has been observed at most stations in southcentral and southeast AK (typically <0.5 inches/yr, 12.7 mm/yr),⁴²² at Tofino, BC (- 0.0661 inches/yr or -1.68 mm/yr),⁴²³ and at Neah Bay, WA (- 0.064 ± 0.014 inches/yr or -1.63 ± 0.36 mm/yr).⁴²⁴
 - On the other hand, three stations recorded sea level rise *exceeding* the 1961-2003 global average: Cordova, AK (0.2268 inches/yr, 5.76 mm/yr),⁴²⁵ Toke Point, WA according to some measurements,⁴²⁶ and South Beach, OR (0.107 inches/yr, 2.72 mm/yr).⁴²⁷ The regional rate of SLR in the Pacific Northwest has been estimated at ~0.091 inches/yr (~2.3 mm/yr).⁴²⁸
 - Measurements from CA are inconclusive due to debate about the accuracy of the vertical reference system (see Box 12).

Future projections are on the next page.

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

⁴¹⁸ Bindoff et al. *Climate Change 2007: The Physical Science Basis: FAQ 5.1 (website)*. (2007)

⁴¹⁹ IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. (2007f, p. 7)

⁴²⁰ IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 2). The 90% uncertainty interval of these values is 1.3 to 2.3 mm/yr (since 1961) and 2.4 to 3.8 mm/yr (since 1993). These uncertainty levels are not necessarily symmetric around the corresponding best estimate. See Footnote 1.1 (p. 2) of same report.

⁴²¹ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007); Abeyirigunawardena and Walker. *Sea level responses to climatic variability and change in northern British Columbia*. (2008); B.C. MoE. *In-depth report: Climate Change*. (2007, p. 25); NOAA. *Tides and Currents: Sea level Trends (website)*. (2010).; Mote et al. *Sea level rise in the coastal waters of Washington State*. (2008, p. 7).

⁴²² NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴²³ Abeyirigunawardena and Walker. *Sea level responses to climatic variability and change in northern British Columbia*. (2008); B.C. MoE. *In-depth report: Climate Change*. (2007, p. 25); NOAA. *Tides and Currents: Sea level Trends (website)*. (2010).

⁴²⁴ Mote et al. *Sea level rise in the coastal waters of Washington State*. (2008, p. 7). NOAA. *Tides and Currents: Sea level Trends (website)*. (2010).

⁴²⁵ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴²⁶ Mote et al. *Sea level rise in the coastal waters of Washington State*. (2008, p. 7). NOAA. *Tides and Currents: Sea level Trends (website)*. (2010).

⁴²⁷ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴²⁸ Ruggiero, Brown and Komar. *Impacts of climate change on Oregon's coasts and estuaries*. (2010, p. 216). The authors cite Burgette et al. (2009) for this information.

Box 10. – *continued*

Future Projections

- Global SLR is projected to increase 5.1-70 inches (13-179 cm) by the end of the 21st century across all models and scenarios presented in this report (compared to the end of the 20th century). The wide range is due, in part, to the inclusion or exclusion of projected changes to ice sheet flow. For example, all values reported in the IPCC AR4 (which range from 7.1-23 inches or 18-59 cm by 2100)⁴²⁹ would increase by 3.6 to 8.4 inches (10-20 cm) if the contribution from increased ice flow from Greenland and Antarctica were to grow linearly with global average temperature change.⁴³⁰
- In the NPLCC region, increases in sea level are projected for BC, parts of WA, OR, and CA by 2100:
 - +0.36 to 1.6 feet (0.11 – 0.5 m) on Vancouver Island and near Vancouver, BC (B1, A1B, A1F1 scenarios; see footnote for baseline information)⁴³¹
 - +0.82 to 1.5 feet (0.25 – 0.46 m) at Prince Rupert, BC (B1, A1B, A1F1 scenarios; see footnote for baseline information)⁴³²
 - +13 inches (34 cm; no range provided) in Puget Sound, WA (1980-1999 baseline; see footnote for scenario)⁴³³
 - +11 inches (29 cm; no range provided) on the central and southern WA coast (1980-1999 baseline; see footnote for scenario)⁴³⁴
 - +50 inches (128 cm) for the areas of the OR coast experiencing little vertical land motions (1980-1999 baseline; no range provided; see footnote for scenario)⁴³⁵
 - Up to +55 inches (1.4 meters) in CA (A2 scenario; no range provided; see footnote for baseline)⁴³⁶
- Decreases or very little relative change are projected elsewhere in the NPLCC region:
 - -2.1 to -3.4 feet (-0.64 to -1.0 m)⁴³⁷ in southcentral and southeast Alaska by 2100 (no baseline provided).
 - Very little relative change on the northwest Olympic Peninsula (WA) will be apparent due to rates of local tectonic uplift that currently exceed projected rates of global SLR.⁴³⁸

Definition and Causes of Sea Level Rise

Sea level relative to the land is mediated by four primary mechanisms:

- Changes in global ocean volume due to melting of ice caps, continental ice sheets and mountain glaciers (known as eustatic sea level rise);
- Global and regional changes in ocean volume due to thermal expansion and salinity effects on water density (warmer, fresher water occupies more volume than colder, saltier water) (known as steric sea level rise);

⁴²⁹ IPCC. *Climate Change 2007: Synthesis Report*. (2007c, Table 3.1, p. 45). Compared to a 1980-1999 baseline.

⁴³⁰ IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 45). In a footnote, the authors state “For discussion of the longer term see Sections 3.2.3 and 5.2.”

⁴³¹ Bornhold. (2008). This study uses IPCC SRES scenarios, which use a 1980-1999 baseline.

⁴³² Bornhold. (2008). This study uses IPCC SRES scenarios, which use a 1980-1999 baseline.

⁴³³ Mote et al. *Sea level rise in the coastal waters of Washington State*. (2008, Table 3, p. 10). The researchers use a “medium” estimate of SLR: the average of the six central values from the six IPCC scenarios (13” or 34cm).

⁴³⁴ Mote et al. (2008, Table 3, p. 10). The researchers use a “medium” estimate of SLR: the average of the six central values from the six IPCC scenarios (13 inches or 34 cm).

⁴³⁵ Ruggiero et al. (2010, p. 218). The researchers use a low-probability high-impact estimate of local SLR for the areas of the coast experiencing little vertical land motions (50 inches or 128 cm).

- Regional volume changes due to dynamic atmospheric and ocean processes, such as shifting major wind systems and ocean currents; and,
- Local changes due to vertical land motions, associated with recovery from the weight of glaciers during the last Ice Age (isostatic rebounding), subsidence (sinking) in river deltas, and tectonic processes in the earth's crustal plates (e.g. oceanic plates move beneath continental plates, resulting in uplift of land in some areas and sinking of land in others).⁴³⁹ If the rate of land uplift is greater than the rate at which sea level is rising, a *net decrease* in relative SLR would be observed.

Observed Trends

Note: Observed trends in sea level are organized into several tables in this section. The time periods provided in these tables differ for two reasons: the available data record varies by location, and the published literature varies by the time period studied. Please refer to the notes and footnotes associated with each table for more information.

Global

Global sea level rose by about 394 feet (120 m) during the several millennia that followed the end of the last ice age (approximately 21,000 years ago), and stabilized between 3,000 and 2,000 years ago.⁴⁴⁰ Sea level indicators suggest that global sea level did not change significantly from then until the late 19th century.⁴⁴¹ The total 20th century rise is estimated to be 0.56 feet (0.40-0.72 ft; 0.17 m with a range of 0.12-0.22 m).⁴⁴² Several researchers have measured SLR and investigated the contribution to SLR from thermal expansion (steric effects) and melting glaciers and ice caps (eustatic effects) (Table 10).

From 1961 to 2003:

- According to the IPCC's AR4, global average sea level rose at an average rate of 0.071 inches per year (0.051-0.091 inches/yr; 1.8 mm/yr with a range of 1.3-2.3 mm/yr), with contributions from thermal expansion, melting glaciers and ice caps, and the polar ice sheets.⁴⁴³

⁴³⁶ CA Natural Resources Agency. (2009, p. 18) Under the A2 emissions scenario, baseline is likely 1990 levels. The authors cite the work of Rahmstorf (2007), which projects SLR for 2100 compared to 1990 levels using a semi-empirical method, for their SLR projections. Please see the global projections for SLR section of this report for further detail on the study by Rahmstorf (2007).

⁴³⁷ AK Department of Environmental Conservation. (2010, p. 2-4). The authors cite Larsen et al. (2004), Kelly et al. (2007), and Pyare (2009) for this information. No baseline is provided.

⁴³⁸ Mote et al. *Sea level rise in the coastal waters of Washington State*. (2008, p. 3)

⁴³⁹ Verbatim or nearly verbatim from Bornhold. (2008, p. 3). Most sea level measurements are *relative to the land*, though the advent of new technologies such as satellite altimetry is expanding the record for measurements of *absolute sea level*.

⁴⁴⁰ Verbatim or nearly verbatim from Bindoff et al. (2007)

⁴⁴¹ Verbatim or nearly verbatim from Bindoff et al. (2007)

⁴⁴² Verbatim or nearly verbatim from IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. (2007f, p. 7)

⁴⁴³ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 2). The 90% uncertainty interval of these values is 1.3 to 2.3 mm/yr (since 1961) and 2.4 to 3.8 mm/yr (since 1993). These uncertainty levels are not necessarily symmetric around the corresponding best estimate. See Footnote 1.1 (p. 2) of same report.

- Domingues et al. (2008) found steric and eustatic effects contributed approximately fifty percent each to SLR, resulting in a total SLR of approximately 0.059 inches/yr (1.5 mm/yr).⁴⁴⁴

From 1993 to 2003:

- According to the IPCC's AR4, global average sea level rose at an average rate of 0.12 inches/yr (0.094-0.15 inches/yr; 3.1 mm/yr with a range of 2.4-3.8 mm/yr).⁴⁴⁵ Thermal expansion of the oceans (eustatic effects) contributed approximately fifty-seven percent of the sum of the estimated individual contributions to sea level rise, with decreases in glaciers and ice caps contributing approximately twenty-eight percent and losses from the polar ice sheets contributing the remainder.⁴⁴⁶ Whether the faster rate for 1993 to 2003 (compared to 1961-2003) reflects decadal variation or an increase in the longer-term trend is unclear.⁴⁴⁷
- Domingues et al. (2008) report SLR of approximately 0.094 inches/yr (2.4 mm/yr) as well as an increase in the eustatic contribution of approximately sixty percent (compared to 1961-2003).⁴⁴⁸
- Hansen et al. (2005) find that steric and eustatic effects contributed approximately fifty percent each to SLR: given a 0.12 inches/yr (3.1 mm/yr) SLR, Hansen et al. (2005) run five simulations to conclude that full ocean temperature changes yield a mean steric sea level rise of 0.63 inches (0.063 inches/yr; 1.6 cm overall and 1.6 mm/yr), with the remaining ~ 0.59 inches (0.059 inches/yr; 1.5 cm overall and 1.5 mm/yr) of SLR due to eustatic effects.⁴⁴⁹

From 2003 to 2008:

- Cazenave et al. (2009) find eustatic contributions from land ice plus land waters has contributed seventy-five to eighty-five percent of recent SLR (~0.087 inches/yr; ~ 2.2 mm/yr), i.e., significantly more than during the decade 1993 to 2003.⁴⁵⁰ Of this, the melting of polar ice sheets and mountain glaciers are roughly equally responsible.⁴⁵¹ Steric contributions are an additional ~ 0.012 inches/yr (0.3 mm/yr), and total SLR is ~0.098 inches/yr (2.5 mm/yr).⁴⁵²

⁴⁴⁴ Verbatim or nearly verbatim from Domingues et al. (2008, p. 1090-1092)

⁴⁴⁵ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 30). The 90% uncertainty interval of these values is 1.3 to 2.3 mm/yr (since 1961) and 2.4 to 3.8 mm/yr (since 1993). These uncertainty levels are not necessarily symmetric around the corresponding best estimate. See Footnote 1.1 (p. 2) of same report.

⁴⁴⁶ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 30). The 90% uncertainty interval of these values is 1.3 to 2.3 mm/yr (since 1961) and 2.4 to 3.8 mm/yr (since 1993). These uncertainty levels are not necessarily symmetric around the corresponding best estimate. See Footnote 1.1 (p. 2) of same report.

⁴⁴⁷ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 30)

⁴⁴⁸ Domingues et al. (2008, p. 1090-1092)

⁴⁴⁹ Verbatim or nearly verbatim from Hansen et al. (2005, p. 1433)

⁴⁵⁰ Cazenave et al. *Sea level budget over 2003-2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo*. (2009, p. 86). The authors cite Bindoff et al. (2007) for information on the 1993-2003 decade.

⁴⁵¹ Cazenave et al. (2009, Table 1, p. 84)

⁴⁵² Cazenave et al. (2009, Table 1, p. 84)

Table 10. Contribution to sea level rise by thermal expansion (steric effects) and melting glaciers and ice caps (eustatic effects) over several time periods. (*inches per year, with millimeters per year in parentheses*)

<i>Study</i>	<i>Time period(s)</i>	<i>Steric SLR</i>	<i>Eustatic SLR</i>	<i>Total SLR</i>
Domingues et al. (2008)	1961-2003	0.030 (~0.75)	0.030 (~0.75)	0.059 (1.5)
	1993-2003	--	+60% from 1961-2003	0.094 (2.4)
Hansen et al. (2005)	1993-2003	0.063 (1.6)	0.059 (1.5)	0.12 (3.1)
IPCC Working Group I (Bindoff et al., Ch.5, AR4; 2007)	1961-2003	--	--	0.071 ± 0.02 (1.8 ± 0.5)
	1993-2003	0.063 ± 0.0098 (1.6 ± 0.25)	0.047 ± 0.0079 (1.2 ± 0.2)*	0.12 ± 0.028 (3.1 ± 0.7)
Cazenave et al. (2009)	2003-2008	0.012 ± 0.0059 (0.31 ± 0.15)	0.087 ± 0.011 (2.2 ± 0.28)	0.098 ± 0.016 (2.5 ± 0.4)

-- Data not provided.; * land ice contribution only *Table created by authors of this report.*

Southcentral and Southeast Alaska

For much of southcentral and southeast Alaska, the available information indicates the rate of SLR is less than the global average reported in the IPCC's AR4 (Table 11).⁴⁵³ Values range from a decline in mean sea level of 0.674 inches per year (17.12 mm/yr) from 1944 to 2007 at Skagway to an increase in mean sea level of 0.2268 inches per year (5.76 mm/yr) from 1964 to 2007 at Cordova.⁴⁵⁴

British Columbia

With the exception of data reported for Prince Rupert by Abeyvirigunawardena and Walker (2008), SLR from 1909 to 2006 in British Columbia is reported as less than the global average (Table 12). Regional changes in ocean volume, tectonic activity, and isostatic rebounding affect SLR in B.C. in the following ways:

- **Regional changes in ocean volume due to thermal expansion, salinity effects, and dynamic atmospheric and ocean processes:**
 - *Thermal expansion and salinity effects:* In the northeast Pacific (along the B.C. coastline), SLR due to temperature and salinity has been estimated at about 0.043 inches per year (1.1 mm/yr).⁴⁵⁵ Throughout the northeast Pacific, about half of the contribution is due to temperature increases and half is due to salinity decreases, but in the Strait of Georgia, salinity effects account for about sixty-three percent of the observed sea level change and temperature accounts for about thirty-seven percent, as a result of coastal runoff.⁴⁵⁶
 - *Dynamic atmospheric and ocean processes:* Prevailing northwesterly (equatorward) alongshore winds in summer, combined with high atmospheric pressure and equatorward coastal currents, normally lower sea levels by about 0.3 feet (0.1 m).⁴⁵⁷ Conversely, southeasterly winds in winter combined with low atmospheric pressure and strong

⁴⁵³ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴⁵⁴ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴⁵⁵ Verbatim or nearly verbatim from Bornhold. (2008, p. 8)

⁴⁵⁶ Verbatim or nearly verbatim from Bornhold. (2008, p. 8)

⁴⁵⁷ Verbatim or nearly verbatim from Bornhold. (2008, p. 7)

poleward coastal currents can increase sea levels by over 1.6 feet (0.5 m).⁴⁵⁸ Further, fluctuations in sea level may also be attributed to an ENSO event and demonstrate that short-term changes may exceed long-term trends.⁴⁵⁹ In other words, while these changes are regionally specific (i.e., of limited time duration and spatial extent), and even though they are not the primary contributors to climate change-induced sea level rise, they may nonetheless exacerbate or mitigate the longer-term effects of global climate change-induced sea level rise.⁴⁶⁰

- **Vertical land motions due to tectonic activity:** The continued stress of the Juan de Fuca tectonic plate as it moves beneath the North American plate results in an annual uplift of the land (and corresponding fall in sea level) of about 0.08 to 0.1 inches per year (2-3 mm/yr).⁴⁶¹ For example, this rate has been measured on Haida Gwaii (Queen Charlotte Islands).⁴⁶² Rates of crustal uplift are estimated to be as high as 0.16 inches per year (4 mm/yr) along the southwest coast of Vancouver Island near Tofino.⁴⁶³ This effect diminishes across Vancouver Island and the Strait of Georgia to near zero on bedrock areas near Vancouver.⁴⁶⁴ However, this tectonically driven uplift is periodically halted by strong subduction zone earthquakes, which cause the ocean floor to drop, some areas (such as the central Olympic Peninsula in Washington State) to rise, and other coastal areas to sink below sea level.⁴⁶⁵
- **Vertical land uplift due to isostatic rebound:** the rate of rebound along the coast is estimated to be 0 to 0.16 inches per year (0-4 mm/yr);⁴⁶⁶ a narrower range of 0.0079 to 0.0098 inches per year (0.20-0.25 mm/yr) has also been reported.⁴⁶⁷

Additional information on sea level rise in British Columbia is available in Box 11.

⁴⁵⁸ Verbatim or nearly verbatim from Bornhold. (2008, p. 7)

⁴⁵⁹ Verbatim or nearly verbatim from B.C. MoE. (2007, p. 26). For example, Abeysirigunawardena and Walker (2008, p. 284) state that at Prince Rupert, there is evidence that the annual maximum sea level over 1945-2003 (1.3 inches/yr; 3.4 mm/yr) increased at twice the rate of the relative sea level trend, likely due to enhanced storm conditions and the influence of major ENSO events (e.g. 1982-1983 and 1997-1998) during this period.

⁴⁶⁰ Comments from reviewers, April & July 2011.

⁴⁶¹ Verbatim or nearly verbatim from Bornhold. (2008, p. 6)

⁴⁶² Verbatim or nearly verbatim from Bornhold. (2008, p. 6)

⁴⁶³ Verbatim or nearly verbatim from B.C. Ministry of Environment. (2007, p. 26). The report cites Peltier (1996) for this information.

⁴⁶⁴ Verbatim or nearly verbatim from Bornhold. (2008, p. 6)

⁴⁶⁵ Verbatim or nearly verbatim from WA Department of Ecology. *Offshore Fault (website)*. (2011)

⁴⁶⁶ Verbatim or nearly verbatim from B.C. Ministry of Environment. (2007, p. 26)

⁴⁶⁷ Bornhold. (2008, p. 6)

Table 11. SLR Trends in Southeast Alaska, 1919-2008.

(inches per year with mm/yr in parentheses. Table created by authors of this report.)

*indicates previously published trends; †90% CI; CI = Confidence Interval; MSL = Mean Sea level

Location	Time Period	MSL trend ⁴⁶⁸	95% CI ⁴⁶⁹	MSL trend*	95% CI*
Ketchikan	1919-2007	- 0.0075 (-0.19)	0.011 (0.27)	- 0.0043 (-0.11)	0.012 (0.31)
Sitka	1924-2007	- 0.0807 (-2.05)	0.013 (0.32)	- 0.0854 (-2.17)	0.016 (0.41)
Juneau	1936-2007	- 0.5087 (-12.92)	0.017 (0.43)	- 0.4996 (-12.69)	0.020 (0.50)
Skagway	1944-2007	- 0.6740 (-17.12)	0.026 (0.65)	- 0.6567 (-16.68)	0.032 (0.82)
Yakutat	1979-2007	- 0.4543 (-11.54)	0.0547 (1.39)	- 0.226 (-5.75)	0.020 (0.52)
Cordova	1964-2007	0.2268 (5.76)	0.034 (0.87)	0.274 (6.97)	0.0465 (1.18)
Valdez	1973-2007	- 0.0992 (-2.52)	0.0535 (1.36)	- 0.013 (-0.34)	0.0776 (1.97)
Seward	1964-2007	- 0.0685 (-1.74)	0.036 (0.91)	- 0.0575 (-1.46)	0.0472 (1.20)
Seldovia	1964-2007	- 0.372 (-9.45)	0.043 (1.10)	- 0.391 (-9.93)	0.0602 (1.53)
Nikiski	1973-2007	- 0.386 (-9.80)	0.059 (1.50)	- 0.4217 (-10.71)	0.091 (2.30)
Anchorage	1972-2007	0.035 (0.88)	0.0606 (1.54)	0.109 (2.76)	0.0894 (2.27)
Global average ⁴⁷⁰	1961-2003			0.071 (1.8)	0.051 – 0.091 [†] (1.3 – 2.3)
	1993-2003			0.12 (3.1)	0.094 – 0.15 [†] (2.4 – 3.8)

⁴⁶⁸ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)⁴⁶⁹ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)⁴⁷⁰ IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. (2007f, p. 5)

Table 12. SLR Trends in British Columbia, 1909-2006.
(CI = Confidence Interval. Table created by authors of this report.)

<i>Location</i>	<i>Time period(s)*</i>	<i>Mean ± 95% CI (measured in inches per year)</i>	<i>Mean ± 95% CI (measured in millimeters per year)</i>
Prince Rupert	1909-2006	- 0.0429 ± 0.011	- 1.09 ± 0.27
	1909-2003	0.04 ± 0.02	1 ± 0.4
	1939-2003	0.055 ± 0.02	1.4 ± 0.6
	1913-2004	0.039**	0.98**
Tofino	1909-2006	- 0.0626 ± 0.013	- 1.59 ± 0.32
	1910-2004	- 0.0661**	-1.68**
Vancouver	1910-1999	0.015 ± 0.011	0.37 ± 0.28
	1911-2004	0.02**	0.4**
Victoria	1909-1999	0.031 ± 0.0098	0.80 ± 0.25
	1910-2003	0.024**	0.62**
Global average ⁴⁷¹	1961-2003	0.071 ± 0.02 [†]	1.8 ± 0.5 [†]
	1993-2003	0.12 ± 0.03 [†]	3.1 ± 0.7 [†]

*All values for 1909-2006 are NOAA (2010) values, as are values for Vancouver (1910-1999) and Victoria (1909-1999). Values for 1913-2004 in Prince Rupert, 1910-2004 in Tofino, 1911-2004 in Vancouver, and 1910-2003 in Victoria are reported by the B.C. Ministry of Environment (2007, p. 25). Values for 1909-2003 and 1939-2003 are reported by Abeyvirigunawardena and Walker. (2008).

**With the exception of Vancouver (chance of no trend >0.1), all stations have a chance of no trend less than 0.05: Prince Rupert (<0.05), Tofino (<0.001), and Victoria (<0.01).

[†]Global averages are reported as 90% CI.

Box 11. Synergistic impacts of SLR, erosion, and flooding increase vulnerability to extreme events in the Fraser River Delta and Queen Charlotte Islands, British Columbia.

Two areas are particularly vulnerable to SLR in B.C.: the Fraser River Delta and the Naikoon area of the Queen Charlotte Islands. The Fraser River Delta is subsiding due to altered patterns of sediment loading at the rate of 0.04 to 0.08 inches per year (1 – 2 mm/yr). Under natural conditions, sediment loading compensates for subsidence, but in the case of developed deltas such as the Fraser River Delta, human intervention (e.g. dredging, construction of training walls and dikes) diverts these sediments into deeper waters away from the delta, thereby adding to the natural subsidence rate. Due to heavy construction, some areas are subsiding further – more than 0.1 inches per year (3 mm/year), though this trend is expected to slow to 0.04 to 0.08 inches per year (1 – 2 mm/yr) over time. The Naikoon area is currently eroding, a trend that is expected to continue. In these two areas, the combination of SLR and changing weather makes them particularly susceptible to erosion and flooding during extreme events.

Source: Bornbold. (2008, p. 7); B.C. MoE. (2007, p. 27)

⁴⁷¹ IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers.* (2007f, p. 5)

Washington

Measurements of SLR in Washington are comparable to the global average reported in the IPCC's AR4, though variability around the mean is greater (Table 13).

Table 13. SLR Trends in Washington. (CI = Confidence Interval. Table created by authors of this report.)			
<i>Location</i>	<i>Time Periods*</i>	<i>Mean ± 95% CI**</i> (<i>measured in inches per year</i>)	<i>Mean ± 95% CI**</i> (<i>measured in millimeters per year</i>)
Cherry Point	1973-2000	0.055 ± 0.037	1.39 ± 0.94
	1973-2007	0.032 ± 0.047	0.82 ± 1.20
Friday Harbor	1934-2007	0.044 ± 0.013	1.13 ± 0.33
Neah Bay	1934-2007	- 0.064 ± 0.014	-1.63 ± 0.36
Port Angeles	1975-2007	0.0075 ± 0.055	0.19 ± 1.39
Port Townsend	1972-2007	0.078 ± 0.045	1.98 ± 1.15
Seattle	1898-2000	0.04 – 0.11	1.04 – 2.80
	1898-2007	0.081 ± 0.0067	2.06 ± 0.17
Toke Point	1973-2000	0.11 ± 0.041	2.82 ± 1.05
	1973-2007	0.063 ± 0.054	1.60 ± 1.38
Global average ⁴⁷²	1961-2003	0.071 ± 0.02 [†]	1.8 ± 0.5
	1993-2003	0.12 ± 0.03 [†]	3.1 ± 0.7

* Data for Cherry Point (1973-2000), Seattle (1898-2000), and Toke Point (1973-2000) are reported in Mote et al. (2008 , p. 7). Global data is reported in the IPCC's AR4. All remaining data is reported by NOAA. *Tides and Currents: Sea level Trends*. (2010).

**The 95% CI is not reported for Cherry Point (1973-2000), Seattle (1898-2000), and Toke Point (1973-2000), as well as global data.

† Global averages are reported as 90% CI.

Oregon

Data from NOAA indicate, in general, a rise in sea level along the coast, with potential decreases in Astoria and Port Orford. However, the magnitude of change is difficult to discern due to wide variability around the mean (Table 14). In the Oregon Climate Assessment Report (OCAR), Ruggiero et al. state while global SLR during the 20th century is estimated to have been approximately 0.067 inches per year (1.7 mm/yr), Burgette et al. (2009), using several approaches, estimate that the regional rate of SLR has been approximately 0.091 inches per year (2.3 mm/yr) in the Pacific Northwest (PNW).⁴⁷³ Figure 13 presents results reproduced from OCAR.

⁴⁷² IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. (2007f, p. 5)

⁴⁷³ Verbatim or nearly verbatim from Ruggiero, Brown and Komar. *Impacts of climate change on Oregon's coasts and estuaries*. (2010, p. 216)

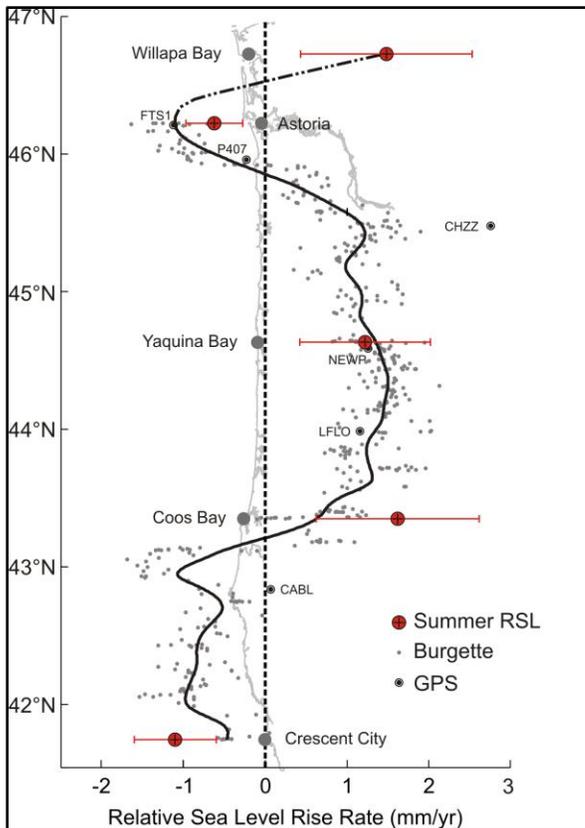


Figure 13. Alongshore varying rates of relative sea level (RSL) as determined by three methods. 1) Tide-gauge records with trends based on averages of the summer only monthly-mean water levels (red circles with pluses, error bars represent the 95% confidence interval on the trends). 2) Subtracting the Burgette et al. (2009) benchmark survey estimates of uplift rates from the regional mean SLR rate (2.3 mm/yr) (small gray dots). 3) Subtracting the uplift rates estimated from GPS sites along the coast from the regional mean sea level rate (small filled black circles)
Source: Reproduced from Ruggiero et al. (2010, p. 219, Figure 6.5) by authors of this report. Ruggiero et al. cite Komar et al. (in press) for this information.

Table 14. SLR Trends in Oregon.
(inches per year with mm/yr in parentheses. Table created by authors of this report.)
*indicates previously published trends; † 90% CI; CI = Confidence Interval; MSL = Mean Sea level

<i>Location</i>	<i>Time Period</i>	<i>MSL trend</i> ⁴⁷⁴	<i>95% CI</i> ⁴⁷⁵	<i>MSL trend</i> *	<i>95% CI</i> *
Astoria	1925-2007	-0.012 (-0.31)	0.02 (0.40)	-0.0063 (-0.16)	0.018 (0.46)
Charleston	1970-2007	0.051 (1.29)	0.0452 (1.15)	0.0685 (1.74)	0.0673 (1.71)
Garibaldi	1970-2007	0.0780 (1.98)	0.0717 (1.82)		
Port Orford	1977-2007	0.0071 (0.18)	0.0858 (2.18)		
South Beach	1967-2007	0.107 (2.72)	0.0406 (1.03)	0.138 (3.51)	0.0563 (1.43)
Global average ⁴⁷⁶	1961-2003			0.071 (1.8)	0.051 – 0.091 [†] (1.3 – 2.3)
	1993-2003			0.12 (3.1)	0.094 – 0.15 [†] (2.4 – 3.8)

Table 15. SLR Trends in Northern California.
(inches per year with mm/yr in parentheses. Table created by authors of this report.)
*indicates previously published trends; -- Data not provided; † 90% CI;
CI = Confidence Interval; MSL = Mean Sea level

<i>Location</i>	<i>Time Period</i>	<i>MSL trend</i> ⁴⁷⁷	<i>95% CI</i> ⁴⁷⁸	<i>MSL trend</i> *	<i>95% CI</i> *
Crescent City	1933-2007	-0.026 (-0.65)	0.014 (0.36)	-0.019 (-0.48)	0.017 (0.44)
North Spit	1977-2007	0.186 (4.73)	0.0622 (1.58)	--	--
Global average ⁴⁷⁹	1961-2003			0.071 (1.8)	0.051 – 0.091 [†] (1.3 – 2.3)
	1993-2003			0.12 (3.1)	0.094 – 0.15 [†] (2.4 – 3.8)

⁴⁷⁴ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴⁷⁵ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴⁷⁶ IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. (2007f, p. 5)

⁴⁷⁷ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴⁷⁸ NOAA. *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr (website)*. (2007)

⁴⁷⁹ IPCC. *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*. (2007f, p. 5)

Northwest California

Over the 20th century, sea level has risen approximately seven inches along the California coast.⁴⁸⁰ However, the available record for northern California is limited to two tide stations at North Spit on Humboldt Bay and Crescent City near the border with Oregon (Table 15). Several reviewers noted the North Spit and Crescent City stations are the subject of intense scrutiny due to the large discrepancy between the mean sea level trends reported (Box 12).

Box 12. The effects of tectonic activity on the vertical reference system and sea level rise measurements in Washington, Oregon, and California.

In Washington, Oregon and particularly in northern California where three tectonic plates intersect, there is significant tectonic activity due to the proximity of the Cascadia Subduction Zone off of the Pacific Coast. In Washington and Oregon reference data points along the coast have been re-leveled to accurately reflect the elevation of land relative to sea level but this work has not yet been done for the southern portion of the Cascadia Subduction Zone between Shelter Cove, CA and the California-Oregon state boundary. Local scientists in California have estimated differences in the reference points since they were re-leveled in 1988 (NAVD88) could be several millimeters per year off. For example, NOAA tide gauges show relative sea level rise on the North Spit of Humboldt Bay and relative sea level decline in Crescent City, suggesting significant vertical errors due to seismic activity. Previously unidentified benchmark instability biases portions of tidal records by up to 0.063 inches per year (1.6 mm/yr). This issue affects the ability to understand if rises in the land surface due to uplift will keep up with SLR and also to understand areas that will subside behind the uplift. Adversely disturbed vertical survey control datum affects every project using these benchmarks including sea level and circulation models, restoration projects, measuring sedimentation, and many others.

The importance of this issue led Burgette and colleagues (2009) to quantify the spatial pattern of uplift rate in western Oregon and northernmost California using tidal and leveling records. Relative uplift rates from leveling are adjusted to the tidal cycles, accounting for uncertainties in both data types. Key sources of uncertainty include benchmark instability, tidal variations, seasonal cycles, river influences, and weather. The result of Burgette et al.’s analysis is adjusted measurements of relative sea level for the Pacific Coast between Crescent City, CA and Astoria, OR from 1925 to 2006:

Adjusted relative sea level rates from 1925-2006 (inches per year with millimeters per year in parentheses)		
<i>Location</i>	<i>Adjusted relative sea level rate</i>	<i>Adjusted standard error</i>
Crescent City, CA	-0.021 (-0.54)	0.003 (0.08)
Port Orford, OR	0.012 (-0.31)	0.004 (0.10)
Charleston, OR	0.011 (0.29)	0.004 (0.09)
South Beach, OR	0.048 (1.22)	0.003 (0.08)
Garibaldi, OR	0.035 (0.88)	0.004 (0.09)
Astoria, OR	0.002 (0.04)	0.003 (0.07)

Sources: Burgette, Weldon II, and Schmidt. Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone. (2009, Table 1, p. 4); personal communication with reviewers.

⁴⁸⁰ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 18)

Future Projections

Global

Sea level rise projections vary by the model, assumptions, and scenarios used (Table 16, Figure 14).⁴⁸¹ By the end of the 21st century, sea level is projected to rise:

- 5.1 inches (13 cm) to 70 inches (179 cm) by the end of the 21st century (compared to the end of the 20th century) across all models and scenarios presented in this report.
- 7.1 inches under the B1 scenario to 23 inches under the A1F1 scenario (18-59 cm) of SLR is projected by the end of the 21st century (2090-2099) by the IPCC in the AR4, compared to a 1980-1999 baseline.⁴⁸²
- 5.1 to 7.1 inches (13-18 cm) under the B1 scenario, 7.1 to 9.8 inches (18-25 cm) under the A1B scenario, and 7.5 to 12 inches (19-30 cm) under the A2 scenario of SLR is projected by 2100 by Meehl et al. (2005), compared to 1999 levels.⁴⁸³
- 20 to 55 inches (50-140 cm) of SLR by 2100, compared to 1990 levels, is projected by Rahmstorf (2007) using a semi-empirical approach that assumes a proportional relationship between global temperature and global SLR.⁴⁸⁴
- 41 inches (104 cm) under the B1 scenario to 56 inches (143 cm) under the A1F1 scenario (full range of 30-75 inches or 75-190 cm) of SLR is projected from 1990 to 2100 by Vermeer and Rahmstorf (2009) using a semi-empirical method, compared to 1990 levels.⁴⁸⁵
- 28 to 42 inches (72-107 cm) under the B1 scenario and 43 to 63 inches (110-160 cm) under the A1F1 scenario of SLR is projected by the end of the 21st century (2090-2099; compared to 1980-1999 baseline) by Grinsted et al. (2009) using a semi-empirical model linking SLR to temperature with more parameters than those used by Rahmstorf (2007) and Vermeer and Rahmstorf (2009).⁴⁸⁶

⁴⁸¹ Grinsted et al. (2009); IPCC. *Climate Change 2007: Synthesis Report*. (2007c); Meehl et al. (2005); Nicholls and Cazenave. (2010); Rahmstorf (2007); Vermeer and Rahmstorf (2009)

⁴⁸² IPCC. *Climate Change 2007: Synthesis Report*. (2007c, Table 3.1, p. 45)

⁴⁸³ Meehl et al. *How much more global warming and sea level rise?* (2005, p. 1770-1771). Meehl's CCSM3 results use a modeling approach similar to the IPCC's. Please see *Appendix 2. SRES Scenarios and Climate Modeling* for an explanation of SRES and climate modeling.

⁴⁸⁴ Rahmstorf. *A semi-empirical approach to projecting future sea level rise*. (2007, p. 369). The corresponding correlation is highly significant ($r = 0.88$, $P = 1.6 \times 10^{-8}$), with a slope of 3.4 mm/year per °C.

⁴⁸⁵ Vermeer and Rahmstorf. *Global sea level linked to global temperature*. (2009, Table 1, p. 21530-21531)

⁴⁸⁶ Grinsted, Moore and Jevrejeva. *Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD*. (2009, Table 2, p. 467)

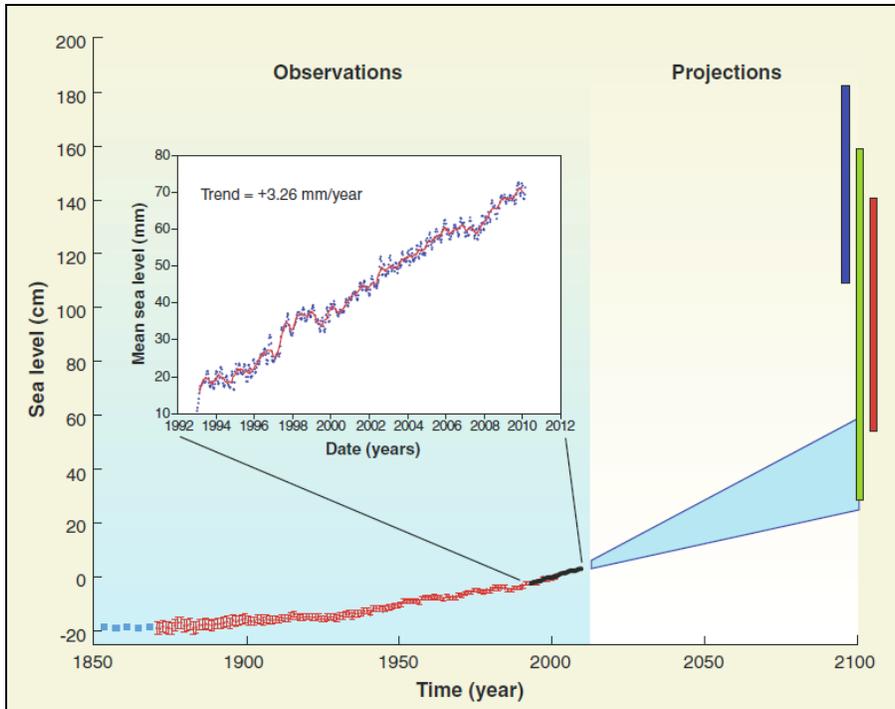


Figure 14. Global mean sea level evolution over the 20th and 21st centuries. The red curve is based on tide gauge measurements (Church and White 2006). The black curve is the altimetry record (zoomed over the 1993–2009 time span) (Cazenave and Llovel 2010). Projections for the the 21st century are also shown. The shaded light blue zone represents IPCC AR4 projections for the A1FI greenhouse gas emission scenario. Bars are semi-empirical projections [red bar: (Rahmstorf 2007); dark blue bar: (Vermeer and Rahmstorf 2009); green bar: (Grinsted et al. 2009)]. *Source: Reproduced from Nicholls & Cazenave. (2010, Fig. 1, p. 1517) by authors of this report.*

Wide variation in projected SLR by the end of the 21st century has been attributed to the observation that sea level changes cannot yet be predicted with confidence using models based on physical processes, because the dynamics of ice sheets and glaciers and to a lesser extent that of oceanic heat uptake is not sufficiently understood.⁴⁸⁷ For example, sea level projections presented in the IPCC’s AR4 do not include uncertainties in climate-carbon cycle feedbacks nor do they include the full effects of changes in ice sheet flow.⁴⁸⁸ Therefore the upper values of the IPCC ranges given are not to be considered upper bounds for sea level rise.⁴⁸⁹ If the contribution from increased ice flow from Greenland and Antarctica were to grow linearly with global average temperature change, the upper ranges of sea level rise reported in the AR4 would increase by 0.3 to 0.7 feet (0.1 to 0.2m).⁴⁹⁰ Two lines of evidence support projections of sea level rise exceeding those reported in the AR4:

- The record of past ice-sheet melting (130,000 to 127,000 years ago) indicates that the rate of future melting and related SLR could be faster than widely thought;⁴⁹¹ both the Greenland Ice Sheet and portions of the Antarctic Ice Sheet may be vulnerable.⁴⁹² During this time, Otto-Bliesner et al. (2006) report the Greenland Ice Sheet and other circum-Arctic ice fields likely

⁴⁸⁷ Verbatim or nearly verbatim from Vermeer and Rahmstorf. (2009, p. 21527)

⁴⁸⁸ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report.* (2007c, p. 45)

⁴⁸⁹ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report.* (2007c, p. 45)

⁴⁹⁰ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report.* (2007c, p. 45) In a footnote, the authors state “For discussion of the longer term see Sections 3.2.3 and 5.2.”

⁴⁹¹ Verbatim or nearly verbatim from Overpeck et al. *Paleoclimatic evidence for future ice-sheet instability and rapid sea level rise.* (2006, p. 1747)

⁴⁹² Verbatim or nearly verbatim from Overpeck et al. (2006, p. 1747)

contributed 7.2 to 11.2 feet (2.2-3.4 m) of SLR.⁴⁹³ Kopp et al. (2009) find the millennial average rate of global SLR is very likely to have exceeded 18 feet per thousand years (5.6 m/kyr; 95% probability exceedance value) but is unlikely (33% exceedance value) to have exceeded 30 feet per thousand years (9.2 m/kyr).⁴⁹⁴

- Recently identified accelerated decline of polar ice sheet mass (both Greenland and Antarctica) in the last few years:⁴⁹⁵
 - **In Greenland:** Rignot and Kanagaratnam (2006) reported accelerated ice discharge in the west and particularly in the east doubled the ice sheet mass deficit from 90 to 220 cubic kilometers per year from 1996 to 2005.⁴⁹⁶ Chen et al. (2006) report similar findings during the period April 2002 to November 2005: the estimated total ice melting rate is 239 ± 23 cubic kilometers per year, mostly from East Greenland.⁴⁹⁷
 - **In Antarctica:** In a 23 square mile (60 km²) area in the Amundsen Sea region of West Antarctica, the glaciers are 60% out of balance, sufficient to raise sea level by 0.0094 inches per year (0.24 mm/yr)⁴⁹⁸ and all surveyed glaciers in this specific region have thinned rapidly during the 1990s.⁴⁹⁹ Further, the catchment regions of the Amundsen Sea glaciers contain enough ice to raise sea level by 4.3 feet (1.3 m), or 0.0094 inches per year (0.24 mm/yr) for the next 5,416 years.⁵⁰⁰ While these glaciers are the most rapidly advancing in Antarctica, they are likely to flow considerably faster once the ice shelves are removed and glacier retreat proceeds into the deeper part of glacier basins.⁵⁰¹

⁴⁹³ Verbatim or nearly verbatim from Otto-Bliesner et al. *Simulating Arctic climate warmth and icefield retreat in the last interglaciation*. (2006, p. 1751)

⁴⁹⁴ Verbatim or nearly verbatim from Kopp et al. *Probabilistic assessment of sea level during the last interglacial stage*. (2009, p. 863). 95% exceedance value indicates there is a 95% chance the listed value exceeds a given value.

⁴⁹⁵ Verbatim or nearly verbatim from Nicholls and Cazenave. *Sea level rise and its impact on coastal zones*. (2010, p. 1517)

⁴⁹⁶ Verbatim or nearly verbatim from Rignot and Kanagaratnam. *Changes in the velocity structure of the Greenland Ice Sheet*. (2006, p. 986). Rignot and Kanagaratnam used satellite radar interferometry in the study.

⁴⁹⁷ Verbatim or nearly verbatim from Chen, Wilson and Tapley. *Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet*. (2006, p. 1958). This study used time-variable gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) satellite mission.

⁴⁹⁸ Verbatim or nearly verbatim from Thomas et al. *Accelerated sea level rise from West Antarctica*. (2004, p. 258). At the time of velocity measurements, glaciers in the study area discharged 253 ± 5 cubic kilometers of ice per year to the ocean, while total snow accumulation was 160 ± 16 cubic kilometers per year over a catchment area of 393,000 square kilometers (see p. 256).

⁴⁹⁹ Verbatim or nearly verbatim from Thomas et al. (2004, p. 256)

⁵⁰⁰ Verbatim or nearly verbatim from Thomas et al. (2004, p. 258). The authors cite Rignot (2001) for information on the ice content of the catchment regions of the Amundsen Sea glaciers.

⁵⁰¹ Verbatim or nearly verbatim from Thomas et al. (2004, p. 258)

Table 16. Global Average Sea level Rise 1961-2100. (inches with cm in parentheses. Table created by authors of this report.)					
Scenario or Year(s)	IPCC model-based range (2090-2099 relative to 1980-1999)	Meehl et al. (2005) (2100 relative to 1999 levels)	Rahmstorf (2007) (2100 relative to 1990 levels)	Vermeer and Rahmstorf (2009) (2100 relative to 1990 levels)*	Grinsted et al. (2009) (2090-2099 relative to 1980-1999)
1961-2003	0.051 – 0.091 inches/yr (1.3 – 2.3 mm/yr)				
1993-2003	0.094 – 0.15 inches/yr (2.4 – 3.8 mm/yr)				
2100			20 – 55 (50 – 140)		
B1	7.1 – 15 (18 – 38)	PCM: 5.1 (13) CCSM3: 7.1 (18)		32 – 52 (81-131)	28 – 42 (72-107)
A1T	7.8 – 18 (20 – 45)			38 – 62 (97-158)	35 – 51 (89-130)
B2	7.8 – 17 (20 – 43)			35 – 57 (89-145)	32 – 47 (82-120)
A1B	8.3 – 19 (21 – 48)	PCM: 7.1 (18) CCSM3: 9.8 (25)		38 – 61 (97-156)	36 – 52 (91-132)
A2	8.1 – 20 8.2 (23 – 51)	PCM: 7.5 (19) CCSM3:12 (30)		39 – 61 (98-155)	37 – 54 (93-136)
A1F1	10 – 23 (26 – 59)			44 – 70 (113-179)	43 – 63 (110-160)
*The model average associated with each scenario is 41” (104 cm) for the B1 scenario, 45” (114 cm) for the B2 scenario, 49” (124 cm) for the A1T, A1B, and A2 scenarios, and 56” (143 cm) for the A1F1 scenario.					

Southcentral and Southeast Alaska

Recent glacier retreat in the Gulf of Alaska coastal area of southeast and southcentral Alaska has resulted in the land surface rising as it readjusts to the loss of glacial ice.⁵⁰² This isostatic rebound, combined with active regional tectonic deformation, results in a rate of land uplift that is greater than the projected rate of global sea level rise.⁵⁰³ Thus, over the next century, the relative sea level in these areas is projected to decrease between 2.1 and 3.4 feet (0.64-1.0 m).⁵⁰⁴

British Columbia

Projections for relative SLR by 2100 (baseline is likely 1980-1999, see footnote) for Prince Rupert, Nanaimo, Victoria, Vancouver, and the Fraser River Delta are based on extreme low, mean, and extreme

⁵⁰² Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, p. 2-4)

⁵⁰³ Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, p. 2-4)

⁵⁰⁴ Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, p. 2-4) The authors cite Larsen et al. (2004), Kelly et al. (2007), and Pyare (2009) for this information. No baseline is provided.

high estimates of global SLR (Table 17).⁵⁰⁵ For the extreme low and mean estimates, three of five locations fall below the global average. The notable exception is the Fraser River Delta, where projected SLR exceeds (or nearly exceeds) the global average. For the extreme high scenario, all locations are projected to exceed the global average SLR. This may be due to differences in modeling scenarios; the study does not provide detailed information on the scenarios used.

Table 17. Relative SLR by 2100 for Selected B.C. Locations.
(feet with meters in parentheses. Table modified from Bornhold (2008, Table 1, p. 8) by authors of this report.)

Location	SLR (<i>extreme low</i> estimate of global SLR)	SLR (<i>mean</i> estimate of global SLR)	SLR (<i>extreme high</i> estimate of global SLR)
Prince Rupert	0.3 – 1.0 (0.10 – 0.31)	0.82 – 1.5 (0.25 – 0.46)	3.1 – 3.81 (0.95 – 1.16)
Nanaimo	- 0.1 (- 0.04)	0.36 (0.11)	2.6 (0.80)
Victoria	0.06 – 0.13 (0.02 – 0.04)	0.56 – 0.62 (0.17 – 0.19)	2.9 – 3.1 (0.89 – 0.94)
Vancouver	0.1 – 0.59 (0.04 – 0.18)	0.66 – 1.1 (0.20 – 0.33)	2.9 – 3.4 (0.89 – 1.03)
Fraser River Delta	1.1 (0.35)	1.6 (0.50)	3.94 (1.20)
Global average ⁵⁰⁶	0.59 – 1.2 (SRES B1) (0.18 – 0.38)	0.69 – 1.6 (SRES A1B) (0.21 – 0.48)	0.85 – 1.9 (SRES A1F1) (0.26 – 0.59)

Washington

In Puget Sound, Mote et al. (2008) project a “medium” estimate of SLR by 2050 is six inches (15 cm) and by 2100 is thirteen inches (34 cm) relative to 1980-1999.⁵⁰⁷ On the northwest Olympic Peninsula, very little relative SLR will be apparent due to rates of local tectonic uplift that currently exceed projected rates of global SLR:⁵⁰⁸ the “medium” estimate projects no net SLR by 2050 and two inches (4 cm) of SLR by 2100.⁵⁰⁹ However, this tectonically driven uplift is periodically halted by strong subduction zone earthquakes, which cause the ocean floor to drop, some areas to rise, and other coastal areas to sink below sea level.⁵¹⁰ Uplift may also be occurring along the central and southern Washington Coast at rates lower than that observed on the northwest Olympic Peninsula; however, there is a lack of available data for this region and it is difficult to predict SLR in the coming century.⁵¹¹ The “medium” estimate for the central and southern coast projects five inches (12.5 cm) SLR by 2050 and eleven inches (29 cm) SLR by 2100.⁵¹²

Combining the IPCC high emissions scenario with 1) higher estimates of ice loss from Greenland and Antarctica, 2) seasonal changes in atmospheric circulation in the Pacific, and 3) vertical land deformation, Mote et al.’s (2008) low-probability high-impact estimate of local SLR for the Puget Sound Basin is 22 inches (about 55 cm) by 2050 and 50 inches (128 cm) by 2100.⁵¹³ Low-probability, high impact estimates are smaller for the central and southern Washington coast – 18 inches (about 45 cm) by 2050 and 43 inches (108 cm by 2100) – and even lower for the northwest Olympic Peninsula – 14 inches (35 cm) by

⁵⁰⁵ Bornhold. (2008). This study uses IPCC SRES scenarios, which use a 1980-1999 baseline.

⁵⁰⁶ IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 45)

⁵⁰⁷ Verbatim or nearly verbatim from Mote et al. (2008, Table 3, p. 10)

⁵⁰⁸ Verbatim or nearly verbatim from Mote et al. (2008, p. 3)

⁵⁰⁹ Verbatim or nearly verbatim from Mote et al. (2008, Table 3, p. 10)

⁵¹⁰ Verbatim or nearly verbatim from WA Department of Ecology. (2011)

⁵¹¹ Verbatim or nearly verbatim from Mote et al. (2008, p. 3) (2008)

⁵¹² Verbatim or nearly verbatim from Mote et al. (2008, Table 3, p. 10)

⁵¹³ Verbatim or nearly verbatim from Mote et al. (2008, p. 3)

2050 and 35 inches (88 cm) by 2100 due to tectonic uplift.⁵¹⁴ These projections are relative to a 1980-1999 baseline.⁵¹⁵

Oregon

Combining the IPCC high emissions scenario with 1) higher estimates of ice loss from Greenland and Antarctica, 2) seasonal changes in atmospheric circulation in the Pacific, and 3) vertical land deformation, a low-probability high-impact estimate of local SLR for the areas of the coast experiencing little vertical land motions (e.g. Tillamook County) is 22 inches (55 cm) by 2050 and 50 inches (128 cm) by 2100.⁵¹⁶

Northwest California

Estimates of up to 55 inches (1.4 meters) of sea level rise under the A2 emissions scenario by 2100 are projected (baseline is likely 1990 levels, see footnote).⁵¹⁷ This projection accounts for the global growth of dams and reservoirs and how they can affect surface runoff into the oceans, but it does not account for the possibility of substantial ice melting from Greenland or the West Antarctic Ice Sheet, which would drive sea levels along the California coast even higher.⁵¹⁸ Projections of sea level rise under the B1 scenario are still several times the rate of historical sea level rise, and would barely differ under a stringent “policy scenario” in which global emissions would be drastically reduced.⁵¹⁹ In short, even on a lower emissions trajectory and without the addition of meltwater from the major continental ice sheets, sea levels in the 21st century can be expected to be much higher than sea levels in the 20th century.⁵²⁰

Information Gaps

Information is needed on regional trends in Oregon and northern California, as the available records are limited or the available data varies widely around the mean. More specific projections for Oregon and northern California are also needed. For the Gulf of Alaska region, Sigler et al. (2008) state three additional climate information needs: sea level and 500 mb pressure maps, and output from the Fifth Generation National Center for Atmospheric Research/Penn State Mesoscale Model (MM5) (which simulates mesoscale and regional scale atmospheric circulation⁵²¹) including winds.⁵²²

⁵¹⁴ Mote et al. (2008, p. 3)

⁵¹⁵ Mote et al. (2008, p. 3)

⁵¹⁶ Verbatim or nearly verbatim from Ruggiero et al. (2010, p. 218)

⁵¹⁷ CA Natural Resources Agency. (2009, p. 18). The authors cite the work of Rahmstorf (2007), which projects SLR for 2100 compared to 1990 levels using a semi-empirical method, for their SLR projections. Please see the global projections for SLR section of this report for further detail on the study by Rahmstorf (2007).

⁵¹⁸ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 18)

⁵¹⁹ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 18)

⁵²⁰ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 18).

⁵²¹ WorldWinds, Inc. *About MM5 (website)*. (2011)

⁵²² Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 69, 73).

7. ALTERED PATTERNS OF COASTAL UPWELLING

Box 13. Summary of observed trends and future projections for coastal upwelling

Observed Trends

- Available data suggests the equatorward alongshore wind stress that drives coastal upwelling increased during upwelling seasons from 1948 to 1988.⁵²³
- Substantial upwelling of nutrients over major portions of the shelf in the Coastal Gulf of Alaska has been reported, despite the fact winds are generally downwelling-favorable most of the year.⁵²⁴
- The coasts of British Columbia, Washington, Oregon, and California are strongly influenced by seasonal upwelling, which typically begins in early spring and ends in late summer or fall.⁵²⁵
 - The intensity of upwelling may have increased over the last half of the 20th century off the coasts of southern Oregon and northern California.⁵²⁶ The trends are not significant.⁵²⁷

Future Projections

- There is evidence that climate change could alter coastal upwelling patterns and boost the delivery of deep, hypoxic (i.e. low-oxygen) waters into productive nearshore zones.^{528,529}
- Along the B.C. coast, summer upwelling-favorable winds are projected to increase in speed by 5-10% and rotate clockwise by ~5% (statistically significant) by 2080-2099 (1976-1995 baseline; A1B).⁵³⁰ Projected changes suggest a coherent pattern: between 2030-2049 and 2080-2099, they amplify by a factor of 2 or 3.⁵³¹
- Using data gathered off the northern Oregon coast, 17 models predict increases in July upwelling (two models project substantial decreases) for 2030-2039 (1980-89 baseline; A1B).⁵³² However, given inherent limitations in properly modeling upwelling, the projections are highly uncertain.⁵³³
- Snyder et al. (2003) have projected increased upwelling between San Francisco and the CA/OR border under scenarios of increased carbon dioxide concentrations (e.g. 580 ppm vs. 280 ppm baseline or using the A1 scenario (635-686 ppm) vs. 338-369 ppm baseline).⁵³⁴ The peak is projected to shift later in the year, while the onset of upwelling is projected to occur up to a month later.⁵³⁵

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

⁵²³ Bakun. *Global climate change and intensification of coastal ocean upwelling*. (1990, p. 200)

⁵²⁴ Hermann et al. *Quantifying cross-shelf and vertical nutrient flux in the Coastal Gulf of Alaska with a spatially nested, coupled biophysical model*. (2009, p. 2474)

⁵²⁵ Feely et al. *Evidence for upwelling of corrosive "acidified" water onto the continental shelf*. (2008)

⁵²⁶ Mote, Gavin and Huyer. *Climate change in Oregon's land and marine environments*. (2010, p. 26-27)

⁵²⁷ Mote, Gavin and Huyer. (2010, p. 26-27)

⁵²⁸ Grantham et al. *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*. (2004)

⁵²⁹ Levin et al. *Effects of natural and human-induced hypoxia on coastal benthos*. (2009)

⁵³⁰ Merryfield, Pal and Foreman. (2009, p. 10)

⁵³¹ Merryfield, Pal and Foreman. (2009, p. 10)

⁵³² Wang, Overland and Bond. (2010, p. 265)

⁵³³ Wang, Overland and Bond. (2010, p. 265)

⁵³⁴ Snyder et al. *Future climate change and upwelling in the California Current*. (2003, p. 8.2, 8-3)

⁵³⁵ Snyder et al. (2003, p. 8-4)

Definition and Causes of Altered Patterns of Coastal Upwelling

The California Current (CCS) is a ~621-mile-wide (1000 km), sluggish current spanning the Pacific Coast from ~20°N (near Guadalajara, Mexico) to 50°N (northern Vancouver Island). It is the dominant current in the NPLCC region south of 50°N.

Superimposed on the mean flow, alongshore winds blowing toward the equator result in the upward movement of deeper, nutrient-rich water (known as upwelling). Dynamics influencing the CCS at finer geographic scales include: coastline shape (straighter in the north), continental shelf shape and width (wider and flatter in the north), the presence of submarine canyons (most are in the north), and significant freshwater input from the Columbia River and Strait of Juan de Fuca. In general, salinity and temperature increase southward and salinity also increases with depth (see Figure 15).

Source: Hickey & Banas. (2008); Hickey & Banas. (2003).

Upwelling refers to the replacement of shallow surface water by deeper, colder, saltier, nutrient-rich, and oxygen-poor water in response to equatorward winds pushing surface waters offshore.⁵³⁶ Upwelling of deep water occurs along the western margin of continents when the wind blows towards the equator (Figure 15).⁵³⁷ As the wind blows the water towards the equator, the Coriolis force causes the water to turn west and away from the coast.⁵³⁸ Along the coast from Vancouver Island to Baja California (i.e. in the coastal waters of the California Current), alongshore winds blowing toward the equator push surface waters offshore from approximately April through October.⁵³⁹ These surface waters must be replaced by other waters, a process that occurs via the upwelling of cold, salty, nutrient-rich, CO₂-rich, and oxygen-poor intermediate depth (328 to 656 ft; 100 to 200 m) offshore waters onto the continental shelf.⁵⁴⁰ Air-sea fluxes during coastal upwelling result in net uptake of atmospheric O₂ and a concomitant release of marine CO₂ (upwelled waters have more CO₂ and less O₂ than the marine air, so marine CO₂ is released to the air and atmospheric O₂ is absorbed into the ocean to restore the balance at the air-sea interface).⁵⁴¹

The central and southern coastal region off western North America is strongly influenced by seasonal upwelling, which typically begins in early spring when the Aleutian low-pressure system moves to the northwest and the Pacific High moves northward, resulting in a strengthening of the northwesterly winds.⁵⁴² The upwelling typically lasts until late summer or fall, when winter storms return⁵⁴³ and winds blow from the equator toward the poles, forcing surface waters onshore instead of offshore (known as downwelling).

⁵³⁶ Feely et al. (2008)

⁵³⁷ Verbatim or nearly verbatim from Monterey Bay Aquarium Research Institute. *Upwelling (website)*. (2010)

⁵³⁸ Verbatim or nearly verbatim from Monterey Bay Aquarium Research Institute. (2010)

⁵³⁹ Verbatim or nearly verbatim from Hauri et al. *Ocean acidification in the California Current System*. (2009, p. 63)

⁵⁴⁰ Verbatim or nearly verbatim from Feely et al. (2008, p. 1491)

⁵⁴¹ Verbatim or nearly verbatim from Lueker. *Coastal upwelling fluxes of O₂, N₂O, and CO₂ assessed from continuous atmospheric observations at Trinidad, CA*. (2004, p. 106)

⁵⁴² Verbatim or nearly verbatim from Feely et al. (2008, p. 1491) The authors cite Hickey in Volume 2 of *The Sea* (Robinson and Brink, Eds, 1998) and Pennington and Chavez (2000) for this data.

⁵⁴³ Verbatim or nearly verbatim from Feely et al. (2008, p. 1491)

As described in Chapter II, recent decades have seen a substantial build-up of CO₂ and other greenhouse gases in the earth's atmosphere.⁵⁴⁴ Resulting inhibition of nighttime cooling and enhancement of daytime heating should lead to intensification of the continental thermal lows adjacent to upwelling regions.⁵⁴⁵ This intensification would be reflected in increased onshore-offshore atmospheric pressure gradients, intensified alongshore winds, and accelerated coastal upwelling circulations.⁵⁴⁶ With intensified upwelling, enrichment (i.e., of the waters with food sources due to upwelling) can be increased which would be beneficial to organisms, however the concentration of sufficient food to sustain a population may be decreased due to increased mixing and retention (i.e., of the organisms and the food sources in the same area) may also be decreased by increased seaward transport of surface water.⁵⁴⁷ Overall this could have a negative effect on the marine ecosystems, as the current balance of these three factors (enrichment, concentration, and retention) will change with changes in upwelling.⁵⁴⁸

Observed Trends

Global

Data from widely separated areas around the world (e.g. California, Peru, Spain) suggest that the equatorward alongshore wind stress that drives coastal upwelling increased during the respective upwelling seasons from 1948 to 1988.⁵⁴⁹

Alaska

The winds off of Alaska are generally downwelling-favorable at the coast over most of the year.⁵⁵⁰ However, Hermann et al. (2009) report substantial upwelling of nutrients over major portions of the shelf in the Coastal Gulf of Alaska, driven by local wind-stress curl.⁵⁵¹ These effects are large enough to overwhelm the smaller downwelling flux at the coast throughout the growing season.⁵⁵² These results are derived from a nutrient transport budget informed by output from a spatially nested, coupled hydrodynamic and lower trophic model of the Coastal Gulf of Alaska.⁵⁵³

Southern British Columbia, Washington, Oregon, and California (the California Current System)

From northern California to southern Vancouver Island, the magnitude of along-shelf wind stress decreases by a factor of eight.⁵⁵⁴ Upwelling-favorable wind stress is weaker by as much as a factor of two off the coast of Washington than off the coast of Oregon.⁵⁵⁵ The Oregon Climate Assessment Report

⁵⁴⁴ Verbatim or nearly verbatim from Bakun. (1990, p. 198). The authors cite Ramanathan (1988) for this information.

⁵⁴⁵ Verbatim or nearly verbatim from Bakun. (1990, p. 198)

⁵⁴⁶ Verbatim or nearly verbatim from Bakun. (1990, p. 198). The authors refer to Figure 1 in the cited report.

⁵⁴⁷ Verbatim or nearly verbatim from Snyder et al. (2003, p. 8-4)

⁵⁴⁸ Verbatim or nearly verbatim from Snyder et al. (2003, p. 8-4)

⁵⁴⁹ Verbatim or nearly verbatim from Bakun. (1990, p. 200)

⁵⁵⁰ Verbatim or nearly verbatim from Hermann et al. (2009, p. 2474)

⁵⁵¹ Verbatim or nearly verbatim from Hermann et al. (2009, p. 2474)

⁵⁵² Verbatim or nearly verbatim from Hermann et al. (2009, p. 2474)

⁵⁵³ Verbatim or nearly verbatim from Hermann et al. (2009, p. 2474)

⁵⁵⁴ Verbatim or nearly verbatim from Hickey and Banas. *Why is the northern end of the California Current System so productive?* (2008, p. 92)

⁵⁵⁵ Verbatim or nearly verbatim from Hickey and Banas. *Oceanography of the U.S. Pacific Northwest Coastal Ocean and Estuaries with Application to Coastal Ecology.* (2003, p. 1028)

(OCAR) reports on three estimates of the alongshore wind stress as indicators of the intensity of upwelling:⁵⁵⁶

- **Wind measurements at Buoy 46050** (about 20 nautical miles, or 37 km, west of Newport): Hourly measurements began in 1985, and data are available from NOAA.⁵⁵⁷ This time series is not yet long enough to determine a long-term trend, but data indicate that the average intensity of upwelling in each year from 2005 to 2008 was stronger than the 20-year average of 1985 to 2005.⁵⁵⁸
- **Wind stress data** (from the National Center for Environmental Prediction, NCEP, and Kalnay et al., 1996; data available since 1948): Daily wind stress values were used to determine the dates of onset and cessation of seasonal upwelling, and to calculate the average and variance of the alongshore wind stress during each upwelling season.⁵⁵⁹ The seasonal average has no significant trend, but the variance has increased significantly over the last fifty years, by about thirty-five percent off the southern Oregon coast (45°N) and by about fifty percent off the northern California coast (41°N).⁵⁶⁰
- **Monthly values of the Coastal Upwelling Index** off the coast of southern Oregon (45°N, 125°W) and northern California (42°N, 125°W) (provided by the Pacific Fisheries Environmental Laboratory, <http://www.pfeg.noaa.gov>): Averaging the June, July, August, and September (JJAS) values together yields an annual estimate of the intensity of upwelling.⁵⁶¹ The average JJAS index at this location increased over the past fifty years, particularly off southern Oregon, though much of the trend is due to a recent decade of strong winds (1995 - 2005).⁵⁶² Slow variations in the eleven-year running average do not seem to be correlated with the PDO.⁵⁶³

Northwest California

Observations show that wind-driven upwelling along the California coast has increased over the past 30 years (specific time period not provided; however, the article was published in 2003).⁵⁶⁴ During upwelling events off the coast of Trinidad Head in northern California, regional air-sea fluxes of O₂, nitrogen (N₂), nitrous oxide (N₂O), and CO₂ were monitored.⁵⁶⁵ As expected, periods of low Potential Oxygen of the Atmosphere (APO, a signal of marine oxygen) coincided with elevated levels of N₂O, offshore flow, and reduced ocean temperatures.⁵⁶⁶ However, it was found that atmospheric APO and N₂O are constraining two independent aspects of coastal biogeochemistry: N₂O constrains the rate of ventilation of the

⁵⁵⁶ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 26)

⁵⁵⁷ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 26)

⁵⁵⁸ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 26)

⁵⁵⁹ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 26)

⁵⁶⁰ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 26)

⁵⁶¹ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 27)

⁵⁶² Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 27)

⁵⁶³ Verbatim or nearly verbatim from Mote, Gavin and Huyer. (2010, p. 27). The authors cite Mantua et al. (1997) and suggest seeing Section 2.2 in OCAR.

⁵⁶⁴ Verbatim or nearly verbatim from Snyder et al. *Future climate change and upwelling in the California Current*. (2003, p. 8-1)

⁵⁶⁵ Lueker. (2004, p. 103)

⁵⁶⁶ Verbatim or nearly verbatim from Lueker. (2004, p. 103). It was also found that upwelling CO₂ fluxes represented about 10% of export production (organic matter from primary production that is not converted to inorganic forms before sinking in the ocean) along the northwest coast of North America (see p. 101).

subsurface waters, while APO constrains a combination of subsurface ventilation and mixed-layer biological production.⁵⁶⁷

Future Projections

Global

There is evidence that climate change could alter coastal upwelling patterns and boost the delivery of deep, hypoxic (i.e. low-oxygen) waters into productive nearshore zones.⁵⁶⁸ With increased global warming, the coastal surface waters in subtropical and tropical eastern ocean boundaries (e.g. the California Current) could cool relative to the surfaces of either the continental land mass on one side or the ocean interior on the other.⁵⁶⁹ Similarly, as atmospheric greenhouse gas content increases, the rate of heating over the land is further enhanced relative to that over the ocean, particularly as night-time radiative cooling is suppressed by an increasing degree of blockage of outgoing longwave radiation.⁵⁷⁰ This causes intensification of the low pressure cells over the coastal interior.⁵⁷¹ A feedback sequence is generated as the resulting pressure gradient increase is matched by a proportional wind increase, which correspondingly increases the intensity of the upwelling in a nonlinear manner (by a power of 2 or more under these strong wind conditions) which, in concert with ocean surface cooling produced by the intensified upwelling, further enhances the land–sea temperature contrast, the associated cross-shore pressure gradient, the upwelling-favorable wind, and so on.⁵⁷²

Southcentral and Southeast Alaska

Information needed.

British Columbia

Merryfield, Pal, and Foreman (2009) examine future trends in modeled winds in response to human-induced climate change along the B.C. coast.⁵⁷³ Two intervals, 2030-2049 and 2080-2099, are compared to the 1976-1995 baseline period (A1B scenario).⁵⁷⁴

In the winter season, when marine winds are generally southerly and downwelling favorable, the multimodel ensemble mean exhibits statistically insignificant changes consisting of an approximately five percent intensification and slight counterclockwise rotation.⁵⁷⁵

In the summer upwelling season, when climatological winds are primarily northwesterly under the influence of the North Pacific High (NPH; a semi-permanent, subtropical area of high pressure in the North Pacific Ocean, strongest in the summer and displaced toward the equator during winter when the

⁵⁶⁷ Verbatim or nearly verbatim from Lueker. (2004, p. 104)

⁵⁶⁸ Grantham et al. (2004); Levin et al. (2009)

⁵⁶⁹ Verbatim or nearly verbatim from Bakun. (1990, p. 200)

⁵⁷⁰ Verbatim or nearly verbatim from Bakun and Weeks. *Greenhouse gas buildup, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems.* (2004, p. 1016)

⁵⁷¹ Verbatim or nearly verbatim from Bakun and Weeks. (2004, p. 1016)

⁵⁷² Verbatim or nearly verbatim from Bakun and Weeks. (2004, p. 1016-1017). The authors cite Trenberth et al. (1990) for information on the specific increase in intensity of upwelling – by a power of 2.

⁵⁷³ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. *Projected future changes in surface marine winds off the west coast of Canada.* (2009, p. 6)

⁵⁷⁴ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 6)

⁵⁷⁵ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 9)

Aleutian Low becomes more dominant), the projected changes implied by the multimodel ensemble mean consist of an increase in wind speed together with a clockwise rotation of the wind vector.⁵⁷⁶ The changes in 2080–2099 relative to the 1976–1995 base period are statistically significant and amount to five to ten percent increases in wind speed and approximately 5° clockwise rotations in wind direction.⁵⁷⁷ In addition the projected changes consistently amplify by a factor of two to three between 2030–2049 and 2080–2099, suggesting a coherent pattern of change.⁵⁷⁸

By comparison, Wang et al. (2008) found that most of the climate models they considered show an increase in alongshore, upwelling favorable wind stress at 45°N along the Oregon coast in summer between 1980–1989 and 2030–2039.⁵⁷⁹ These changes appear consistent with a gross northward shift in the pattern of upwelling favorable winds along the North American west coast.⁵⁸⁰ Such a shift in turn is consistent with modeled changes in June–July–August mean sea level pressure, which corresponds to a northward shift in the NPH.⁵⁸¹

Washington

Information needed.

Northern Oregon

Wang, Overland, and Bond (2010) assessed the decadal averaged upwelling index for July off the coast of northern Oregon (45°N, 125°W) and projected changes from 1980-89 to 2030-39 using the A1B scenario.⁵⁸² They state that for the California Current region, seventeen models predict increases in July upwelling with only two models (CSIRO-mk3.0 and PCM) indicating substantial decreases.⁵⁸³ Given the inherent limitations of the models to properly handle upwelling, the projections from Wang, Overland, and Bond's analysis are highly uncertain, and further analysis is warranted.⁵⁸⁴

Southern Oregon and Northwest California

According to Diffenbaugh, Snyder and Sloan (2004), Snyder et al. (2003) have shown that both the seasonality and peak strength of upwelling in the California Current (along the California coast only) are sensitive to elevated CO₂ concentrations, with radiative forcing resulting in an intensified peak season in the northern region (north of Point Conception).⁵⁸⁵ Using a regional climate model run under four cases (constant concentrations of 280 ppm and 580 ppm CO₂; and comparing 1980-1999 to 2080-2099 under

⁵⁷⁶ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 10). The authors cite Bograd et al. (2002, Fig. 1b) for information on winds in the summer upwelling season under the influence of the North Pacific High.

⁵⁷⁷ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 10)

⁵⁷⁸ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 10)

⁵⁷⁹ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 10)

⁵⁸⁰ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 10). The authors cite J. Fyfe, personal communication (2008) for this information.

⁵⁸¹ Verbatim or nearly verbatim from Merryfield, Pal and Foreman. (2009, p. 10). The authors refer the reader to Fig. 8 (bottom) in the cited report.

⁵⁸² Verbatim or nearly verbatim from Wang, Overland and Bond. *Climate projections for selected large marine ecosystems*. (2010, p. 265)

⁵⁸³ Verbatim or nearly verbatim from Wang, Overland and Bond. (2010, p. 265)

⁵⁸⁴ Verbatim or nearly verbatim from Wang, Overland and Bond. (2010, p. 265)

⁵⁸⁵ Verbatim or nearly verbatim from Diffenbaugh, Snyder and Sloan. *Could CO₂-induced land-cover feedbacks alter near-shore upwelling regimes?* (2004, p. 27). The authors cite Snyder et al. (2003)

the A1 scenario), Snyder et al. (2003) show that increased CO₂ forcing affects wind-stress curl by causing an increase in the land-ocean temperature gradient.⁵⁸⁶ This temperature gradient, which is substantial during the summer months, contributes to the alongshore winds that drive upwelling.⁵⁸⁷ For the Upper Northern region (San Francisco Bay to the California/Oregon border) the wind-stress curl increases are concentrated in the warmest months of June through September.⁵⁸⁸ Temporally, the peak of the upwelling season is projected to shift later in the year and the onset is projected to occur up to a month later.⁵⁸⁹

In contrast to Snyder et al., Mote and Mantua (2002) find that the high-pressure cells associated with mid-latitude coastal upwelling are robust features of the climate and are relatively unaffected by climate change under two global climate simulations (comparing the 2080s to the 1990s).⁵⁹⁰ However, the model underestimates interdecadal variability, which complicates detection of an anthropogenic influence on upwelling.⁵⁹¹ Bakun and Weeks (2004) state that the inconclusive results produced by global-scale climate change models such as those used by Mote and Mantua (2002) necessarily confound the smaller-scale near-coastal intensification response with an opposite larger basin-scale relaxation response.⁵⁹² Further, they state that Snyder et al.'s (2003) simulations have clearly supported the intensification hypothesis because they use a regional climate model possessing sufficiently higher resolution to effectively differentiate between the two effects.⁵⁹³

These studies illustrate future projections of coastal upwelling due to climate change remain uncertain. We leave further discussion of coastal upwelling and its impacts under a changing climate to other sections in this report, namely Section 8 of this Chapter (Altered patterns of coastal hypoxia and anoxia), Sections 1 and 2 in Chapter IV (Altered nutrient cycling and Altered ocean productivity, respectively), Sections 2 and 3 in Chapter VI (Altered phenology and development, and Shifts in community composition, competition, & survival, respectively), and Chapter VII (IMPLICATIONS FOR KEY FISH, WILDLIFE, PLANTS, PLANKTON, & SHELLFISH).

⁵⁸⁶ Verbatim or nearly verbatim from Snyder et al. (2003, p. 8-4). In the 1980-1999 period, CO₂ concentrations ranged from 338 to 369 ppm. In the 2080-2099 period, CO₂ concentrations ranged from 635 to 686 ppm.

⁵⁸⁷ Verbatim or nearly verbatim from Snyder et al. (2003, p. 8-4)

⁵⁸⁸ Verbatim or nearly verbatim from Snyder et al. (2003, p. 8-4)

⁵⁸⁹ Verbatim or nearly verbatim from Snyder et al. (2003, p. 8-4)

⁵⁹⁰ Verbatim or nearly verbatim from Mote and Mantua. *Coastal upwelling in a warmer future*. (2002, p. 1,2)

⁵⁹¹ Verbatim or nearly verbatim from Mote and Mantua. (2002, p. 3). If the simulations presented by Mote and Mantua are correct, then no long-term trend in upwelling would be expected, and the variability and trends in observed upwelling have no anthropogenic component. If, on the other hand, the models' underrepresentation of interdecadal variability is somehow connected with an inability to represent anthropogenic influence, for instance through unrealistic locking to geographic features, then these projections of a changeless upwelling regime are unlikely. Note: these sentences are from the cited report, page 3.

⁵⁹² Verbatim or nearly verbatim from Bakun and Weeks. (2004, p. 1017)

⁵⁹³ Verbatim or nearly verbatim from Bakun and Weeks. (2004, p. 1017)

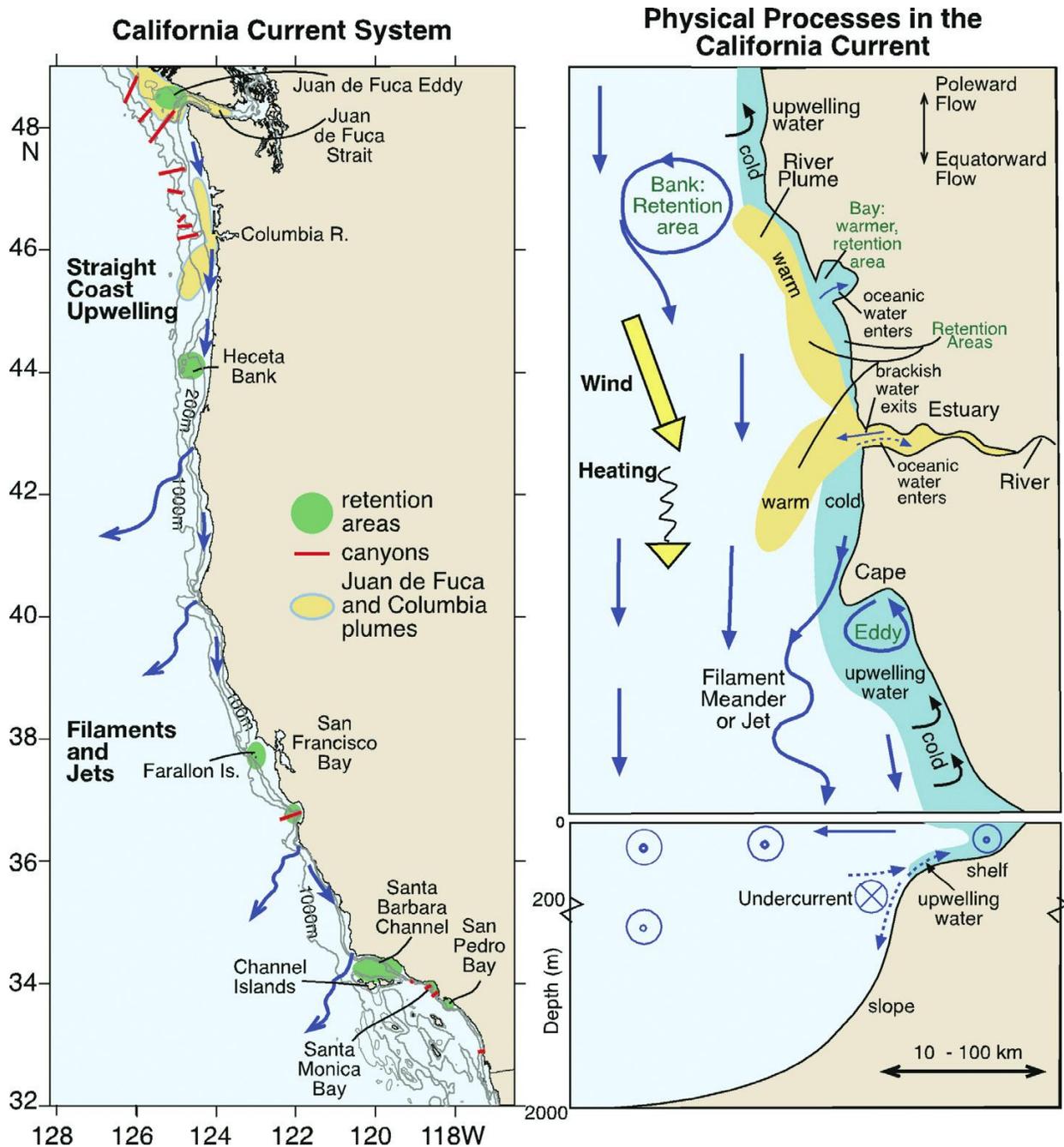


Figure 15. Primary physical processes in the California Current System (CCS) in summer. (Left) A map of the CCS with bottom topography and typical surface currents (blue arrows), showing the location of submarine canyons (red), regions with longer than average residence times (green, “retention areas”), and primary sources of freshwater (yellow, the Strait of Juan de Fuca and the Columbia River). The Columbia River plume is depicted in the bi-directional pattern frequently seen in the summer season. Regions where upwelling is primarily two dimensional (“straight coast upwelling”) are differentiated from those farther south that are more three dimensional (“filaments and jets”). (Right) A cartoon showing typical circulation patterns for an arbitrary subregion of the CCS in plan view (upper) and cross section (lower). In the cross section, circles with dots indicate equatorward flow; circles with crosses indicate poleward flow. Retention areas over banks, behind capes, and within bays and estuaries are noted in green text. Upwelling water next to the coast is shown as darker blue. Note that river plumes are generally warmer than coastal waters in summer. *Source: Reproduced from Hickey and Banas. (2008, Fig. 1, p. 92) by authors of this report.*

Information Gaps

Information is needed on regional trends and projections of coastal upwelling, particularly for Alaska, British Columbia, and Washington. Since climate change is likely to affect upwelling in various (poorly understood) ways, Peterson and Schwing (2008) identify a number of information needs relative to climate change and upwelling response.⁵⁹⁴

- Dates of spring and fall transition, length of upwelling season, overall average magnitude of upwelling, and some measure of the frequency of upwelling events in relation to meanders in the jet stream (sensu Bane et al., 2007). A forecast of the approximate date of spring transition would be useful in forecasting migration and recruitment for many species.
- An index of when the upwelling system has truly transformed from a winter unproductive state to a summer productive state. This will require an index of biological variables.
- Actual measures of the effectiveness of upwelling in terms of the depths from which water upwells, and the nutrient content of that water. A connection between upwelling and stratification will allow study of the biological effectiveness of upwelling.
- Better spatially-resolved coastal wind fields, from satellites or blended measured-modeled products.
- Improved atmospheric models with high-resolution winds, ocean models with upper ocean and coastal circulation and density and nutrients
- Improved regional climate models with projections of the timing, intensity and location of coastal upwelling.
- Ocean models with reliable coastal physics and high resolution to capture Ekman transport and ocean stratification, and can be coupled to biological models to determine phytoplankton production, biomass, subduction, and grazing.
- Forecast models to give short-term and seasonal predictions of wind forcing and upwelling in coastal areas.
- An El Niño/La Niña forecast to assist in determining the timing and strength of upwelling, as well as the quality of source water.

⁵⁹⁴ Verbatim or nearly verbatim from Peterson and Schwing. (2008, p. 55)

8. ALTERED PATTERNS OF COASTAL HYPOXIA AND ANOXIA

Box 14. Summary of observed trends and future projections for coastal hypoxia and anoxia

Observed Trends

- Seasonal hypoxia is a normal occurrence off the coasts of southern BC, WA, OR, and CA.⁵⁹⁵ However, an increase in severe hypoxic events has been observed off the OR and WA coasts since 2002:⁵⁹⁶
 - Severe hypoxia (0.21 - 1.57 mL/L DO) was detected 1.2-3.1 miles (2–5 km) off the central OR coast in July-September 2002.⁵⁹⁷
 - Hypoxia covered an especially large area of WA's continental shelf in 2006, and the lowest dissolved oxygen (DO) concentrations to-date (<0.5 mL/L) were recorded at the inner shelf.⁵⁹⁸ From 2003-2005, hypoxic events were within the range of WA's historical record.⁵⁹⁹
- In deeper waters off the coast of British Columbia, the hypoxic boundary rose from approximately 1300 feet to about 980 feet (400 m to about 300 m) deep over fifty years (1956-2006).⁶⁰⁰

Future Projections

- Present-day anomalous hypoxic events are consistent with expectations of how these systems might be altered due to climate change.⁶⁰¹ However, it has not been proven that climate change is the cause.⁶⁰²
- As oxygen declines in the subarctic Pacific, the hypoxic threshold will rise.⁶⁰³
- It would take a little more than 20 years to create hypoxia in waters off the BC coast, assuming no ventilation and an oxygen consumption rate of about 4 $\mu\text{mol kg}^{-1} \text{yr}^{-1}$.⁶⁰⁴ A more precise time period was not provided; however, the study was published in 2007.

Note to the reader: In Boxes, we summarize peer-reviewed studies, government reports, and publications from non-governmental organizations. The rest of the report is constructed by combining sentences, typically verbatim, from these sources. Please see the Preface: Production and Methodology for further information on this approach.

Definition and Causes of Altered Patterns of Coastal Hypoxia and Anoxia

“Hypoxia” describes the condition of a water column that is largely deficient of dissolved oxygen – generally, a body of water is considered hypoxic when there is less than two milligrams of dissolved oxygen per liter of water (2.0 mg/L).⁶⁰⁵ “Anoxia” is used to describe a water body that is devoid of

⁵⁹⁵ Chan et al. (2008); Connolly et al. (2010); Grantham et al. (2004); Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO). (2009)

⁵⁹⁶ Connolly et al. (2010); Grantham et al. (2004); PISCO. (2009)

⁵⁹⁷ Grantham et al. (2004, p. 750)

⁵⁹⁸ Connolly et al. (2010, p. 1)

⁵⁹⁹ Connolly et al. (2010, p. 1, 8)

⁶⁰⁰ Whitney, Freeland and Robert. (2007, p. 179)

⁶⁰¹ PISCO. *Hypoxia off the Pacific Northwest Coast*. (2009)

⁶⁰² PISCO. (2009)

⁶⁰³ Whitney, Freeland and Robert. (2007, p. 196)

⁶⁰⁴ Whitney, Freeland and Robert. (2007, p. 197). The authors cite Feely et al. (2004) for the oxygen consumption rate.

⁶⁰⁵ Information as cited in Grantham et al. (2004), *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*.

dissolved oxygen. For each °F (°C) that water warms, oxygen solubility (the capacity to dissolve oxygen) decreases by about 1% (about 2%).⁶⁰⁶ Several physical and biological processes interact to create hypoxic events (Figure 16):

- **Changing wind patterns and ocean currents:** Changing wind patterns and ocean currents promote upwelling and advection of low-oxygen, nutrient rich (i.e. nitrogen-rich) deep ocean waters.⁶⁰⁷ These “oxygen minimum zones” can occur naturally in deep waters, where respiration removes oxygen that is not replenished by contact with the sea surface.⁶⁰⁸ Upwelling, however, can transport these oxygen-poor waters onto productive continental shelves, where respiration can further reduce water-column dissolved oxygen (DO) content and thus subject coastal ecosystems to the risk of hypoxia or anoxia.⁶⁰⁹
- **Oxygen demand exceeds oxygen supply:** Biological oxygen demand exceeds the supply of oxygen from surface waters, typically as a result of increased microbial respiration, stimulated by accumulated carbon from enhanced primary production in surface waters.⁶¹⁰ The enhanced production results from increased nitrogen (and sometimes phosphorus) availability.⁶¹¹
- **Stratification:** Oxygen depletion is exacerbated in situations where water masses are highly stratified or isolated from oxygenated water bodies.⁶¹² Stratification results from strong thermal or salinity gradients; for example, from excessive rain or runoff from land.⁶¹³
- **Age, temperature, and salinity:** Hypersaline waters and warm waters hold less dissolved oxygen than cold, fresher water.⁶¹⁴ Where warm, saline waters enter the ocean or where waters are very old, hypoxia is more likely.⁶¹⁵

⁶⁰⁶ Verbatim or nearly verbatim from Najjar et al. *The potential impacts of climate change on the mid-Atlantic coastal region*. (2000, p. 226)

⁶⁰⁷ Grantham et al. (2004)

⁶⁰⁸ Grantham et al. (2004)

⁶⁰⁹ Verbatim or nearly verbatim from Chan et al. *Emergence of anoxia in the California Current large marine ecosystem*. (2008, p. 1)

⁶¹⁰ Verbatim or nearly verbatim from Levin et al. (2009, p. 3566)

⁶¹¹ Verbatim or nearly verbatim from Levin et al. (2009, p. 3566)

⁶¹² Verbatim or nearly verbatim from Levin et al. (2009, p. 3567)

⁶¹³ Verbatim or nearly verbatim from Levin et al. (2009, p. 3567)

⁶¹⁴ Verbatim or nearly verbatim from Levin et al. (2009, p. 3568)

⁶¹⁵ Verbatim or nearly verbatim from Levin et al. (2009, p. 3568)

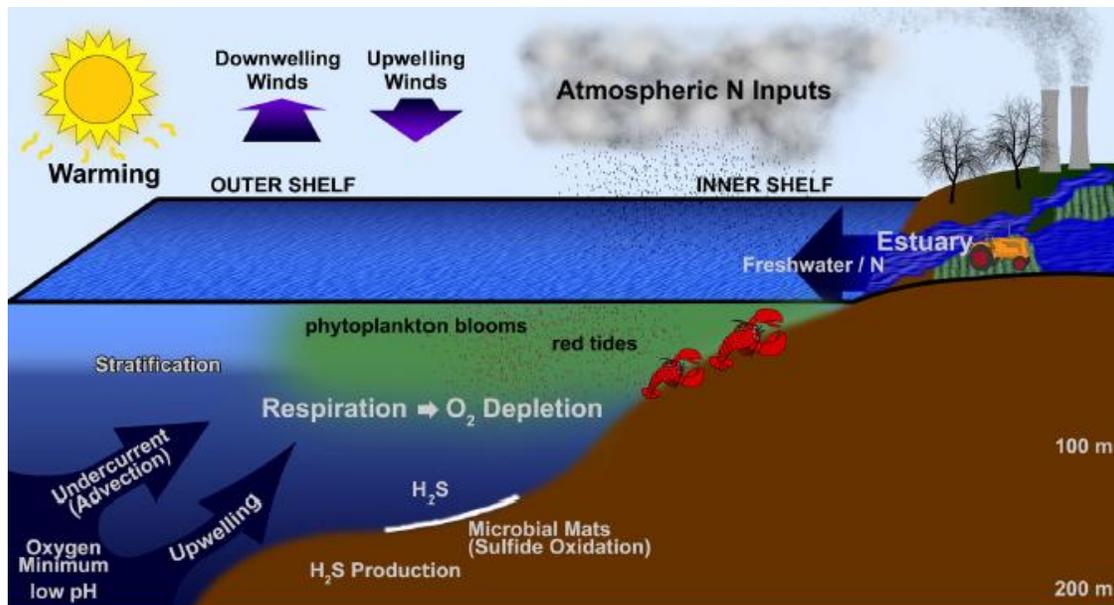


Figure 16. Schematic diagram illustrating the mechanisms underlying the formation of hypoxia experienced by benthos along continental shelves. *Source: Reproduced from Levin et al. (2009, Fig. 1, p. 3648) by authors of this report.*

Global climate change could increase the likelihood of hypoxia in the oceans and coastal environments by altering the physical environment in at least five ways:

- **Increased water temperature:** As a result of increasing SST, less oxygen will be able to dissolve into the warmer waters.⁶¹⁶
- **Increasing stratification:** Most of the time, stratification is a natural process, but long-term warming trends in the ocean, climate-related precipitation changes, and altered riverine input can insert a human element.⁶¹⁷
- **Altered wind and upwelling patterns:** The wind patterns that cause upwelling are due in part to temperature differences between the land and ocean surface, and it is thought that global climate change will promote more heating over the land than over the neighboring ocean, thereby resulting in more intense upwelling events that may bring low-oxygen water closer to the shore and ocean surface.⁶¹⁸
- **Ocean acidification:** Reduced transport of organic matter to the deeper layers of the ocean (caused by impacts to calcifying organisms) leads to enhanced remineralization of organic matter in shallow waters.⁶¹⁹ This effect leads to higher oxygen demand in the upper ocean, resulting in a drop in the dissolved oxygen concentration there.⁶²⁰ Because these waters constitute the source of the upwelling waters in the California Current System (located off the coasts of California,

⁶¹⁶ Verbatim or nearly verbatim from California Natural Resources Agency *California Climate Adaptation Strategy*. (2009, p. 66)

⁶¹⁷ Verbatim or nearly verbatim from Levin et al. (2009, p. 3567)

⁶¹⁸ Verbatim or nearly verbatim from Bakun. (1990); Bakun and Weeks. (2004)

⁶¹⁹ Verbatim or nearly verbatim from Hauri et al. (2009, p. 69). The authors cited Balch and Utgoff (2009) for this information.

⁶²⁰ Verbatim or nearly verbatim from Hauri et al. (2009, p. 69). The authors cited Hofmann and Schellnhuber (2009) for this information.

Oregon, Washington, and southern British Columbia), such a decrease likely will cause more frequent low-oxygen events along the U.S. West coast in the future.⁶²¹ However, Hauri et al. (2009) note that such concomitant perturbations also complicate their detection and surveillance.⁶²²

Researchers suggest that, in areas with strong seasonality such as the coastal waters of the western coast of North America, organisms are susceptible to mortality when dissolved oxygen concentrations fall below 1.0 mL/L and mass mortality occurs at concentrations less than 0.5 mL/L.⁶²³ These conditions occurred off the Oregon coast in 2002 and 2006, resulting in mass mortality of fish, Dungeness crab, and bottom-dwelling invertebrates.⁶²⁴ Box 15 and Figure 17 provide additional information on the biological impacts of hypoxia and anoxia. *Please see Chapter VII.4 (Shellfish) for further information on the impacts of these hypoxic events on shellfish.*

Observed Trends

Regional

Along the continental margins of the northeast Pacific Ocean, there is an extensive oxygen minimum zone (OMZ; ~66-4856 feet, or ~20-1480 m, deep), where dissolved oxygen falls below 0.5 mL/L.⁶²⁵ Helly and Levin (2004) report the lower boundary of the OMZ would not be expected to shift significantly over seasonal to decadal intervals, although the upper boundary may experience seasonal fluctuations (e.g. of 82 feet, or 25 m, off Chile) and interannual shifts of up to 213 to 328 feet (65-100 m).⁶²⁶

Southcentral and Southeast Alaska

Information needed.

British Columbia

Off the coast of British Columbia, the hypoxic boundary has shoaled from about 1300 feet (400 m) to about 980 feet (300 m) over fifty years (1956-2006).⁶²⁷ In the depth range ~410-980 feet (125-300 m), oxygen decreased between 17% and 30% (20-40 $\mu\text{mol kg}^{-1}$) from 1956 to 2006.⁶²⁸ Concomitant with this change is an overall trend in warming and oxygen loss in the waters below the ocean mixed layers to depths of at least 3280 feet (1000 m).⁶²⁹

⁶²¹ Verbatim or nearly verbatim from Hauri et al. (2009, p. 69)

⁶²² Verbatim or nearly verbatim from Hauri et al. (2009, p. 69)

⁶²³ Verbatim or nearly verbatim from Connolly et al. (2010, p. 3)

⁶²⁴ Verbatim or nearly verbatim from Grantham et al. (2004)

⁶²⁵ Verbatim or nearly verbatim from Grantham et al. (2004, p. 751). The authors cite Kamykowski and Zentara (1990) for this data. Please see Helly and Levin (2004, Fig. 2, p. 1163) for the depth of the OMZ in the eastern Pacific.

⁶²⁶ Verbatim or nearly verbatim from Helly and Levin. *Global distribution of naturally occurring marine hypoxia on continental margins.* (2004, p. 1165)

⁶²⁷ Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 179)

⁶²⁸ Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 196)

⁶²⁹ Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 179)

Washington

Along Washington's outer coast, the historical record (1950-1986) shows hypoxia is more prevalent and severe than that observed off the coast of northern Oregon, likely due to small-scale differences in ocean topography.⁶³⁰ From 2003 to 2005, hypoxic events off the Washington coast occurred at levels previously observed in the historical data.⁶³¹ The year 2006 was an exception, with hypoxia covering an especially large area of the Washington continental shelf and dissolved oxygen concentrations below 0.5 mL/L at the inner shelf, lower than any known previous observations at that location.⁶³²

In a study of hypoxia in central Puget Sound and Hood Canal by Brandenberger et al. (2008), data from sediment cores suggest hypoxia has occurred to a greater degree prior to significant human alterations beginning in the 1900s.⁶³³ However, the data do not resolve the timing of short-lived hypoxia events that led to fish kills in Hood Canal during the early 21st century.⁶³⁴ The decoupling between the increase in anthropogenic factors and the low oxygen conditions in the deep waters of the basin is somewhat counterintuitive and opposite to what has been observed in other coastal systems, in which the onset of low oxygen conditions came as a result of a rise in land use changes (i.e. agriculture and deforestation).⁶³⁵ In fact, the paleoecological indicators suggest that climate oscillations, such as the Pacific Decadal Oscillation (PDO), may influence the ventilation of deep water in Puget Sound and particularly their least mixed regions such as the southern end of Hood Canal.⁶³⁶

Oregon

In a study by Grantham et al. (2004), between July and September 2002, severe (0.21 - 1.57 mL/L DO) inner-shelf hypoxia was detected in central Oregon, from Florence to Newport.⁶³⁷ Bottom dissolved-oxygen concentrations of 0.21–1.57 mL/L were found to extend from the shelf break to nearshore stations (1.2-3.1 miles; 2–5 km offshore).⁶³⁸ In shallow waters, researchers note the severe hypoxia is particularly surprising given the potential for air-sea oxygen equilibration caused by turbulent conditions (e.g. significant wave height exceeding three meters).⁶³⁹ In addition, strong winds favoring upwelling were ineffective in eroding stratification on the inner shelf, and upwelling therefore resulted in the net shoreward transport of cold, saline, dissolved-oxygen-depleted deep water onto the inner shelf.⁶⁴⁰

In 2006, researchers documented anoxia on the inner shelf in central Oregon, where it had never before been recorded (although hypoxic waters have historically been upwelled onto the continental shelf, these waters have generally remained on the deeper, outer portions of the shelf).⁶⁴¹ Chan et al. (2008) report that five decades of available records show little evidence of shelf hypoxia and no evidence of severe

⁶³⁰ Verbatim or nearly verbatim from Connolly et al. (2010, p. 1, 7)

⁶³¹ Verbatim or nearly verbatim from Connolly et al. (2010, p. 1, 8)

⁶³² Verbatim or nearly verbatim from Connolly et al. (2010, p. 1)

⁶³³ Verbatim or nearly verbatim from Brandenberger et al. *Reconstructing trends in hypoxia using multiple paleoecological indicators recorded in sediment cores from Puget Sound, WA.* (2008, p. iii)

⁶³⁴ Verbatim or nearly verbatim from Brandenberger et al. (2008, p. iii)

⁶³⁵ Verbatim or nearly verbatim from Brandenberger et al. (2008, p. iv-v)

⁶³⁶ Verbatim or nearly verbatim from Brandenberger et al. (2008, p. v)

⁶³⁷ Verbatim or nearly verbatim from Grantham et al. (2004, p. 750)

⁶³⁸ Verbatim or nearly verbatim from Grantham et al. (2004, p. 750)

⁶³⁹ Verbatim or nearly verbatim from Grantham et al. (2004, p. 751)

⁶⁴⁰ Verbatim or nearly verbatim from Grantham et al. (2004, p. 751)

⁶⁴¹ Chan et al. *Emergence of anoxia in the California Current large marine ecosystem.* (2008)

inner-shelf hypoxia before 2000.⁶⁴² More specifically, hypoxic water in depths less than 165 feet (50.3 m) in this region is considered unusual, and was not reported before 2002 although measurements were made along the Oregon coast for over fifty years.⁶⁴³

Northwest California

Information needed.

Box 15. Impacts of hypoxia on the structure, function, and processes of biological communities in the marine environment.

A recent paper by Ekau et al. (2010) provides an extensive review of the impacts of hypoxia on the structure and processes in pelagic (open ocean) communities. Discussion of impacts is organized by taxonomic group and includes gelatinous plankton, crustacea, mollusks/squid, and fish. Effects on physiology, reproduction, spatial distribution, growth, and other factors are also discussed. Figure 17 summarizes the behavioral and physiological responses of marine organisms to varying oxygen saturation levels.

A literature review conducted by Vaquer-Sunyer and Duarte (2008) suggests hypoxia affects benthic (bottom-dwelling) marine organisms above the commonly used hypoxic threshold of two milligrams of oxygen per liter (2 mg O₂/L).⁶⁴⁴ Based on their review, the researchers state fish and crustaceans are most vulnerable, while mollusks, cnidarians, and priapulids were most tolerant.⁶⁴⁵ Since some benthic marine organisms may be sensitive to exposure to higher oxygen levels than previously thought, the vulnerability of these organisms and the coastal ecosystem as a whole to hypoxia may be greater than currently recognized.⁶⁴⁶

⁶⁴² Verbatim or nearly verbatim from Chan et al. (2008, p. 1)

⁶⁴³ Verbatim or nearly verbatim from PISCO. (2009, p. 2)

⁶⁴⁴ Vaquer-Sunyer and Duarte. *Thresholds of hypoxia for marine biodiversity*. (2008)

⁶⁴⁵ Vaquer-Sunyer and Duarte. (2008).

⁶⁴⁶ Vaquer-Sunyer and Duarte. (2008, p. 15456).

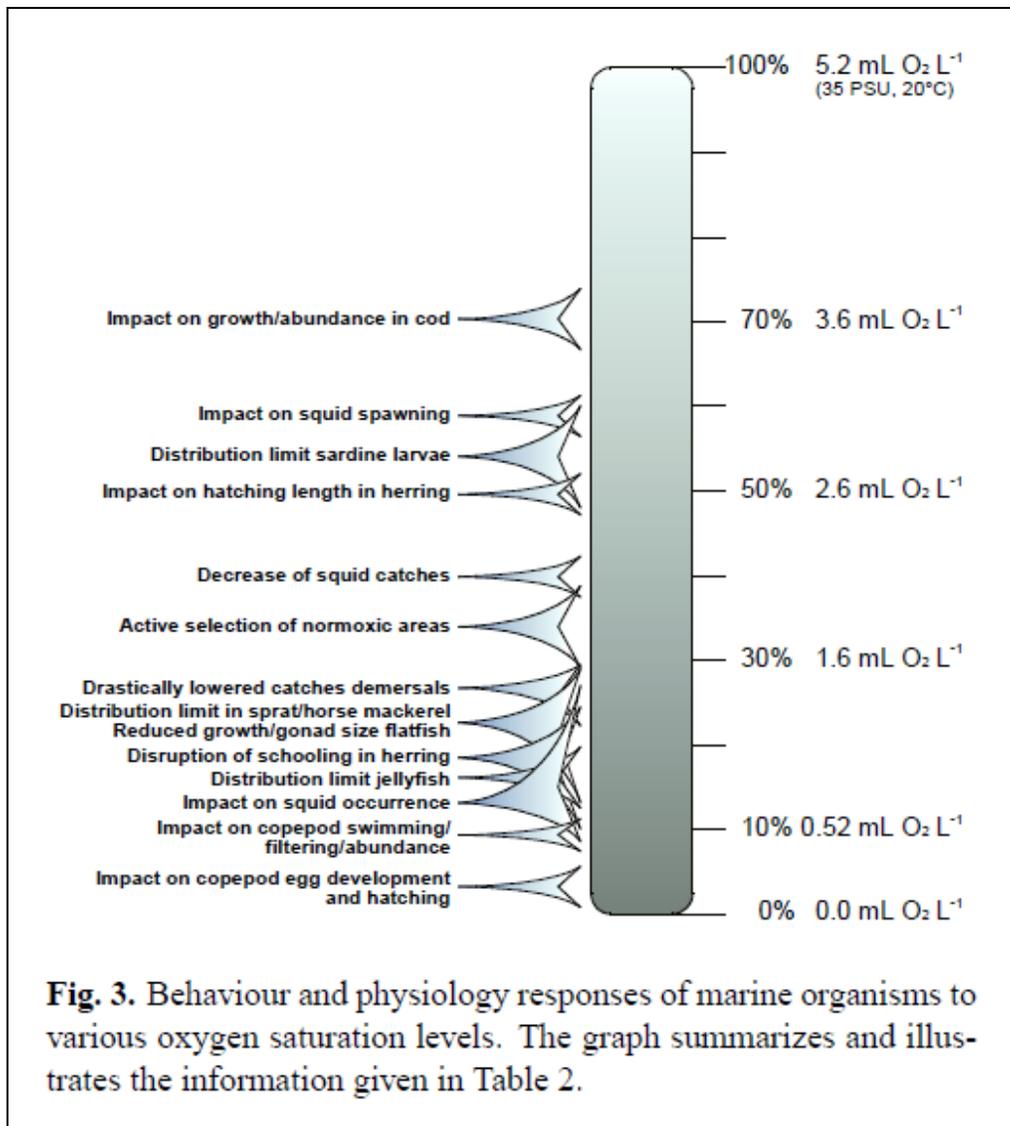


Figure 17. Behavior and physiology responses of marine organisms to various oxygen saturation levels. *Source: Reproduced from Ekau et al. (2010, Fig. 3, p. 1682) by authors of this report.*

Future Projections

Regional

Scientists have suggested hypoxic events in the northeast Pacific are due to anomalous upwelling driven by unusual changes in wind patterns.⁶⁴⁷ These wind patterns are what might be expected to result from increased differences between land and sea surface temperatures due to global climate change.⁶⁴⁸ Specifically, temperature gradients across the shore support more intense alongshore winds, which drive

⁶⁴⁷ Grantham et al. (2004)

⁶⁴⁸ Bakun and Weeks. (2004)

surface water off the coast and result in the upwelling of deeper waters.⁶⁴⁹ Further, as oxygen declines in the subarctic Pacific, the hypoxic threshold will rise.⁶⁵⁰ The changes in oceanic and atmospheric conditions that have produced the anomalous hypoxic events are consistent with expectations of how these systems might be altered due to climate change; however, it has not been proven that climate change is the cause.⁶⁵¹

Southcentral and Southeast Alaska

Information needed.

British Columbia

Assuming no ventilation and an oxygen consumption rate of about four micromoles per kilogram per year, it would take a little more than twenty years to create hypoxia in waters off the coast of British Columbia.⁶⁵²

Washington

Information needed.

Oregon

Information needed.

Northwest California

Information needed.

Information Gaps

Information is needed on trends in hypoxia and anoxia off the coasts of southcentral and southeast Alaska, as well as northern California. More specific information on future projections in hypoxia and anoxia throughout the NPLCC region is also needed.

⁶⁴⁹ Bakun. (1990); Bakun and Weeks. (2004)

⁶⁵⁰ Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 196)

⁶⁵¹ PISCO. (2009)

⁶⁵² Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 197). The authors cite Feely et al., (2004) for the oxygen consumption rate.

IV. IMPLICATIONS FOR MARINE & COASTAL ECOSYSTEMS

Marine ecosystems are centrally important to the biology of the planet.⁶⁵³ Ecosystem production and structure respond to changes in ocean regimes.⁶⁵⁴ Although there is considerable uncertainty about the spatial and temporal details, climate change is clearly and fundamentally altering ocean ecosystems.⁶⁵⁵ Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, the following implications of climate change for marine and coastal ecosystems in the NPLCC region have been identified:

1. Altered nutrient cycling
2. Altered ocean productivity
3. Altered food web dynamics
4. Multiple stressors and thresholds

Two large marine ecosystems (LME) are found in the NPLCC region – the Gulf of Alaska LME and the California Current Ecosystem (CCE).⁶⁵⁶ The Gulf of Alaska LME lies off the southern coast of Alaska and the western coast of Canada.⁶⁵⁷ The California Current is a ~621-mile-wide (1000 km), sluggish current spanning the North American Pacific Coast from ~20°N (near Guadalajara Mexico) to 50°N (northern Vancouver Island) (Figure 15).⁶⁵⁸ The cold Subarctic Current, as it bifurcates towards the south, serves as the boundary between the Gulf of Alaska and the California Current LME.⁶⁵⁹

Recent changes in Alaska’s coastal waters include general warming of ocean surface waters, warming of the southeast Bering Sea bottom waters over the continental shelf, a more strongly stratified ocean, hypothesized decrease in ocean productivity, alteration of pelagic ocean habitat, and changes in the distribution of species.⁶⁶⁰ These changes have the potential to affect the structure, function, productivity, and composition of Alaska’s marine ecosystems, which may negatively impact the protected marine species that live or migrate through these ecosystems (e.g. North Pacific right whale).⁶⁶¹ In the Gulf of Alaska, Sigler, Napp, and Hollowed (2008) identify ocean acidification, as well as climate regimes and ecosystem productivity, as major climate-related concerns.⁶⁶²

The northern end of the CCE is dominated by strong seasonal variability in winds, temperature, upwelling, plankton production, and the spawning times of many fishes, whereas the southern end of the

⁶⁵³ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1523)

⁶⁵⁴ Verbatim or nearly verbatim from ISAB. *Climate change impacts on Columbia River Basin Fish and Wildlife*. (2007, p. 69)

⁶⁵⁵ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1523)

⁶⁵⁶ Osgood (Ed.). *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs*. (2008, Fig. 1, p. 2); NOAA. *Gulf of Alaska: LME #2 (website)*. (2009); NOAA. *California Current: LME #3 (website)*. (2009)

⁶⁵⁷ Verbatim or nearly verbatim from NOAA. *Gulf of Alaska: LME #2 (website)*. (2009)

⁶⁵⁸ Verbatim or nearly verbatim from Hickey and Banas. (2008, p. 93)

⁶⁵⁹ Verbatim or nearly verbatim from NOAA. *Gulf of Alaska: LME #2 (website)*. (2009)

⁶⁶⁰ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs: Alaskan Ecosystem Complex*. (2008, p. 66). The authors refer the reader to Figure 2 in the cited report for Bering Sea information.

⁶⁶¹ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 66).

⁶⁶² Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 66).

CCE has much less seasonal variability in these parameters.⁶⁶³ For some groups of organisms, the northern end of the CCE is dominated by sub-arctic boreal fauna whereas the southern end is dominated by tropical and sub-tropical species.⁶⁶⁴ Higher trophic level organisms often take advantage of the strong seasonal cycles of production in the north by migrating to the region during the summer to feed.⁶⁶⁵ Animals exhibiting this behavior include pelagic seabirds such as black-footed albatross and sooty shearwaters, fishes such as Pacific whiting and sardines, and humpback whales.⁶⁶⁶ Overall, the climate-species linkages in the CCE are extremely complex.⁶⁶⁷ The five issues of greatest concern in the CCE are:

- Increased variability in climate forcing,
- Changes to the magnitude and timing of freshwater input,
- Changes in the timing and strength of the spring transition and their effect on marine populations,
- Ocean warming and increased acidification and their impact on pelagic habitat, and
- Changes in ocean circulation and their impact on species distribution and community structure.⁶⁶⁸

The following structure will be used to present information on the implications of climate change for the NPLCC region's marine and coastal ecosystems:

- **Observed Trends** – observed changes at the global level, for the Gulf of Alaska LME, and for the California Current Ecosystem. Section 3 (Altered food web dynamics) also describes region-wide changes.
- **Future Projections** – projected direction and/or magnitude of change at the global level, for the Gulf of Alaska LME, and for the California Current Ecosystem. Section 3 (Altered food web dynamics) also describes region-wide projections.
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

Note: Section 4 (Multiple stressors and thresholds: Discussion) is presented as a discussion because the available information could not be classified as observed trends or future projections.

⁶⁶³ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs: California Current Ecosystem.* (2008, p. 44)

⁶⁶⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁶⁵ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁶⁶ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁶⁷ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁶⁸ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 44-45)

1. ALTERED NUTRIENT CYCLING

Observed Trends

Global

Information needed.

Gulf of Alaska LME

Several recent studies have assessed nutrient cycling processes in the Gulf of Alaska:

- In a study of glacier runoff in freshwater discharge, Neal, Hood, and Smikrud (2010) conclude changes in timing and magnitude of freshwater delivery to the Gulf of Alaska could impact coastal circulation as well as biogeochemical fluxes in nearshore marine ecosystems and the eastern North Pacific Ocean.⁶⁶⁹ Hood and Scott (2008) find that different levels of glacial coverage can alter the timing and magnitude of freshwater, dissolved organic matter, and nutrient yields.⁶⁷⁰ Taken together, their results indicate that decreasing watershed glacial coverage leads to lower riverine yields of freshwater, inorganic phosphorus, and labile dissolved organic matter.⁶⁷¹
- Hood et al. (2009) find that direct runoff from Gulf of Alaska glaciers produces a conservative dissolved organic carbon flux of 0.13 ± 0.01 Teragrams per year (Tg/yr) to downstream ecosystems.⁶⁷² Furthermore, the dissolved organic carbon bioavailability value from the most heavily glaciated catchment suggests that ~ 0.1 Tg of the annual dissolved organic carbon derived from Gulf of Alaska glaciers is readily bioavailable.⁶⁷³ Because glacial streamwater turbidities are high and riverine transit times from glaciers to their estuaries are short across broad regions of the Gulf of Alaska, a substantial portion of this labile dissolved organic carbon is probably delivered to marine heterotrophic communities without biological or photochemical alteration.⁶⁷⁴ Thus, changes in riverine yields of dissolved organic matter and nutrients due to reductions in glacier extent in coastal watersheds may affect the productivity and function of nearshore coastal ecosystems.⁶⁷⁵ As stated above, the results of studies by Neal, Hood, and Smikrud (2010) and Hood and Scott (2008) indicate that decreasing watershed glacial coverage leads to lower riverine yields of freshwater, inorganic phosphorus, and labile dissolved organic matter.⁶⁷⁶

California Current Ecosystem

Information needed.

⁶⁶⁹ Verbatim or nearly verbatim from Neal, Hood and Smikrud. *Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska*. (2010, p. 1)

⁶⁷⁰ Verbatim or nearly verbatim from Hood and Scott. (2008, p. 583)

⁶⁷¹ Verbatim or nearly verbatim from Hood and Scott. (2008, p. 585)

⁶⁷² Verbatim or nearly verbatim from Hood et al. *Glaciers as a source of ancient and labile organic matter to the marine environment*. (2009, p. 1046)

⁶⁷³ Verbatim or nearly verbatim from Hood et al. (2009, p. 1046)

⁶⁷⁴ Verbatim or nearly verbatim from Hood et al. (2009, p. 1046)

⁶⁷⁵ Verbatim or nearly verbatim from Hood and Scott. (2008, p. 583)

⁶⁷⁶ Verbatim or nearly verbatim from Hood and Scott. (2008, p. 585)

Future Projections

Global

Information needed.

Gulf of Alaska LME

Iron is an essential micronutrient that limits primary productivity in much of the ocean, including the Gulf of Alaska.⁶⁷⁷ Dust is thought to be one of the most important sources of iron to the Gulf of Alaska, but as with most regions, there are few measurements.⁶⁷⁸ Crusius et al. (2011) recently described a potentially important but largely undocumented source of dust and iron to the Gulf of Alaska: glacial flour-rich riverbed sediments of coastal Alaska (results described in next section).⁶⁷⁹ In their conclusion, they state it remains important to examine whether dust fluxes are increasing in high-latitude locations in response to glacial recession and climate change, and what the impact might be on marine ecosystems.⁶⁸⁰ If glaciers continue their present-day pattern of increasing mass loss due to a warming climate, more glacial flour may be transported to the Gulf of Alaska by dust plumes and other mechanisms, affecting phytoplankton growth and Gulf of Alaska ecosystems.⁶⁸¹

Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity and control of phytoplankton growth rates.⁶⁸² Decreased freshwater inflows increase water residence time and decrease vertical stratification, and vice versa.⁶⁸³ For example, increased melting of glaciers in the Gulf of Alaska coupled with warmer sea surface temperatures will result in increased stratification of the Gulf.⁶⁸⁴ Areas with enhanced riverine input into the coastal ocean will also see greater vertical stratification.⁶⁸⁵

California Current Ecosystem

Since some of the source waters that supply the northern California Current originate in the Gulf of Alaska, more stratified source waters will contribute to increased stratification of coastal waters of the northern California Current.⁶⁸⁶

Comparing the 2081-2120 period to a 40-year period representative of 1860 climate conditions (A2 scenario), Rykaczewski and Dunne (2010) find that despite increased surface temperatures, associated increased stratification, and relatively modest changes in upwelling, nitrate concentration in the upper 200 m of the CCE is projected to increase eighty percent by year 2100.⁶⁸⁷ This significant increase in nitrate

⁶⁷⁷ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

⁶⁷⁸ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

⁶⁷⁹ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

⁶⁸⁰ Verbatim or nearly verbatim from Crusius et al. (2011, p. 5)

⁶⁸¹ Verbatim or nearly verbatim from *Eos* "Research Spotlights" (2011, p. 18)

⁶⁸² Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328)

⁶⁸³ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328). The authors cite Moore et al. (1997) for this information.

⁶⁸⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 56)

⁶⁸⁵ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 56)

⁶⁸⁶ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 56)

⁶⁸⁷ Verbatim or nearly verbatim from Rykaczewski and Dunne. *Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model.* (2010, p. 2). The authors

concentration is in opposition to the decreased concentration in the subtropical North Pacific (20°N to 45°N) that is expected given the increased stratification.⁶⁸⁸

Through the NPLCC region, the decrease in biodiversity in hypoxic areas will reduce ecosystem resilience and resistance and may decrease its function in nutrient cycling processes.⁶⁸⁹

Information Gaps

Information is needed on observed patterns of nutrient cycling in the California Current Ecosystem, as well as observed trends and future projections for global patterns of nutrient cycling. Further, quantitative projections of nutrient cycling patterns under scenarios of future climatic change are needed for the NPLCC region.

refer the reader to Fig. S2b for information on increased stratification and to Fig. 1b for information on nitration concentration (both in cited report).

⁶⁸⁸ Verbatim or nearly verbatim from Rykaczewski and Dunne. (2010, p. 2)

⁶⁸⁹ Verbatim or nearly verbatim from Ekau et al. *Impacts of hypoxia on the structure and processes in pelagic communities*. (2010, p. 1691)

2. ALTERED OCEAN PRODUCTIVITY

Observed Trends

Global

The annual primary production (accumulation of plant growth during a specified time period, typically by photosynthesizers such as phytoplankton) of the world's oceans has decreased by at least six percent since the early 1980s, with nearly seventy percent of this decline occurring at higher latitudes and with large relative decreases occurring within Pacific and Indian ocean gyres (see Chapter III.4, Altered ocean currents, for further information on gyres).⁶⁹⁰ Global declines in net primary production (as estimated from the SeaWiFS satellite sensor) between 1997 and 2005 were attributed to ocean surface warming.⁶⁹¹

In a meta-analysis of the effects of ocean acidification on marine organisms, ocean acidification did not have a significant overall mean effect on photosynthesis.⁶⁹² Although calcifying organisms had a more negative mean effect than non-calcifying organisms, the difference was not significant.⁶⁹³ The mean effect was different amongst taxonomic groups, with a significant negative mean effect on calcifying algae.⁶⁹⁴

Gulf of Alaska LME

Iron is an essential micronutrient that limits primary productivity in much of the ocean, including the Gulf of Alaska.⁶⁹⁵ In a study of hydrologic and meteorological controls and their importance as a source of bioavailable iron in glacial flour dust storms, Crusius et al. (2011) found that glacial flour (i.e., fine-grained sediment resulting from glacial erosion) dust plumes are transported several hundred kilometers beyond the continental shelf into iron-limited waters of the Gulf of Alaska.⁶⁹⁶ They estimated the mass of dust transported from the Copper River valley during one event in 2006 to be twenty-five to eighty kilotons.⁶⁹⁷ Based on conservative estimates, this equates to a soluble iron loading of 30 to 200 tons.⁶⁹⁸ Crusius et al. suggest the total amount from the entire Gulf of Alaska coastline is two to three times larger – comparable to the annual iron flux to Gulf of Alaska surface waters from eddies of coastal origin.⁶⁹⁹

⁶⁹⁰ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Gregg et al. (2003) for information about higher latitudes and Polovina et al. (2008) for information about the Pacific and Indian oceans.

⁶⁹¹ Verbatim or nearly verbatim from Janetos et al. (2008, p. 166)

⁶⁹² Verbatim or nearly verbatim from Kroeker et al. *Meta-analysis reveals negative yet variable effects on ocean acidification on marine organisms*. (2010, p. 1425)

⁶⁹³ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 2 in the cited report and provide statistics for this result: $Q_M = 0.30$, d.f. = 1, $P = 0.59$.

⁶⁹⁴ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 3 in the cited report and provide statistics for taxonomic groups ($Q_M = 12.03$, d.f. = 3, $P = 0.02$) and calcifying algae ($\text{LnRR} = -0.33$, 95% bias-corrected confidence interval = -0.39 to -0.22).

⁶⁹⁵ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

⁶⁹⁶ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

⁶⁹⁷ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

⁶⁹⁸ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

⁶⁹⁹ Verbatim or nearly verbatim from Crusius et al. (2011, p. 1)

California Current Ecosystem

The vertical gradient in ocean temperature off California has intensified over the past several decades.⁷⁰⁰ Roemmich and McGowan (1995) credited this change in temperature structure for the observed long-term decline in zooplankton biomass.⁷⁰¹ In recent years, the northern California Current appears to have recovered from two summers of poor productivity (2005 and 2006) – the ocean was cold during the winter of 2006-07, the spring transition to upwelling conditions was very early (February), and zooplankton biomass returned to levels not seen since summer of 2004.⁷⁰²

Future Projections

Global

Sarmiento et al. (2004) examined six different coupled climate model simulations to determine the ocean biological response to climate warming between the beginning of the industrial revolution and 2050.⁷⁰³ Three different primary production algorithms were used to estimate the response of primary production to climate warming based on estimated chlorophyll concentrations.⁷⁰⁴ The three algorithms give a global increase in primary production of 0.7% at the low end to 8.1% at the high end, with very large regional differences.⁷⁰⁵

Steinacher et al. (2010), on the other hand, project decreases in global mean primary productivity and export of particulate organic carbon by 2100 relative to preindustrial conditions (A2 scenario; multi-model analysis).⁷⁰⁶

Finally, algae growth in lagoons and estuaries may respond positively to elevated dissolved inorganic carbon (DIC), though marine macroalgae do not appear to be limited by dissolved organic carbon levels.⁷⁰⁷

Region-wide

Beyond the coastal waters of the NPLCC region (i.e., farther out to sea than the California Current), production and chlorophyll concentration over most of the North Pacific are projected to decline with future warming, consistent with the changes in nutrient concentration discussed in the previous section.⁷⁰⁸ The projected decline in production is greatest in the subtropical region (20% median decline by 2100 relative to 1860 levels between 20° and 45° N; A2 scenario) where primary production is limited by the

⁷⁰⁰ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 56). The authors cite Palacios et al. (2004) for this information and refer the reader to Figure 4 in the cited report.

⁷⁰¹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 56)

⁷⁰² Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 45)

⁷⁰³ Verbatim or nearly verbatim from Sarmiento et al. *Response of ocean ecosystems to climate warming*. (2004, p. 1)

⁷⁰⁴ Verbatim or nearly verbatim from Sarmiento et al. (2004, p. 1)

⁷⁰⁵ Verbatim or nearly verbatim from Sarmiento et al. (2004, p. 1)

⁷⁰⁶ Verbatim or nearly verbatim from Steinacher et al. *Projected 21st century decrease in marine productivity: a multi-model analysis*. (2010, p. 979)

⁷⁰⁷ Nicholls et al. (2007, p. 329-330). The authors cite Beer and Koch (1996) for this information.

⁷⁰⁸ Verbatim or nearly verbatim from Rykaczewski and Dunne. (2010, p. 2). The authors refer the reader to Fig. 1c in the cited report.

supply of macronutrients.⁷⁰⁹ In the subarctic Pacific, where production is colimited by iron, light, and macronutrients, the relative decline in production is less (5% decline between 45° and 65° N); increased stratification acts to reduce light limitation and thus iron demand in the subarctic, enhancing the efficiency of nitrate uptake.⁷¹⁰

Gulf of Alaska LME

If global warming results in shorter winters in the north Pacific, areas where production is light limited may see higher productivity.⁷¹¹ For example, phytoplankton blooms are initiated currently as early as February off northern California in years when storm intensity is low.⁷¹²

California Current Ecosystem

The coastal plain estuaries of the Pacific Northwest, with the exception of the Columbia River, are relatively small, with large tidal forcing and highly seasonal direct river inputs that are low to negligible during the growing season.⁷¹³ Primary production in these estuaries is likely controlled not by river-driven stratification but by coastal upwelling and exchange with the ocean.⁷¹⁴

Future ocean productivity in the California Current is mediated by several mechanisms, each of which interacts to determine productivity. Available research on these mechanisms supports both increased and decreased ocean productivity. Increases in ocean productivity may occur in the following situations:

- Rykaczewski and Dunne (2010) examined changes in nutrient supply and productivity of the California Current Ecosystem under projected conditions of future global climate.⁷¹⁵ Comparing the 2081-2020 period to a 40-year period representative of 1860 (A2 scenario), they conclude primary production is projected to increase in the CCE with future warming (10% by 2100) in response to increased nitrate supply tempered by increased iron and light colimitation.⁷¹⁶
- Currently light limited areas (e.g., the northern California Current) may see higher productivity in the future.⁷¹⁷ Early blooms result in bursts in egg production by both copepods and euphausiids, initiating a cohort of animals that reach adulthood one-two months earlier than a cohort that is initiated with the onset of upwelling in March or April.⁷¹⁸ The result would be a longer plankton production season.⁷¹⁹

Decreases in ocean productivity may occur in the following situations:

- Given that the future climate will be warmer, the upper ocean at the basin scale will almost certainly be, on average, more stratified.⁷²⁰ Peterson and Schwing (2008) note this will make it

⁷⁰⁹ Verbatim or nearly verbatim from Rykaczewski and Dunne. (2010, p. 2)

⁷¹⁰ Verbatim or nearly verbatim from Rykaczewski and Dunne. (2010, p. 2)

⁷¹¹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 53)

⁷¹² Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 53-54)

⁷¹³ Verbatim or nearly verbatim from Hickey and Banas. (2003, p. 1010)

⁷¹⁴ Verbatim or nearly verbatim from Hickey and Banas. (2003, p. 1010)

⁷¹⁵ Verbatim or nearly verbatim from Rykaczewski and Dunne. (2010, p. 1)

⁷¹⁶ Verbatim or nearly verbatim from Rykaczewski and Dunne. (2010, p. 2)

⁷¹⁷ Peterson, W. & Schwing, F. (2008, p. 53)

⁷¹⁸ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 54)

⁷¹⁹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 54)

⁷²⁰ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 53)

more difficult for winds and upwelling to mix the upper layers of the coastal ocean, and will make offshore Ekman pumping less effective at bringing nutrients into the photic zone.⁷²¹ The result will be lower primary productivity everywhere (with the possible exception of the nearshore coastal upwelling zones).⁷²²

- Some global climate models predict a higher frequency of El Niño events, while others predict the intensity of these events will be stronger.⁷²³ If true, primary and secondary production will be greatly reduced in the CCE, with negative effects transmitted up the food chain.⁷²⁴ However, despite considerable progress in understanding the impact of climate change on many of the processes that contribute to El Niño variability, it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change.⁷²⁵

Information Gaps

Information is needed on observed patterns of ocean productivity in southcentral and southeast Alaska, as the research presented here is from a single study. Quantitative data on observed patterns of ocean productivity throughout the NPLCC region is also needed. For future projections, information is needed for the Gulf of Alaska LME as well as globally.

⁷²¹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 53)

⁷²² Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 53)

⁷²³ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 45)

⁷²⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 45)

⁷²⁵ Verbatim or nearly verbatim from Collins et al. *The impact of global warming on the tropical Pacific Ocean and El Niño*. (2010, p. 391)

3. ALTERED FOOD WEB DYNAMICS

Observed Trends

Global

Information needed.

Region-wide

In the Pacific Ocean, Chavez et al. (2003) report that air and ocean temperatures, atmospheric carbon dioxide, landings of anchovies and sardines, and the productivity of coastal and open ocean ecosystems have varied over periods of about fifty years.⁷²⁶ Sardine and anchovy “regimes” are associated with large-scale changes in ocean temperatures; for twenty-five years the Pacific is warmer than average (the warm, sardine regime) and then switches to cooler than average for the next twenty-five years (the cool, anchovy regime).⁷²⁷ In the northeast Pacific, an intensification (sardine) or relaxation (anchovy) of the Aleutian Low has also been observed.⁷²⁸ Instrumental data provide evidence for two full cycles:⁷²⁹

- **Cool (anchovy) phases from about 1900 to 1925 and 1950 to 1975:**⁷³⁰ A stronger and broader California Current, brought about during the anchovy regime, is associated with a shallower coastal thermocline from California to British Columbia, leading to enhanced primary production.⁷³¹
- **Warm (sardine) phases from about 1925 to 1950 and 1975 to the mid-1990s:**⁷³² The “sardine regime” of the 1930s and 1940s was most notable for the sardine fishery off California and its collapse.⁷³³ During the sardine regime from the late 1970s to the early 1990s, zooplankton and salmon declined off Oregon and Washington but increased off Alaska.⁷³⁴ Seabird populations decreased off California and Peru.⁷³⁵

As implied above, in the mid-1970s, the Pacific changed from a cool “anchovy regime” to a warm “sardine regime.”⁷³⁶ The mid-1970s change has been widely recognized in a myriad of North Pacific climatic and biological time series and has been referred to as the 1976–1977 regime shift, even though its

⁷²⁶ Verbatim or nearly verbatim from Chavez et al. *From anchovies to sardines and back: multidecadal change in the Pacific Ocean.* (2003, p. 217)

⁷²⁷ Verbatim or nearly verbatim from Chavez et al. (2003, p. 217)

⁷²⁸ Verbatim or nearly verbatim from Chavez et al. (2003, p. 218). The authors cite Miller et al. (1994) for this information.

⁷²⁹ Verbatim or nearly verbatim from Chavez et al. (2003, p. 217)

⁷³⁰ Verbatim or nearly verbatim from Chavez et al. (2003, p. 217)

⁷³¹ Verbatim or nearly verbatim from Chavez et al. (2003, p. 218). The authors refer the reader to Figure 2 in the cited report.

⁷³² Verbatim or nearly verbatim from Chavez et al. (2003, p. 217)

⁷³³ Verbatim or nearly verbatim from Chavez et al. (2003, p. 217). The authors cite Lluch-Cota, Hernández-Vázquez and Lluch-Cota (1997) and refer the reader to Figure 1E in the cited report for information on the sardine regime of the 1930s and 1940s.

⁷³⁴ Verbatim or nearly verbatim from Chavez et al. (2003, p. 218). The authors cite Hare and Mantua (2000) and Benson and Trites (2002) for this information.

⁷³⁵ Verbatim or nearly verbatim from Chavez et al. (2003, p. 218). The authors cite Veit, Pyle and McGowan (1996) for information on California.

⁷³⁶ Verbatim or nearly verbatim from Chavez et al. (2003, p. 217)

precise timing is difficult to assess.⁷³⁷ Some indices suggest that the shift occurred rapidly whereas others suggest a more gradual change, though all indicate a shift in the 1970s.⁷³⁸ Table 18 further describes the atmospheric, biological, and ecological changes associated with this regime shift.

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Increasing hypoxia seems to benefit gelatinous plankton and/or squid as observed in the Benguela and California current regions.⁷³⁹ Other components of the “classical” marine foodweb are negatively affected: certain copepods and fish.⁷⁴⁰ Within these groups, Ekau et al. (2010) indicate the response is very complex.⁷⁴¹

- In general, small pelagic fish species, such as clupeids, could be more vulnerable than higher evolved and more adaptable species such as gobies or flat fish.⁷⁴²
- No systematic investigation exists on whether higher evolved fishes are more tolerant or adaptive to hypoxic conditions than less evolved ones.⁷⁴³

Jumbo squid (*Dosidicus gigas*) are opportunistic predators with high turnover rates and high consumption rates.⁷⁴⁴ Climate change has already been shown to force the range expansions of many marine species towards the poles, with animals with the greatest turnover rates showing the most rapid distributional responses to warming.⁷⁴⁵ Results from a food web study by Field et al. (2007) reflect the widely held perception of jumbo squid being a highly flexible predator with the ability to rapidly adapt to new environmental conditions during range expansions.⁷⁴⁶

Currently there is insufficient information to estimate plausible or possible impacts on California Current food webs, due to a lack of abundance information and incomplete knowledge of how movement and food habits may differ across seasons and between inshore and offshore waters.⁷⁴⁷ However, that jumbo squid are opportunistic predators with high turnover rates and high consumption rates, and that among their important prey are several of the current (and historically) largest fisheries (e.g., by volume along the U.S. West Coast, suggest that impacts are plausible.⁷⁴⁸ For example, stomach samples collected by

⁷³⁷ Verbatim or nearly verbatim from Chavez et al. (2003, p. 217). The authors cite Ebbesmeyer et al. (1991) for information on climatic time series, Hare and Mantua (2000) and Benson and Trites (2002) for information on biological time series, and Miller et al. 19994) and Frances and Hare (1994) for information on the 1976-1977 regime shift.

⁷³⁸ Verbatim or nearly verbatim from Chavez et al. (2003, p. 217)

⁷³⁹ Verbatim or nearly verbatim from Ekau et al. (2010, p. 1690)

⁷⁴⁰ Verbatim or nearly verbatim from Ekau et al. (2010, p. 1690)

⁷⁴¹ Verbatim or nearly verbatim from Ekau et al. (2010, p. 1690)

⁷⁴² Verbatim or nearly verbatim from Ekau et al. (2010, p. 1690)

⁷⁴³ Verbatim or nearly verbatim from Ekau et al. (2010, p. 1690)

⁷⁴⁴ Verbatim or nearly verbatim from Field et al. *Range expansion and trophic interactions of the jumbo squid (*Dosidicus gigas*) in the California Current.* (2007, p. 143)

⁷⁴⁵ Verbatim or nearly verbatim from Field et al. (2007, p. 142). The authors cite Perry et al. (2005) for this information.

⁷⁴⁶ Verbatim or nearly verbatim from Field et al. (2007, p. 142)

⁷⁴⁷ Verbatim or nearly verbatim from Field et al. (2007, p. 143)

⁷⁴⁸ Verbatim or nearly verbatim from Field et al. (2007, p. 143)

Field et al. included Pacific hake (*Merluccius productus*), small flatfish, rockfish, Pacific sardine (*Sardinops sagax*), Northern anchovy (*Engraulis mordax*), and California market squid (*Loligo opalescens*).⁷⁴⁹ Such impacts could drive changes at both higher and lower trophic levels.⁷⁵⁰

Table 18. Synthesis of Pacific conditions during sardine and anchovy regimes.

Type of impact	Warm “sardine regime” (mid 1970s to mid 1990s)		Cool “anchovy regime” (1950s through early 1970s)	
	34 th to 48 th parallel*	North of 48 th parallel	34 th to 48 th parallel*	North of 48 th parallel
Atmospheric & Physical†	<ul style="list-style-type: none"> • Weaker upwelling • Slower CA Current & weaker CA Undercurrent • Lower precipitation in WA & lower salinity • Higher SST & stratification 	<ul style="list-style-type: none"> • Strong Aleutian Low • More downwelling • Higher precipitation & streamflow • Higher/strong stratification, higher SST 	<ul style="list-style-type: none"> • Stronger upwelling • Faster CA Current & stronger CA Undercurrent • Higher precipitation in WA & higher salinity • Lower SST & stratification 	<ul style="list-style-type: none"> • Weak Aleutian Low • Less downwelling • Lower precipitation & streamflow, • Lower/weaker stratification, lower SST
Biological & Ecological†	<ul style="list-style-type: none"> • More sardines • Less salmon, seabirds, rockfish, & anchovies • Lower nutrients, zooplankton, & PP 	<ul style="list-style-type: none"> • More salmon • Higher zooplankton, PP, & nutrients 	<ul style="list-style-type: none"> • More anchovies, salmon, seabirds, rockfish • Less sardines • Higher nutrients, zooplankton, & PP 	<ul style="list-style-type: none"> • Less salmon • Lower PP, nutrients, & zooplankton

*The 34th to 48th parallel is the area approximately between southern CA and the Strait of Juan de Fuca.
† “SST” is sea surface temperature. “PP” is primary production.
Source: Modified from Chavez et al. (2003, Fig. 3, p. 220) by authors of this report.

Future Projections

Global

Animal metabolism is temperature-dependent, and consequently ecological processes such as predator-prey interactions are likely to be altered as warming occurs.⁷⁵¹ When combined with changing patterns of

⁷⁴⁹ Field et al. (2007, Fig. 4, p. 138)

⁷⁵⁰ Verbatim or nearly verbatim from Field et al. (2007, p. 143)

⁷⁵¹ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Hochachka and Somero (2002) for information on the temperature-dependence of animal metabolism and Sanford (1999) for information on predator-prey interactions.

primary productivity and metabolic rate, Hoegh-Guldberg and Bruno (2010) note these fundamental influences have the potential to substantially modify ocean food web dynamics, from coastal to open-ocean ecosystems.⁷⁵²

- Respiration is more sensitive than photosynthesis to changes in temperature, resulting in the caloric demands of consumers being potentially more strongly influenced by increased temperature when compared to the temperature response of primary production.⁷⁵³ Energetic demands are increased at warmer temperatures, requiring increased consumption of prey to maintain a given growth rate.⁷⁵⁴ These findings have implications for the ability of pelagic (open-ocean) systems to capture and store carbon dioxide, with the potential for these critical ocean processes to decline as temperature increases.⁷⁵⁵
- Warming has also been found to decrease the size of individual phytoplankton, further altering the functioning and biogeochemistry of shallow pelagic ecosystems and, in particular, reducing their potential for carbon sequestration (see Chapter VII.6, Plankton, for further information).⁷⁵⁶

With regard to ocean acidification, the negative responses of corals and coccolithophores to ocean acidification could have profound repercussions for marine ecosystems, with scleractinian corals serving as habitat for coral reef ecosystems and coccolithophores serving as the foundation of its food web.⁷⁵⁷

Region-wide

Several reviewers requested information on whether the “sardine” or “anchovy” regime described previously is likely for the future. However, Chavez et al. (2003) do not make projections about which regime is more likely in the future. Instead, they note that studies of anthropogenic effects and management of ocean resources must consider natural, multidecadal oscillations.⁷⁵⁸ As an example, they state overfishing or global warming may alter the response of populations to natural multidecadal change.⁷⁵⁹

Gulf of Alaska LME

With some assurance that oxygen levels will continue to decline (and nutrient levels increase), Whitney et al. (2007) state it is reasonable to project that continental shelf and slope ecosystems in the subarctic Pacific Ocean will lose oxygenated habitat if coastal upwelling strengthens.⁷⁶⁰ For example:

- The few fish species such as sablefish and some rock fishes that tolerate low oxygen may expand their territory, but in general mid-water organisms will be forced to find shallower habitat or

⁷⁵² Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525-1526)

⁷⁵³ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite López-Urrutia et al. (2006) for information on the sensitivity of respiration to temperature, and refer the reader to Figure 3, A to F, in the cited publication.

⁷⁵⁴ Verbatim or nearly verbatim from ISAB. (2007, p. 69)

⁷⁵⁵ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite López-Urrutia et al. (2006) for this information.

⁷⁵⁶ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Morán et al. (2010) for information on the size of individual phytoplankton.

⁷⁵⁷ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1428)

⁷⁵⁸ Verbatim or nearly verbatim from Chavez et al. (2003, p. 221)

⁷⁵⁹ Verbatim or nearly verbatim from Chavez et al. (2003, p. 221)

⁷⁶⁰ Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 191)

perish.⁷⁶¹ This will increase competition for resources and may expose some species to greater predation from above.⁷⁶²

California Current Ecosystem

The source waters that feed into the California Current from the north and offshore can exert some control over the phytoplankton and zooplankton species that dominate the current.⁷⁶³ A particular biological concern identified by Peterson and Schwing (2008) is variability in the transport of organisms, which impacts zooplankton species composition and regional recruitment patterns for demersal (bottom-dwelling) fish stocks.⁷⁶⁴ Waters from the Gulf of Alaska carry large, lipid-rich copepods to the shelf waters, whereas waters coming from an offshore source carry small, oceanic lipid-poor copepods to the shelf waters.⁷⁶⁵ When the PDO is in the warm phase, a greater proportion of the water entering the northern end of the Current is sub-tropical in character rather than sub-Arctic (i.e. originating from offshore rather than the Gulf of Alaska).⁷⁶⁶ Based on ongoing observations, a positive PDO (corresponding to warmer ocean conditions in the California Current) results in dominance of small warm-water zooplankton (which are lipid-depleted) which may result in food chains with lower bioenergetic content.⁷⁶⁷

By about 2030, it is expected that the minima ocean temperatures due to decadal variability will be above the historical mean of the 20th Century (i.e., the greenhouse gas warming trend will be as large as natural variability).⁷⁶⁸ Thus changes reflected by PDO shifts may result in local food chains that have vastly different bio-energetic content.⁷⁶⁹

Information Gaps

Information is needed on observed trends in the Gulf of Alaska LME and globally. Quantitative future projections for the NPLCC region are also needed, as the information presented here only discusses the possible direction and magnitude of future change. High-resolution coastal ocean/atmosphere models are needed to resolve important processes (e.g., coastal upwelling, eddies, coastal wind features) in conjunction with global models or as nested components of global models. Chavez et al. (2003) state that unraveling the processes behind multidecadal variability and how they affect ocean ecosystems and biogeochemical cycling will require a concerted and integrated observational and modeling effort.⁷⁷⁰ Measurement networks, analogous to those established by meteorologists, will be required for ocean physics, ecology, and biogeochemistry.⁷⁷¹ As longer time series are collected and integrated into a basin-

⁷⁶¹ Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 191)

⁷⁶² Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 191)

⁷⁶³ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 59). The authors refer the reader to Figure 5 in the cited report.

⁷⁶⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁶⁵ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 59)

⁷⁶⁶ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 59)

⁷⁶⁷ Peterson, W. & Schwing, F. (2008, p. 45)

⁷⁶⁸ Peterson, W. & Schwing, F. (2008, p. 45)

⁷⁶⁹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 59)

⁷⁷⁰ Verbatim or nearly verbatim from Chavez et al. (2003, p. 221)

⁷⁷¹ Verbatim or nearly verbatim from Chavez et al. (2003, p. 221)

scale or global view, longer period fluctuations may be uncovered.⁷⁷² These time series will help answer many of the fundamental questions associated with regime shifts.⁷⁷³

Peterson and Schwing (2008) identify a number of information gaps for the California Current region:

- The combined impact of ocean warming and increased acidification on pelagic habitat requires data on the factors that contribute to upper ocean stratification.⁷⁷⁴ These include coastal wind (for estimating wind stress, mixing, and latent heat exchange), air-sea heat fluxes, and streamflow and freshwater discharge throughout the CCE region.⁷⁷⁵
- High-resolution synoptic mapping of ocean variables that define biological “hot spots” must be maintained to monitor changes in the pelagic habitat and relations to climate variability.⁷⁷⁶
- Regional models with reliable precipitation and stream flow projections are necessary to model future coastal pelagic ocean conditions.⁷⁷⁷
- IPCC projections of future temperature and stratification are needed to allow long-term estimates of changes in upper ocean structure and productivity, which will determine the pelagic habitat for many coastal species.⁷⁷⁸

⁷⁷² Verbatim or nearly verbatim from Chavez et al. (2003, p. 221)

⁷⁷³ Verbatim or nearly verbatim from Chavez et al. (2003, p. 221)

⁷⁷⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁷⁵ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁷⁶ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁷⁷ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁷⁸ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 58)

4. MULTIPLE STRESSORS AND THRESHOLDS: DISCUSSION

Although most of the ocean is undergoing impacts from multiple anthropogenic stressors, little is known about the potential for large-scale synergisms (or antagonisms).⁷⁷⁹ Even additive effects have great potential to overwhelm key species and entire ecosystems.⁷⁸⁰ Recent evidence suggests that there is now a growing risk that several thresholds will soon be exceeded.⁷⁸¹ Carbon dioxide concentrations of 400 to 450 ppm or a +3.6°F (+2°C) increase in average global temperature above pre-industrial values have been identified as thresholds for key ocean components such as aragonite undersaturation of the Southern Ocean, loss of polar sea ice, and the melting of the Greenland and Western Antarctic ice sheets.⁷⁸² From 2000 to 2004, the actual emissions trajectory was close to that of the high-emissions A1F1 scenario (nearly 1000 ppm⁷⁸³).⁷⁸⁴ A new study by Arora et al. (2011) suggests that limiting warming to roughly 3.6°F (2.0°C) by 2100 is unlikely since it requires an immediate ramp down of emissions followed by ongoing carbon sequestration after 2050.⁷⁸⁵

Multiple stressors and thresholds were identified as climate-related concerns for marine and coastal ecosystems globally⁷⁸⁶ and information specific to the NPLCC region was available for the California Current Ecosystem.⁷⁸⁷

Eastern boundary upwelling systems, such as the California Current System (CCS) are naturally more acidic than most of the rest of the surface ocean.⁷⁸⁸ Recent research suggests systems like the CCS are particularly vulnerable to future ocean acidification.⁷⁸⁹ However, ocean acidification is just one of several stress factors, which include hypoxia, anomalous sea surface temperatures, pollution, and overfishing:⁷⁹⁰

- Increasing SST and stratification tend to enhance low-oxygen (i.e. potentially hypoxic) conditions in the CCS, adding another stressor, with resultant cascading effects on benthic (bottom-dwelling) and pelagic (open ocean) ecosystems.⁷⁹¹
- Ocean deoxygenation due to the effects of reduced production of mineral ballast by calcifying organisms could substantially amplify the impact of ocean acidification on marine ecosystems in the CCS.⁷⁹²

⁷⁷⁹ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1528). The authors cite Halpern et al. (2008) for information on multiple anthropogenic stressors and Darling and Côté (2008) for information on large-scale synergisms or antagonisms.

⁷⁸⁰ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1528)

⁷⁸¹ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1528). The authors cite Rockström et al. (2009) for this information.

⁷⁸² Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1528). The authors cite McNeil et al. (2008) for information on the Southern Ocean, Wang and Overland (2009) for information on polar sea ice, Gregory et al. (2004) for information on Greenland, and Naish et al. (2009) for information on Western Antarctica.

⁷⁸³ Meehl et al. (2007, p. 803). This information was extrapolated from Figure 10.26 by the authors of this report.

⁷⁸⁴ Raupach et al. *Global and regional drivers of accelerating CO₂ emissions*. (2007)

⁷⁸⁵ Verbatim or nearly verbatim from Arora et al. *Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases*. (2011)

⁷⁸⁶ Hoegh-Guldberg and Bruno. (2010)

⁷⁸⁷ Hauri et al. (2009)

⁷⁸⁸ Verbatim or nearly verbatim from Hauri et al. (2009, p. 60)

⁷⁸⁹ Verbatim or nearly verbatim from Hauri et al. (2009, p. 61)

⁷⁹⁰ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68)

⁷⁹¹ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68-69). The authors cited Bograd et al. (2008) for this information.

However, when assessing the potential vulnerability of organisms and ecosystems to ocean acidification in the CCS, it is important to consider that organisms are already frequently exposed to water with low pH and saturation levels (of aragonite and calcite, important for shell formation), especially during upwelling events and in nearshore regions.⁷⁹³ Furthermore, the growth and success of an individual species in a changing ocean depends on many environmental factors.⁷⁹⁴

Information Gaps

Information is needed on observed trends and future projections for the Gulf of Alaska LME and the California Current Ecosystem, as the information presented here is a discussion only.

⁷⁹² Verbatim or nearly verbatim from Hauri et al. (2009, p. 69). The authors cited Brewer and Peltzer (2009) for this information.

⁷⁹³ Verbatim or nearly verbatim from Hauri et al. (2009, p. 66)

⁷⁹⁴ Verbatim or nearly verbatim from Hauri et al. (2009, p. 66)

V. IMPLICATIONS FOR COASTAL NEARSHORE HABITATS & ECOSYSTEMS

Waves, currents, and sediment supply are the primary controls on coastal evolution; any changes in global climate which alter the timing and magnitude of storms and/or raise global sea level will have severe consequences for beaches, coastlines, and coastal structures.⁷⁹⁵ Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, the following implications of climate change for coastal nearshore habitats and ecosystems in the NPLCC region have been identified:

1. Altered patterns of coastal erosion and increased coastal squeeze
2. Altered sedimentation patterns
3. Habitat loss, degradation, and conversion

Many physical processes important for determining nearshore habitat characteristics will be affected by climate change.⁷⁹⁶ Climate change will also affect biological processes important for nearshore habitat.⁷⁹⁷ The affected physical and biological processes include:

- Significant sea level rise and storm surge will adversely affect coastal ecosystems; low-lying and subsiding areas are most vulnerable.⁷⁹⁸
- Storms may also have increased precipitation intensity; this would increase both erosion and salinity stress for coastal marine ecosystems.⁷⁹⁹
- Changes in salinity and temperature and increased sea level, atmospheric CO₂, storm activity and ultraviolet irradiance alter sea grass distribution, productivity and community composition.⁸⁰⁰
- Changes in precipitation could change nutrient loading and sediment accumulation.⁸⁰¹
- Changes in water temperature, water salinity, or soil salinity beyond the tolerance of certain plants could change the mix of plant species in salt marshes and the viability of invertebrates (e.g., crab, shrimp and sponges) that play a key role in the health and functioning of nearshore systems.⁸⁰²

Among the most clear and profound influences of climate change on the world's oceans are its impacts on habitat-forming species such as corals, sea grass, mangroves, salt marsh grasses, and oysters.⁸⁰³ Collectively, these organisms form the habitat for thousands of other species.⁸⁰⁴ Projected changes would

⁷⁹⁵ Verbatim or nearly verbatim from Adams and Inman. *Climate change hotspots and potential hotspots of coastal erosion along the southern California coast: Final Paper (CEC-500-2009-022-F)*. (2009, p. 1)

⁷⁹⁶ Verbatim or nearly verbatim from Snover et al. (2005, p. 29)

⁷⁹⁷ Verbatim or nearly verbatim from Snover et al. (2005, p. 29)

⁷⁹⁸ Verbatim or nearly verbatim from Karl, Melillo and Peterson. (2009, p. 149)

⁷⁹⁹ Verbatim or nearly verbatim from Hoffman. (2003, p. 135)

⁸⁰⁰ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 329). The authors cite Short and Neckles (1999) for this information.

⁸⁰¹ Verbatim or nearly verbatim from Snover et al. (2005, p. 29)

⁸⁰² Verbatim or nearly verbatim from Snover et al. (2005, p. 29)

⁸⁰³ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1526)

⁸⁰⁴ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1526)

fundamentally alter the region's coastal habitats and the species they support.⁸⁰⁵ Some species may be able to respond to changes by finding alternative habitats or food sources, but others will not.⁸⁰⁶

The following structure will be used to present information on the implications of climate change for the NPLCC region's coastal nearshore habitats and ecosystems:

- **Observed Trends** – observed changes at the global level and for each jurisdiction in the NPLCC geography (Alaska, British Columbia, Washington, Oregon, California).
- **Future Projections** – projected direction and/or magnitude of change at the global level and for each jurisdiction in the NPLCC geography
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

⁸⁰⁵ Verbatim or nearly verbatim from Glick, Clough and Nunley. *Sea level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon.* (2007, p. v)

⁸⁰⁶ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. v)

1. ALTERED PATTERNS OF COASTAL EROSION AND INCREASED COASTAL SQUEEZE

Observed Trends

Global

Information needed.

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

The Washington Climate Change Impacts Assessment (WACCIA) reports that natural rates of erosion vary widely among locations in Washington State: in Island County, fifty-one percent of the shoreline is classified as “unstable”,⁸⁰⁷ as opposed to twenty percent of Bainbridge Island⁸⁰⁸ and only three percent of San Juan County.⁸⁰⁹ The Southwest Washington Coastal Erosion Project has identified several erosion “hot spots”.⁸¹⁰ These are located at the south end of Ocean Shores; near the southern jetty at the Grays Harbor entrance north of Westport; at the north end of the Long Beach peninsula (Leadbetter Point); and just north of the Columbia River entrance near Fort Canby.⁸¹¹

Examples of erosion rates (landward progression) from different areas of Washington include:

- In Island County, erosion rates have been measured from 0.30 inches (1 cm) to more than two feet (0.61 meters) per year.⁸¹²
- On Whidbey Island, typical erosion rates are approximately 1.2 inches per year (3 cm/yr).⁸¹³ Recently, high waves have caused large amounts of erosion on Whidbey Island, particularly in drift cells on the southeastern portion of the island and on large spits on Cultus Bay.⁸¹⁴
- On Bainbridge Island, bluff erosion rates are generally between two and six inches per year (5-15 cm/yr), depending on physical characteristics such as beach profile, substrate, and slope angle, as

⁸⁰⁷ Verbatim or nearly verbatim from Huppert et al. *Impacts of climate change on the coasts of Washington State*. (2009, p. 294). The authors cite Shipman (2004) for this information.

⁸⁰⁸ Verbatim or nearly verbatim from Huppert et al. (2009, p. 296). The authors cite Shipman (2004) for this information.

⁸⁰⁹ Verbatim or nearly verbatim from Huppert et al. (2009, p. 296). The authors cite Shipman (2004) for this information.

⁸¹⁰ Verbatim or nearly verbatim from Huppert et al. (2009, p. 292)

⁸¹¹ Verbatim or nearly verbatim from Huppert et al. (2009, p. 292)

⁸¹² Verbatim or nearly verbatim from Huppert et al. (2009, p. 294). The authors cite Island County (2006) for this information.

⁸¹³ Verbatim or nearly verbatim from Huppert et al. (2009, p. 294)

⁸¹⁴ Verbatim or nearly verbatim from Huppert et al. (2009, p. 295). The authors cite Johannessen and MacLennan (2007) for this information.

well as the presence or absence of human-built protective structures such as bulkheads.⁸¹⁵ As on Whidbey Island, bluff erosion events are episodic.⁸¹⁶ After heavy rains and soil saturation, Bainbridge Island has experienced a number of bluff erosion events.⁸¹⁷

- Bluff erosion rates are negligible in San Juan County.⁸¹⁸
- At Washaway Beach (formerly known as Shoalwater Bay) at the north entrance of Willapa Bay, 65 feet per year (19.7 m/yr) of beach have been lost, on average, since the 1880s.⁸¹⁹
- High erosion rates have also been observed at Ocean Shores, just north of Cape Leadbetter (more precise data not provided).⁸²⁰

Beach erosion appears to occur when large waves approach at a steeper angle from the south, especially during El Niño conditions, when winter sea level is as much as one foot (0.3 m) higher than July levels.⁸²¹ Researchers also suspect that higher storm waves are reaching the southwest Washington coast due to a northward shift in the storm track as a consequence of broader global climate changes.⁸²² Hence, there are at least three possible factors contributing to erosion along the beaches of southwest Washington, (a) reduced sediment supply; (b) gradual SLR as a longer-term factor, and (c) northward shift in Pacific winter storm tracks.⁸²³ Increased storm intensity may be an additional climate-related factor, but there is less than broad agreement among the climate scientists about the relative importance of these factors.⁸²⁴

Oregon

Information needed.

Northwest California

Information needed.

Future Projections

Global

Global climate change may accelerate coastal erosion due to sea level rise and increased wave height.⁸²⁵ Shifts in storm tracks as a result of climate change may alter wind patterns, such that waves hit the beach with more force or from new directions (resulting in new patterns of erosion).⁸²⁶ An acceleration in sea

⁸¹⁵ Verbatim or nearly verbatim from Huppert et al. (2009, p. 296). The authors cite City of Bainbridge Island (2007) for this information.

⁸¹⁶ Verbatim or nearly verbatim from Huppert et al. (2009, p. 296)

⁸¹⁷ Verbatim or nearly verbatim from Huppert et al. (2009, p. 296)

⁸¹⁸ Verbatim or nearly verbatim from Huppert et al. (2009, p. 296). The authors cite Shipman (2004) for this information.

⁸¹⁹ Huppert et al. (2009, p. 292)

⁸²⁰ Verbatim or nearly verbatim from Huppert et al. (2009, p. 292)

⁸²¹ Verbatim or nearly verbatim from Huppert et al. (2009, p. 292)

⁸²² Verbatim or nearly verbatim from Huppert et al. (2009, p. 292)

⁸²³ Verbatim or nearly verbatim from Huppert et al. (2009, p. 292-293)

⁸²⁴ Verbatim or nearly verbatim from Huppert et al. (2009, p. 293)

⁸²⁵ Huppert et al. (2009)

⁸²⁶ Carter, L. *U.S. National Assessment of the Potential Consequences of Climate Variability and Change. Educational Resources Regional Paper: Pacific Northwest (website)*. (2003).

level rise will widely exacerbate beach erosion around the globe, although the local response will depend on the total sediment budget.⁸²⁷ Specific findings include:

- **For sandy beaches**, the major long-term threat worldwide is coastal squeeze, which leaves beaches trapped between erosion and rising sea level on the wet side and encroaching development from expanding human populations on land, thus leaving no space for normal sediment dynamics.⁸²⁸ It is not expected that predicted temperature changes will have dramatic effects on the world's beaches by 2025, but the expected rise in sea level, if coupled with an increase in the frequency and/or intensity of storms, as predicted for some regions, is likely to lead to escalating erosion and consequent loss of habitat.⁸²⁹
- **Gravel beaches** are threatened by sea level rise, even under high accretion rates.⁸³⁰ The persistence of gravel and cobble boulder beaches will also be influenced by storms, tectonic events and other factors that build and reshape these highly dynamic shorelines.⁸³¹
- **Hard rock cliffs** have a relatively high resistance to erosion, while cliffs formed in softer lithologies are likely to retreat more rapidly in the future due to increased toe erosion resulting from sea level rise.⁸³²
- **Soft rock cliff** stability is affected by four physical features of climate change – temperature, precipitation, sea level and wave climate.⁸³³ For soft cliff areas with limited beach development, there appears to be a simple relationship between long-term cliff retreat and the rate of sea level rise, allowing useful predictions for planning purposes.⁸³⁴

Coastal squeeze refers to the squeeze of coastal ecosystems between rising sea levels and naturally or artificially fixed shorelines, such as beaches lacking adequate sediment supply backed by coastal bluffs and nearshore areas prohibited from upland migration by hard engineering defenses. This results in loss of shallow water habitat. For example, loss of birds from some estuaries appears to be the result of coastal squeeze and relative SLR. Adaptation activities such as creation or restoration of intertidal habitat may help to offset losses due to coastal squeeze.

Source: Nicholls et al. (2007); Parry et al. (2007)

⁸²⁷ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 324). The authors cite Brown and MacLachlan (2002) for information on SLR and exacerbated beach erosion, and Stive et al. (2002) and Cowell et al. (2003a,b) for information on the sediment budget and local response.

⁸²⁸ Verbatim or nearly verbatim from Defeo et al. *Threats to sandy beach ecosystems: a review*. (2009, p. 8)

⁸²⁹ Brown and McLachlan. *Sandy shore ecosystems and the threats facing them: some predictions for the year 2025*. (2002, p. 62)

⁸³⁰ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 325). The authors cite Orford et al. (2001, 2003) and Chadwick et al. (2005) for information on SLR and gravel beaches. The authors cite Codignotto et al. (2001) for information on high accretion rates, SLR, and gravel beaches.

⁸³¹ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 325). The authors cite Orford et al. (2001) for this information.

⁸³² Verbatim or nearly verbatim from Nicholls et al. (2007, p. 325-326). The authors cite Cooper and Jay (2002) for this information.

⁸³³ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 326). The authors cite Cowell et al. (2006) for this information.

⁸³⁴ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 326). The authors cite Walkden and Dickson (2006) for this information.

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

The severity of coastal erosion is expected to increase as a result of sea level rise and intensification of storm activity.⁸³⁵ Sea level rise will shift coastal beaches inland and increase erosion of unstable bluffs.⁸³⁶ On Whidbey Island, future possible impacts include increased bluff erosion and landslide, and inundation.⁸³⁷ On Bainbridge Island, inundation and, to a lesser extent, bluff erosion are possible.⁸³⁸ Willapa Bay would see possible increases in shoreline erosion.⁸³⁹ In the San Juan Islands, while there are some unstable bluffs vulnerable to erosion and landslides, the resistance of bedrock bluffs to wave action erosion makes it unlikely that an increase in SLR will significantly affect bluff erosion patterns.⁸⁴⁰

Oregon

By the mid 21st century the projected increase in rates of SLR are expected to exceed the rates of uplift of the land all along the Oregon coast, resulting in erosion even where at present there have been little or no erosion impacts.⁸⁴¹ The scenario as to when enhanced erosion and flooding begins at a specific coastal site, and the magnitude of that enhancement, depends however on the contributions by other oceanic processes and their climate controls, particularly the increase in storm intensities and the heights of their generated waves.⁸⁴²

Increased erosion along Oregon's ocean shore from rising sea levels and coastal storms may seriously alter beaches, and in some cases, the infrastructure necessary for safe access to and from beaches and coastal parks.⁸⁴³ Beach and bluff erosion will result in shoreline retreat.⁸⁴⁴ Some portions of Oregon's ocean shorelines have been armored against erosion from ocean waves, primarily in front of properties developed before 1977.⁸⁴⁵ As shorelines erode landward in response to higher sea level and storms, armored properties are at risk of becoming peninsulas, then islands, and then overtopped.⁸⁴⁶ An increase

⁸³⁵ Verbatim or nearly verbatim from Bauman et al. *Impacts of climate change on Washington's economy: a preliminary assessment of risks and opportunities (pdf)*. (2006)

⁸³⁶ Verbatim or nearly verbatim from Littell et al. *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate - Executive Summary*. (2009, p. 16)

⁸³⁷ Verbatim or nearly verbatim from Littell et al. (2009, p. 16)

⁸³⁸ Verbatim or nearly verbatim from Littell et al. (2009, p. 16)

⁸³⁹ Verbatim or nearly verbatim from Littell et al. (2009, p. 16)

⁸⁴⁰ Verbatim or nearly verbatim from Huppert et al. (2009, p. 296)

⁸⁴¹ Verbatim or nearly verbatim from Ruggiero et al. (2010, p. 218)

⁸⁴² Verbatim or nearly verbatim from Ruggiero et al. (2010, p. 218). The authors cite Ruggiero (2008) for this information.

⁸⁴³ Verbatim or nearly verbatim from OCMP. (2009, p. 14)

⁸⁴⁴ Verbatim or nearly verbatim from OCMP. (2009, p. 17)

⁸⁴⁵ Verbatim or nearly verbatim from OCMP. (2009, p. 14)

⁸⁴⁶ Verbatim or nearly verbatim from OCMP. (2009, p. 14)

in significant wave heights is likely to damage or cause failure of some hardened shorelines, potentially resulting in damage to nearby unprotected property and infrastructure.⁸⁴⁷

Northwest California

On behalf of the Pacific Institute, Philip Williams & Associates, Ltd. assessed California’s coastal erosion response to sea level rise.⁸⁴⁸ Their analysis projects dune and cliff erosion for California’s coastal counties.⁸⁴⁹ Del Norte, Humboldt, Mendocino, and Sonoma counties are in the NPLCC region.⁸⁵⁰ With approximately 4.6 feet of sea level rise (1.4 meters), dune and cliff erosion across all four of these counties is projected to total 21.1 square miles (54.7 km²), with 6.9 square miles (18 km², 33%) attributable to dune erosion and 14.1 square miles (36.4 km², 67%) attributable to cliff erosion.⁸⁵¹ Table 19 lists projected dune and cliff erosion by county.

Table 19. Erosion area with a 4.6 ft (1.4 m) sea level rise, by county.
Source: Table modified from Philip Williams and Associates, Ltd. (2009, Table 4, p. 17) by authors of this report.

County	Dune erosion miles ² (km ²)	Cliff erosion miles ² (km ²)	Total erosion miles ² (km ²)
Del Norte	1.9 (4.9)	2.6 (6.7)	4.5 (11.7)
Humboldt	3.7 (9.6)	2.4 (6.2)	6.1 (15.8)
Mendocino	0.7 (1.9)	7.5 (19.4)	8.3 (21.5)
Sonoma	0.6 (1.6)	1.6 (4.1)	2.2 (5.7)
Total	6.9 (18)	14.1 (36.4)	21.1 (54.7)

Information Gaps

Information is needed on regional trends and projections for coastal erosion throughout the geographic extent of the NPLCC, particularly quantitative data for the extent of current and projected erosion at different locations with the NPLCC geography. Information is also needed on global trends and projections for coastal erosion.

⁸⁴⁷ Verbatim or nearly verbatim from OCOMP. (2009, p. 14)

⁸⁴⁸ Philip Williams and Associates, Ltd. *California Coastal Erosion Response to Sea level Rise - Analysis and Mapping.* (2009, Table 4, p. 17)

⁸⁴⁹ Philip Williams and Associates, Ltd. *California Coastal Erosion Response to Sea level Rise - Analysis and Mapping.* (2009)

⁸⁵⁰ California State Association of Counties. *CA County Map.* Available at <http://www.counties.org/default.asp?id=6> (accessed 6.10.2011).

⁸⁵¹ Philip Williams and Associates, Ltd.. *California Coastal Erosion Response to Sea level Rise - Analysis and Mapping.* (2009, Table 4, p. 17)

2. ALTERED SEDIMENTATION PATTERNS

Observed Trends

Global

Deltas, some of the largest sedimentary deposits in the world, are widely recognized as highly vulnerable to the impacts of climate change, particularly sea level rise and changes in runoff, as well as being subject to stresses imposed by human modification of catchment and delta plain land use.⁸⁵² Most deltas are already undergoing natural subsidence that results in accelerated rates of relative sea level rise above the global average.⁸⁵³ Many are impacted by the effects of water extraction and diversion, as well as declining sediment input as a consequence of entrapment in dams.⁸⁵⁴ Dikes built in river deltas to “reclaim” marsh areas impact physical processes associated with sediment, water, and organic material movement, both inside and outside of the diked area.⁸⁵⁵

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwest California

Information needed.

Future Projections

Global

The IPCC AR4 states climate change and sea level rise affect sediment transport in complex ways and abrupt, non-linear changes may occur as thresholds are crossed.⁸⁵⁶ In situations where the area of intertidal environments has been reduced by embanking or reclamation, the initial response will be a lowering of remaining tidal flats and infilling of tidal channels.⁸⁵⁷ Depending on tidal characteristics, the

⁸⁵² Verbatim or nearly verbatim from Nicholls et al. (2007, p. 327)

⁸⁵³ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 327)

⁸⁵⁴ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 327)

⁸⁵⁵ Hood. (2004)

⁸⁵⁶ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 320). The authors cite Alley et al. (2003) for this information.

⁸⁵⁷ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328)

availability of marine sediment, and the rate of sea level rise, the remaining tidal flats may either be further drowned, or their relative level in the tidal frame may be maintained.⁸⁵⁸

If sea level rises slowly, the balance between sediment supply and morphological adjustment can be maintained if a saltmarsh accretes, or a lagoon infills, at the same rate.⁸⁵⁹ An acceleration in the rate of sea level rise may mean that morphology cannot keep up, particularly where the supply of sediment is limited, as for example when coastal floodplains are inundated after natural levees or artificial embankments are overtopped.⁸⁶⁰ Exceeding the critical sea level thresholds can initiate an irreversible process of drowning.⁸⁶¹

An indirect, less-frequently examined influence of sea level rise on the beach sediment budget is due to the infilling of coastal embayments.⁸⁶² As sea level rises, estuaries and lagoons attempt to maintain equilibrium by raising their bed elevation in tandem, and hence potentially act as a major sink of sand which is often derived from the open coast.⁸⁶³ This process can potentially cause erosion an order of magnitude or more greater than that predicted by the Bruun model (which suggests shoreline recession is in the range of 50 to 200 times the rise in relative sea level), implying the potential for major coastal instability due to sea level rise in the vicinity of tidal inlets.⁸⁶⁴

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Pacific Northwest

Information needed. Inundation of tidal flats in some areas would reduce stopover and wintering habitat for migratory shorebirds.⁸⁶⁵ It could also have a major impact on the economically-important shellfish industry.⁸⁶⁶

Northwest California

Information needed.

⁸⁵⁸ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328). The authors cite Dronkers (2005) for this information.

⁸⁵⁹ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 320)

⁸⁶⁰ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 320)

⁸⁶¹ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 320). The authors cite Williams et al. (1999), Doyle et al. (2003), and Burkett et al. (2005) for this information.

⁸⁶² Verbatim or nearly verbatim from Nicholls et al. (2007, p. 324)

⁸⁶³ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 324) The authors cite van Goor et al. (2001), van Goor et al. (2003), and Stive (2004) for this information.

⁸⁶⁴ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 324) The authors cite Woodworth et al. (2004) for information on the Bruun model projections in comparison to infilling of coastal embayments. The definition of the Bruun model is also on p. 324.

⁸⁶⁵ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. v)

⁸⁶⁶ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. v)

Information Gaps

Information is needed on observed sedimentation patterns in the NPLCC region, as well as projected sedimentation patterns throughout the NPLCC region.

3. HABITAT LOSS, DEGRADATION, AND CONVERSION

Observed Trends

Global

In their report on global climate change in aquatic ecosystems, Poff et al. (2002) note coastal wetland ecosystems are among the most altered and threatened natural systems.⁸⁶⁷ Important impacts include increased nutrient loading leading to eutrophication, direct loss through habitat destruction, changes in hydrology, introduction of toxic materials, and changes in species composition due to over-harvest and introduction of new species.⁸⁶⁸

During periods of sea level rise, coastal wetlands can persist only when they accrete soil vertically at a rate at least equal to water-level rise.⁸⁶⁹ A number of studies have shown that coastal marshes are indeed able to accrete at a rate equal to the historical rate of sea level rise (0.04-0.08 inches per year; 1-2 mm/year) and persist for hundreds to thousands of years.⁸⁷⁰ However, many rivers emptying into coastal estuaries now carry only a fraction of the inorganic sediment that they did historically.⁸⁷¹

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwest California

Information needed. Most coastal wetland loss has been due to draining and filling.⁸⁷² In some coastal states, such as California, almost all coastal wetlands have been lost.⁸⁷³

⁸⁶⁷ Verbatim or nearly verbatim from Poff, Brinson and Day. (2002, p. 23)

⁸⁶⁸ Verbatim or nearly verbatim from Poff, Brinson and Day. (2002, p. 23-24). The authors cite Day et al. (1989), Mitsch and Gosselink (1993), and Neumann et al. (2000) for this information.

⁸⁶⁹ Verbatim or nearly verbatim from Poff, Brinson and Day. (2002, p. 25). The authors cite Cahoon et al. (1995a) for this information.

⁸⁷⁰ Verbatim or nearly verbatim from Poff, Brinson and Day. (2002, p. 26). The authors cite Gornitz et al. (1982) for the historical rate of SLR and Redfield (1972), McCaffey and Thompson (1980), and Orson et al. (1987) for information on wetland persistence.

⁸⁷¹ Verbatim or nearly verbatim from Poff, Brinson and Day. (2002, p. 26)

⁸⁷² Verbatim or nearly verbatim from Poff, Brinson and Day. (2002, p. 24)

⁸⁷³ Verbatim or nearly verbatim from Poff, Brinson and Day. (2002, p. 24)

Future Projections

Global

Coastal vegetated wetlands are sensitive to climate change and long-term sea level change as their location is intimately linked to sea level.⁸⁷⁴ Global mean sea level rise will generally lead to higher relative coastal water levels and increasing salinity in estuarine systems, thereby tending to displace existing coastal plant and animal communities inland.⁸⁷⁵ Instead of migrating inland, estuarine plant and animal communities may persist as sea level rises if migration is not blocked and if the rate of change does not exceed the capacity of natural communities to adapt or migrate.⁸⁷⁶ Climate change impacts on one or more “leverage species,” however, can result in sweeping community level changes.⁸⁷⁷

Climate change will likely have its most pronounced effects on brackish and freshwater marshes in the coastal zone through alteration of hydrological regimes,⁸⁷⁸ specifically, the nature and variability of hydroperiod and the number and severity of extreme events.⁸⁷⁹ Other variables – altered biogeochemistry, altered amounts and pattern of suspended sediments loading, fire, oxidation of organic sediments, and the physical effects of wave energy – may also play important roles in determining regional and local impacts.⁸⁸⁰ Specific impacts identified in the IPCC AR4 include:

- Modeling of all coastal wetlands (but excluding sea grasses) by McFadden et al. (2007) suggests global losses from 2000 to 2080 of thirty-three percent and forty-four percent given a 14 inch (0.36 m) and 28 inch (0.72 m) rise in sea level, respectively.⁸⁸¹
- Sea grasses appear to be declining around many coasts due to human impacts, and this is expected to accelerate if climate change alters environmental conditions in coastal waters.⁸⁸²
- Increases in the amount of dissolved CO₂ and, for some species, bicarbonate (HCO₃⁻) present in aquatic environments, will lead to higher rates of photosynthesis in submerged aquatic vegetation, similar to the effects of CO₂ enrichment on most terrestrial plants, if nutrient availability or other limiting factors do not offset the potential for enhanced productivity.⁸⁸³ Please see Chapter VII.5, Eelgrass, for more specific information on the impacts of climate change in seagrasses.

⁸⁷⁴ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328)

⁸⁷⁵ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328)

⁸⁷⁶ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328)

⁸⁷⁷ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328). The authors cite Harley et al. (2006) for this information.

⁸⁷⁸ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 329). The authors cite Burkett and Kusler (2000), Baldwin et al. (2001), and Sun et al. (2002) for this information.

⁸⁷⁹ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 329)

⁸⁸⁰ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 329)

⁸⁸¹ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 328)

⁸⁸² Verbatim or nearly verbatim from Nicholls et al. (2007, p. 329). The authors cite Duarte (2002) for this information.

⁸⁸³ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 329)

Southcentral Alaska

In Alaska, changes in sea level and increases in storms and erosion could result in the following habitat impacts:

- Low-lying habitats critical to the productivity and welfare of coastal dependent species could be lost.⁸⁸⁴
- Low-lying coastal staging areas that support millions of shorebirds, geese, and ducks during spring and fall staging could degrade.⁸⁸⁵ This includes areas in the Stikine Delta, Cook Inlet marshes, and the Copper River Delta and barrier islands.⁸⁸⁶
- If brackish/salt intrusion is restored to the Copper River Delta, reversion to graminoid sedge marsh from current shrub/forest succession could occur.⁸⁸⁷ Positive changes for dusky Canada geese may result.⁸⁸⁸

A study by Glick et al. (2010) using the Sea level Affecting Marshes Model (SLAMM, version 6, see Box 16) projects widespread changes to coastal habitats in Cook Inlet.⁸⁸⁹ SLAMM 6 was run using the A1B-mean scenario, which predicts approximately 1.3 feet (0.40 m) of global sea level rise (SLR) by 2100.⁸⁹⁰ SLAMM was also run assuming 3.28 feet (1 m), 4.92 feet (1.5 m), and 6.56 feet (2 m) of eustatic SLR (sea level rise due to changes in ocean mass and volume) by the year 2100 to accommodate the recent literature suggesting that the rate of sea level rise is likely to be higher than the 2007 IPCC projections.⁸⁹¹ Six sites in Cook Inlet were evaluated, four on the Kenai Peninsula and two near Anchorage.⁸⁹² The study results underscore the fact that Alaska poses unique challenges for sea level rise modeling (e.g. significant data gaps, especially high quality elevation data, and coarse quality of some other data inputs).⁸⁹³

For the Kenai study region as a whole, less than one percent of dry land is predicted to be lost to the effects of sea level rise.⁸⁹⁴ Between zero and two percent of the total study area swamp lands are predicted to be lost across all scenarios.⁸⁹⁵ While the site is predicted to lose fourteen percent of its tidal flat, some of this may have occurred since the late 1970s.⁸⁹⁶ Substantial losses of ocean beach seem to be triggered at eustatic (due to changes in ocean mass/volume) rates of sea level rise above 4.92 feet (1.5 m).⁸⁹⁷

⁸⁸⁴ Verbatim or nearly verbatim from AK State Legislature. (2008, p. 91). Report by the Alaska State Legislature, available online at http://www.housemajority.org/coms/cli/cli_final_report_20080301.pdf (last accessed 12.14.2010).

⁸⁸⁵ Verbatim or nearly verbatim from AK State Legislature. (2008, p. 91)

⁸⁸⁶ Verbatim or nearly verbatim from AK State Legislature. (2008, p. 91)

⁸⁸⁷ Verbatim or nearly verbatim from AK State Legislature. (2008, p. 92)

⁸⁸⁸ Verbatim or nearly verbatim from AK State Legislature. (2008, p. 92)

⁸⁸⁹ Glick, Clough and Nunley. (2010)

⁸⁹⁰ Glick, Clough and Nunley. (2010, p. 3)

⁸⁹¹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 3). The authors cite Grinstead et al. (2009), Vermeer and Rahmstorf (2009), and Pfeffer and O'Neel (2008) for information suggesting the rate of SLR is likely to be higher than the 2007 IPCC projections.

⁸⁹² Glick, Clough and Nunley. (2010)

⁸⁹³ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 1)

⁸⁹⁴ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 8)

⁸⁹⁵ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 8)

⁸⁹⁶ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 8)

⁸⁹⁷ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 8)

Box 16. SLAMM: Alternatives & Limitations.

SLAMM simulates dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise (SLR). Within later versions of SLAMM (5.0, 6.0, 6.0.1 Beta), five primary processes can affect wetland fate under different scenarios of SLR: inundation, erosion, overwash, saturation, and salinity.

Key limitations include no mass balance of solids, no models of seagrasses or marine flora, it is not a detailed bathymetrical model, there is no concept of “marsh health,” accretion rates are based on an empirical relationship, feedbacks among variables are not modeled, and it lacks a socioeconomic component for estimating the costs of SLR.

Alternatives to SLAMM include the Kirwan marsh model, the USGS Coastal Vulnerability Index, BTELSS, the more straight-forward “bathtub” models, and support tools such as the Dynamic Interactive Vulnerability Assessment Tool and SimCLIM. See Appendix 4. Sea level Affecting Marshes Model (SLAMM): Limitations, Improvements, & Alternatives for further information.

Sources: *Clough, Park & Fuller. (2010); Glick, Clough & Nunley (2010); Glick, Clough & Nunley (2007); Kirwan & Guntenaspergen. (2009); Mcleod et al. (2010); Warren Pinnacle Consulting, Inc. (2010a); Warren Pinnacle Consulting, Inc. (2010b).*

At the four sites on the Kenai Peninsula, the following changes are projected by Glick et al. (2010):

- Erosion of tidal flats and reformulation of ocean beach at Fox River Flats, Eastern Kachemak Bay.⁸⁹⁸
- Conversion of freshwater swamps to transitional salt marsh as the south portion of the study site in Chickaloon Bay falls below the salt boundary.⁸⁹⁹
- The freshwater swamps along the Kenai River near the Town of Kenai are predicted to start to show salinity effects, especially under the highest rate of sea level rise estimated (6.56 feet, or 2 meters by 2100).⁹⁰⁰
- Some saline intrusion of the dry lands and swamps to the east of the river at the Northern Coho/Kasilof site are predicted, especially under higher eustatic scenarios of sea level rise.⁹⁰¹

For the Anchorage study site as a whole, results from Glick et al. (2010) show only minor susceptibility to the effects of sea level rise.⁹⁰² Dry land, which comprises slightly more than one-third of the study area, is calculated to lose between two and three percent of its initial land coverage across all SLR scenarios.⁹⁰³ Swamp lands – which comprise roughly four percent of the study area – are predicted to lose between four and ten percent of their initial land coverage across all SLR scenarios.⁹⁰⁴

Projections for the two sites in the Anchorage area include:

- North of Chugiak, near Birchwood Airport, the dry lands and swamps at the north end of the study area are predicted to be subject to saline inundation, especially under the highest scenarios run.⁹⁰⁵
- At the Anchorage sub-site, the most substantial

predictions seem to be the potential inundation of developed land at the northern portion of the study site in the Ship Creek/Port of Anchorage area and the potential vulnerability of the tidal swamp northwest of Potter Marsh, under the more aggressive prediction of a eustatic sea level rise of 6.56 feet (2 m).⁹⁰⁶

⁸⁹⁸ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 9)

⁸⁹⁹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 10)

⁹⁰⁰ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 11)

⁹⁰¹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 12)

⁹⁰² Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 13)

⁹⁰³ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 13)

⁹⁰⁴ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 13)

⁹⁰⁵ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 14)

⁹⁰⁶ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2010, p. 15)

British Columbia

Information needed.

Washington and northwest Oregon

Estimates of sea level rise for the Puget Sound suggest that on beaches with armored shoreline substantial surf smelt spawning habitat might be lost in the next few decades and most spawning habitat might be lost by 2100.⁹⁰⁷ A Puget Sound study suggests sea level rise is likely to cause substantial loss of surf smelt spawning habitat on beaches with armored shorelines because armoring prevents beach migration inland, thereby reducing the area of beach with elevations preferred for spawning.⁹⁰⁸

Using the SLAMM 5.0 model, Glick et al. (2007) projected widespread changes to coastal habitats in eleven sites around the Puget Sound (WA), southwest Washington, and northwest Oregon.⁹⁰⁹ Model results vary considerably by site, but overall the region is likely to face a dramatic shift in the extent and diversity of its coastal marshes, swamps, beaches, and other habitats due to sea level rise.⁹¹⁰ For example, if global average sea level increases by 27.3 inches (0.69 m), the following impacts are predicted by 2100 across the sites investigated:

- Estuarine beaches will undergo inundation and erosion to total a sixty-five percent loss.
- As much as forty-four percent of tidal flat will disappear.⁹¹¹
- Thirteen percent of inland fresh marsh and twenty-five percent of tidal fresh marsh will be lost.⁹¹²
- Eleven percent of inland swamp will be inundated with salt water, while sixty-one percent of tidal swamp will be lost.⁹¹³
- Fifty-two percent of brackish marsh will convert to tidal flats, transitional marsh and saltmarsh.⁹¹⁴
- Two percent of undeveloped land will be inundated or eroded to other categories across all study areas.⁹¹⁵

Localized impacts of 27.3 inches (0.69 m) of SLR by 2100 across six sites illustrate the variability in these results:

- **Ediz Hook near Port Angeles (WA), through the Dungeness Spit and Sequim Bay:** Tidal flats at this site are extremely vulnerable, as is Dungeness Spit itself, especially to higher sea level rise scenarios in which complete loss of the spit is predicted.⁹¹⁶ Additionally, over fifty-eight percent of area beaches (estuarine and ocean together) are predicted to be lost by 2100 under all scenarios.⁹¹⁷

⁹⁰⁷ Verbatim or nearly verbatim from Krueger et al. *Anticipated effects of sea level rise in Puget Sound on two beach-spawning fishes.* (2010, p.176)

⁹⁰⁸ Verbatim or nearly verbatim from Krueger et al. (2010, p.171). The authors cite Griggs and others (1994) for information on SLR, armoring, beach migration inland, and habitat loss.

⁹⁰⁹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007)

⁹¹⁰ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. iii)

⁹¹¹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. iii)

⁹¹² Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. iii)

⁹¹³ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁴ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁵ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. iii)

⁹¹⁶ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹¹⁷ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

- **Dyes Inlet, Sinclair Inlet, and Bainbridge Island (WA):** Most dry land in this portion of Puget Sound is of sufficient elevation to escape conversion even in the more aggressive sea level rise scenarios.⁹¹⁸ Over half of beach land is predicted to be lost, however, primarily converted to tidal flats.⁹¹⁹ Saltmarsh and transitional marsh increase, primarily due to loss of dry land.⁹²⁰
- **Elliott Bay and the Duwamish Estuary (WA):** Limited effects are predicted for the Seattle area due to a higher density of development and high land elevations overall.⁹²¹ However, 300 to 400 hectares (741-988 acres; 3-4 km²) of dry land are predicted to be at risk of being converted to transitional marsh, saltmarsh, and tidal flats.⁹²² In addition, fifty-five percent of estuarine beach at this site could be lost by 2100 under this scenario.⁹²³ Understandably, the assumption that developed areas will be protected from the effects of sea level rise is significant at this site which is nearly fifty percent composed of developed land.⁹²⁴ If the protection of developed land was not assumed, regions along the Duwamish Waterway and Harbor Island would be subject to additional inundation effects, especially under scenarios with higher rates of sea level rise.⁹²⁵
- **Annas Bay and Skokomish Estuary (WA):** High land elevations for dry land and swamp make this site less likely to be influenced by sea level rise than many of the other sites studied.⁹²⁶ The most significant change is loss of estuarine beaches, which decline by about one-third under all scenarios.⁹²⁷
- **Commencement Bay, Tacoma, and Gig Harbor (WA):** The Tacoma area is well protected by dikes around the Puyallup River, so results of sea level rise are limited near that river.⁹²⁸ Three to four percent of undeveloped land is predicted to be lost at this site overall, though, converting to transitional marsh and saltmarsh.⁹²⁹ Over two-thirds of area beaches are predicted to be lost by 2100 due to erosion and inundation.⁹³⁰
- **Olympia, Budd Inlet, and Nisqually Delta (WA):** The largest predicted changes for this site pertain to the loss of estuarine beach and the inundation of some dry lands.⁹³¹ Estuarine beach, in particular, declines by eighty-one percent.⁹³² As with the other sites, all developed lands (including Olympia) are assumed to remain protected.⁹³³

Impacts on the remaining sites (Bellingham Bay, Skagit Bay, Willapa Bay, and the Lower Columbia River; see Figure 18 and Figure 19) have been re-analyzed by Ducks Unlimited using LiDAR (Light Detection And Ranging, a technology for assessing elevation using lasers) and a newer version of

⁹¹⁸ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹¹⁹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²⁰ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²¹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²² Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²³ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. iv)

⁹²⁴ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. 57)

⁹²⁵ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. 57)

⁹²⁶ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹²⁷ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. 60)

⁹²⁸ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹²⁹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³⁰ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³¹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³² Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. v)

⁹³³ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, Table 1, p. v)

SLAMM (version 6.0).⁹³⁴ Grays Harbor was also analyzed.⁹³⁵ Given a global average sea level rise of 27.3 inches (0.69 meters) under the A1B scenario, preliminary results from this ongoing project indicate that, across the study sites, substantial increases in transitional marsh (+12,101 acres, or 266%), and decreases in saltmarsh (-533 acres, or 2%), freshwater tidal areas (-3953 acres, or 24%), and low tidal areas (-60,766 acres, or 58%) are likely by 2100 (Table 20).⁹³⁶

Significant local results include loss of two-thirds of low tidal areas in Willapa Bay and Grays Harbor, and a loss of eleven to fifty-six percent of freshwater tidal marsh in Grays Harbor, Puget Sound, and Willapa Bay (see Figure 18 for Willapa Bay results).⁹³⁷ Much of these habitats are replaced by transitional marsh.⁹³⁸ The Lower Columbia River may be the most resilient site of those studied because losses to low tidal, saltmarsh, and freshwater tidal habitats are minimized, while gains in transitional areas are substantial (Figure 19).⁹³⁹

Changes in the composition of tidal wetlands could significantly diminish the capacity for those habitats to support salmonids, especially juvenile Chinook and chum salmon.⁹⁴⁰ A significant reduction in the area of estuarine beaches, for example, would affect important spawning habitat for forage fish, which make up a critical part of the marine food web.⁹⁴¹ Unless species are able to find alternative spawning areas, their populations could decline.⁹⁴² Further, loss of coastal marshes would affect habitat for thousands of wintering waterfowl that visit the region each year.⁹⁴³

⁹³⁴ Ducks Unlimited, Inc. (DU). *Update of Puget Sound SLAMM Analysis*. (2010d); DU. *SLAMM Analysis of Willapa Bay, Washington*. (2010c); DU. *SLAMM Analysis of the Lower Columbia River, Washington and Oregon*. (2010b). All reports are unpublished technical reports.

⁹³⁵ DU. *SLAMM Analysis of Grays Harbor, Washington (unpublished technical report)*. (2010a)

⁹³⁶ The DU analysis grouped habitat types as follows. *Low tidal* areas include estuarine beach, tidal flats, vegetated tidal flats, ocean beaches, and ocean flats. *Saltmarsh* includes saltmarshes. *Transitional marsh* includes irregularly flooded marsh and scrub/shrub areas. *Freshwater tidal areas* include tidal swamps and tidal/fresh marshes.

⁹³⁷ DU. (2010a); DU. (2010c); DU. (2010d)

⁹³⁸ DU. (2010a); DU. (2010c); DU. (2010d)

⁹³⁹ DU. (2010b)

⁹⁴⁰ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. v)

⁹⁴¹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. v)

⁹⁴² Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. v)

⁹⁴³ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. v)

Table 20. Changes to the Area of Four Coastal Habitats in Washington & Oregon.

	Current Area (acres)	Projected Area (acres)	Total Change (acres)	Percent Change
Whatcom, Skagit Bay, and Snohomish, WA				
Low tidal areas	10623	8723	-1900	-18
Saltmarsh	5701	5836	135	2
Transitional areas	637	2133	1496	235
Freshwater tidal areas	1569	937	-632	-40
Grays Harbor, WA				
Low tidal areas	37646	12271	-25375	-67
Saltmarsh	2758	3716	958	35
Transitional areas	1135	6373	5238	461
Freshwater tidal areas	6993	5317	-1676	-24
Willapa Bay, WA				
Low tidal areas	50268	16889	-33379	-66
Saltmarsh	7806	7307	-499	-6
Transitional areas	1972	6046	4074	207
Freshwater tidal areas	1653	724	-929	-56
Lower Columbia River, WA/OR				
Low tidal areas	5545	5433	-112	-2
Saltmarsh	5975	4848	-1127	-19
Transitional areas	810	2103	1293	160
Freshwater tidal areas	6370	5654	-716	-11
All Study Sites				
Low tidal areas	104082	43316	-60766	-58
Saltmarsh	22240	21707	-533	-2
Transitional areas	4554	16655	12101	266
Freshwater tidal areas	16585	12632	-3953	-24
<i>Data Source: Ducks Unlimited (table created by authors of this report)</i>				

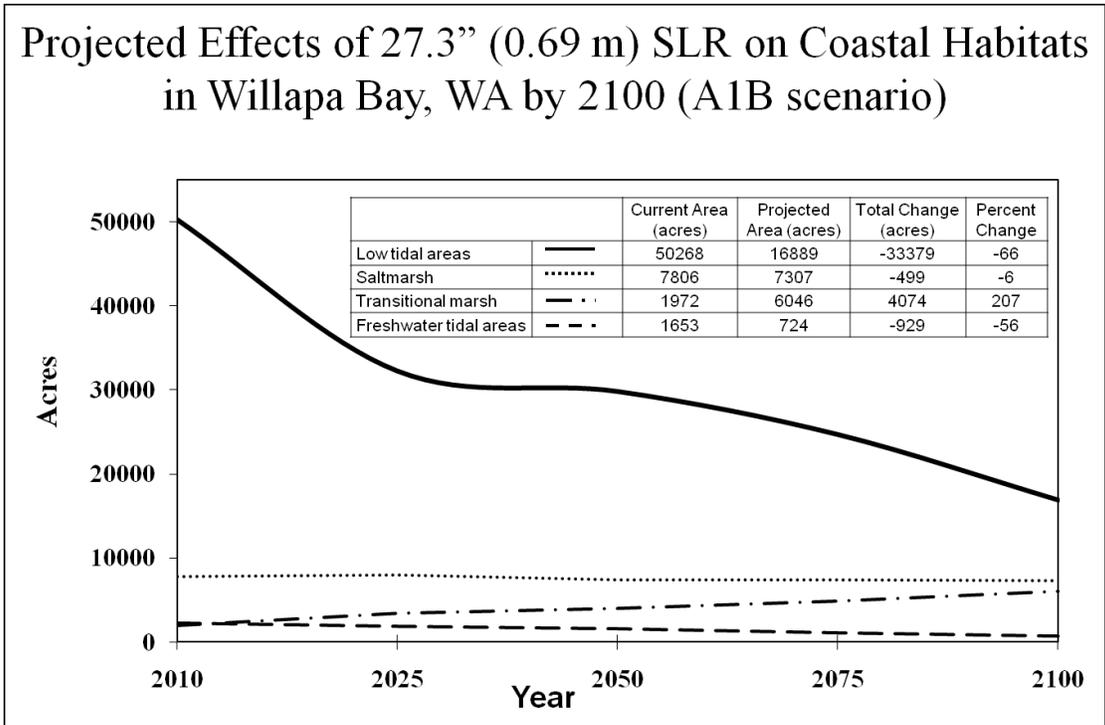


Figure 18. Projected effects of 27.3 inches (0.69 meters) sea level rise on coastal habitats in Willapa Bay, WA by 2100 (A1B scenario). *Data Source: Ducks Unlimited (figure created by authors of this report)*

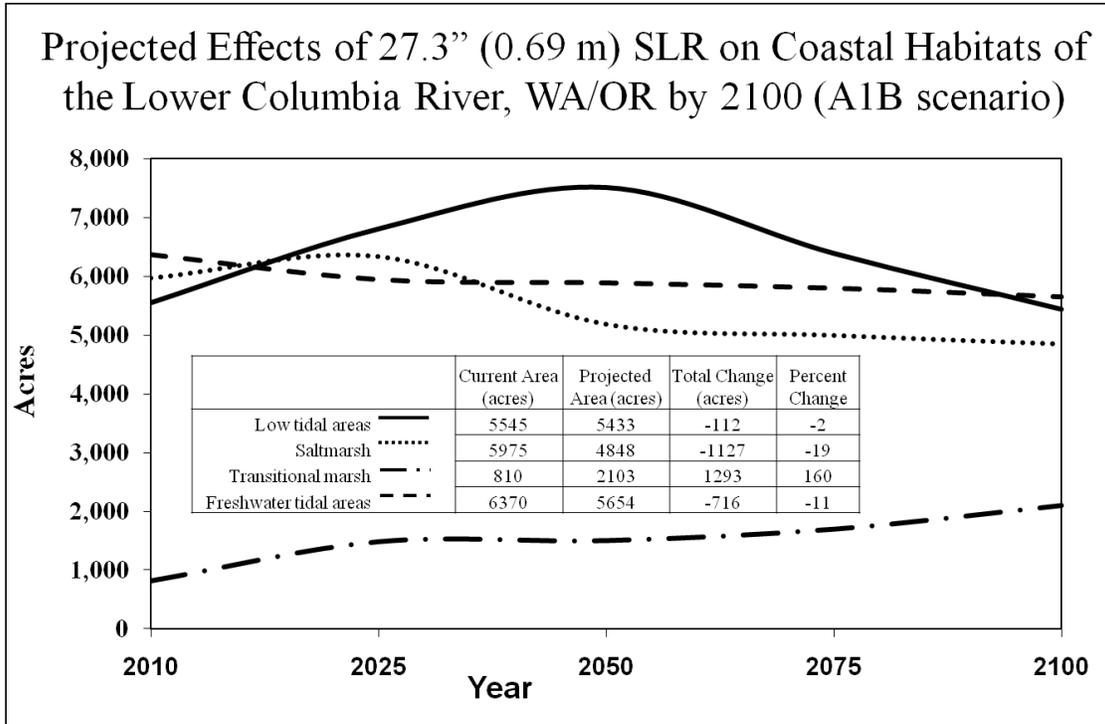


Figure 19. Projected effects of 27.3 inches (0.69 meters) sea level rise on coastal habitats in the Lower Columbia River (WA and OR) by 2100 (A1B scenario).

Data Source: Ducks Unlimited (figure created by authors of this report)

Northwest California

In a study by Galbraith et al. (2005) using SLAMM 4.0 under three sea level rise scenarios, current and projected future percent changes in intertidal and upland habitat at Humboldt Bay were assessed.⁹⁴⁴ One reviewer from California noted LiDAR data was not used in this analysis.⁹⁴⁵ The three scenarios are:

- The historical rate of sea level change (based on actual past sea level changes at the site),⁹⁴⁶
- A higher-probability scenario of approximately 13 inches (34 cm) of sea level rise by 2100 (assumes 3.6°F or 2°C of warming), and
- A lower-probability scenario of approximately 30 inches (77 cm) of sea level rise by 2100 (assumes 8.5°F or 4.7°C of warming).⁹⁴⁷

By 2050 and 2100, the following habitat changes in Humboldt Bay are projected:⁹⁴⁸

- **Tidal flats in 2050:** Compared to the 2005 value of approximately 2664 acres, losses of approximately 2.7 acres (-0.1%) under the historic scenario, 346.3 acres (-13.0%) under the high-probability scenario, and 1129.5 (-42.4%) acres under the low-probability scenario are projected.
- **Tidal flats in 2100:** Compared to the 2005 value of approximately 2664 acres, losses of approximately 2.7 acres (-0.1%) under the historic scenario, 761.8 acres (-28.6%) under the high-probability scenario, and 2432.2 acres (-91.3%) are projected.
- **Salt marsh in 2050:** Compared to the 2005 value of approximately 99 acres, gains of approximately 71.9 (+72.6%) under the historic scenario, 87.9 acres (+88.9%) under the high-probability scenario, and 226.9 acres (+229.2%) are projected.
- **Salt marsh in 2100:** Compared to the 2005 value of approximately 99 acres, gains of approximately 71.9 acres (+72.6%) under the historic scenario, 173.6 acres (+175.6%) under the high-probability scenario, and 1867.1 acres (+1,886%) under the low-probability scenario are projected.
- **Upland and other habitat types in 2050:** Compared to the 2005 value of approximately 31,506 acres, losses of 63.0 acres (-0.2%) under the historic scenario, 94.5 acres (-0.3%) under the high-probability scenario, and 220.5 acres (-0.7%) under the low-probability scenario are projected.
- **Upland and other habitat types in 2100:** Compared to the 2005 value of approximately 31,506 acres, losses of approximately 63.0 (-0.2%) under the historic scenario, 189.0 (-0.6%) under the high-probability scenario, and 1890.4 acres (-6.0%) are projected.

Information Gaps

Information is needed on observed trends throughout the NPLCC and globally. Updated projections for the northern California coast, as well as information on projected habitat loss, degradation, and/or conversion in coastal British Columbia, are also needed. Lastly, additional projections throughout the NPLCC region would be helpful, as this section presents results from single studies.

⁹⁴⁴ Galbraith et al. (2005, p. 1121). Information obtained from Table 1 in the cited report.

⁹⁴⁵ Personal communication, Reviewer (January 2011)

⁹⁴⁶ Verbatim or nearly verbatim from Galbraith et al. (2005, p. 1121). Information obtained from Table 1 in the cited report.

⁹⁴⁷ Verbatim or nearly verbatim from Galbraith et al. (2005, p. 1120).

⁹⁴⁸ Galbraith et al. (2005).

VI. IMPLICATIONS FOR SPECIES, POPULATIONS, & COMMUNITIES

The growth and success of an individual species in a changing ocean depends on many environmental factors.⁹⁴⁹ Moderate increases in temperature increase metabolic rates, which ultimately determine life history traits, population growth, and ecosystem processes.⁹⁵⁰ For increases in global average temperature exceeding 2.7 to 4.5°F (1.5 to 2.5°C) and in concomitant atmospheric CO₂ concentrations, there are projected to be major changes in ecosystem structure and function, species' ecological interactions and shifts in species' geographical ranges, with predominantly negative consequences for biodiversity and ecosystem goods and services, e.g. water and food supply.⁹⁵¹ Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, the following implications of climate change for species, populations, and communities in the NPLCC region have been identified:

1. Shifts in species range and distribution
2. Altered phenology and development
3. Shifts in community composition, competition, and survival
4. Altered interaction with non-native and invasive species

The following structure will be used to present information on the implications of climate change for the NPLCC region's species, populations, and communities.:

- **Observed Trends** – observed changes for the Gulf of Alaska Large Marine Ecosystem (LME) and the California Current Ecosystem (CCE). A few sections also include information on changes observed globally.
- **Future Projections** – projected direction and/or magnitude of change for the Gulf of Alaska LME and the CCE. A few sections also include information on global future projections.
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

Chapter VII discusses implications for key fish, wildlife, plants, plankton, and shellfish in the NPLCC region.

⁹⁴⁹ Verbatim or nearly verbatim from Hauri et al. (2009, p. 66)

⁹⁵⁰ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525)

⁹⁵¹ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 48)

1. SHIFTS IN SPECIES RANGE AND DISTRIBUTION

Observed Trends

Global

The distribution of fish and planktonic species are predominantly determined by climatic variables, and there is recent evidence that marine species are moving poleward, and that timing of plankton blooms is shifting (Figure 20).⁹⁵² Similar patterns have been observed in invertebrates and plant communities.⁹⁵³

Gulf of Alaska LME and California Current Ecosystem

Since 2003, jumbo squid have been frequently reported in beach strandings, commercial and recreational fisheries, and resource surveys along the West Coast and through southeast Alaska.⁹⁵⁴ During the 1997–98 El Niño event, jumbo squid were observed in substantial numbers off California, as well as in coastal waters off of Oregon and Washington states.⁹⁵⁵ In situ video observations taken from remotely operated vehicle (ROV) surveys from the Monterey Bay region show that jumbo squid continue to be present and sporadically abundant since the 1997–98 El Niño, particularly between 2003 and 2006.⁹⁵⁶

On the Quileute and Hoh reservations (WA), a study by Papiez (2009) reports that some potential range shifts have already been observed in avian and marine species:⁹⁵⁷

- The loggerhead turtle (*Caretta caretta*) was indicated as a new, unusual sighting by Quileute fishermen and other local people.⁹⁵⁸
- The leatherback turtle (*Dermochelys coriacea*) has been sighted during El Niño years, which is very rare and unusual according to local ecological knowledge (LEK) and traditional ecological knowledge (TEK) (see Box 17).⁹⁵⁹

TEK indicates that these new species were not present during the time of their Quileute and Hoh ancestors:⁹⁶⁰

- According to many interviews with elders, LEK, tribal fishermen, and natural resource staff, the brown pelicans are a new arrival to the coast.⁹⁶¹ The consensus arrival time was around the mid-

⁹⁵² Verbatim or nearly verbatim from Janetos et al. (2008, p. 164). The authors cite Hay et al. (2005) and Roessig et al. (2004) for information on climatic variables and distribution, and Beaugrand et al. (2002), Hays et al. (2005), and Richardson and Schoeman (2004) for information on poleward movements and the timing of plankton blooms.

⁹⁵³ Verbatim or nearly verbatim from Janetos et al. (2008, p. 164). The authors cite Beaugrand et al. (2002) and Sagarin et al. (1999) for this information.

⁹⁵⁴ Field et al. (2007, p. 132). The authors cite Cosgrove (2005), Brodeur et al. (2006), and Wing (2006) for this information.

⁹⁵⁵ Field et al. (2007, p. 132). The authors cite Pearcy (2002) for this information.

⁹⁵⁶ Field et al. (2007, p. 132)

⁹⁵⁷ Papiez. *Climate Change Implications for the Quileute and Hoh Tribes* (pdf). (2009, p. 13)

⁹⁵⁸ Verbatim or nearly verbatim from Papiez. (2009, p. 15). The author cites Moon (2008), J. Schumack (2008), and Williams (2008) as the Quileute fishermen interviewed. The author cites Dickerson (2008) and G. Johnson (2008) as the local people interviewed.

⁹⁵⁹ Verbatim or nearly verbatim from Papiez. (2009, p. 15). The author cites G. Johnson (2008) as the LEK interviewee and Moon (2008) and Ratcliff (2008) as the TEK interviewees.

⁹⁶⁰ Verbatim or nearly verbatim from Papiez. (2009, p. 17)

1980s.⁹⁶² Now, the brown pelican has begun to stay longer on the coast.⁹⁶³ They are now arriving during the second or third week in June and departing the last week in October.⁹⁶⁴

The sunfish or common mola (*Mola mola*) were frequently referred to as a new arrival to the coast by Quileute and Hoh fishermen.⁹⁶⁵ Sunfish were first seen during strong El Niño years, but have now been present during the cooler La Niña cycle.⁹⁶⁶

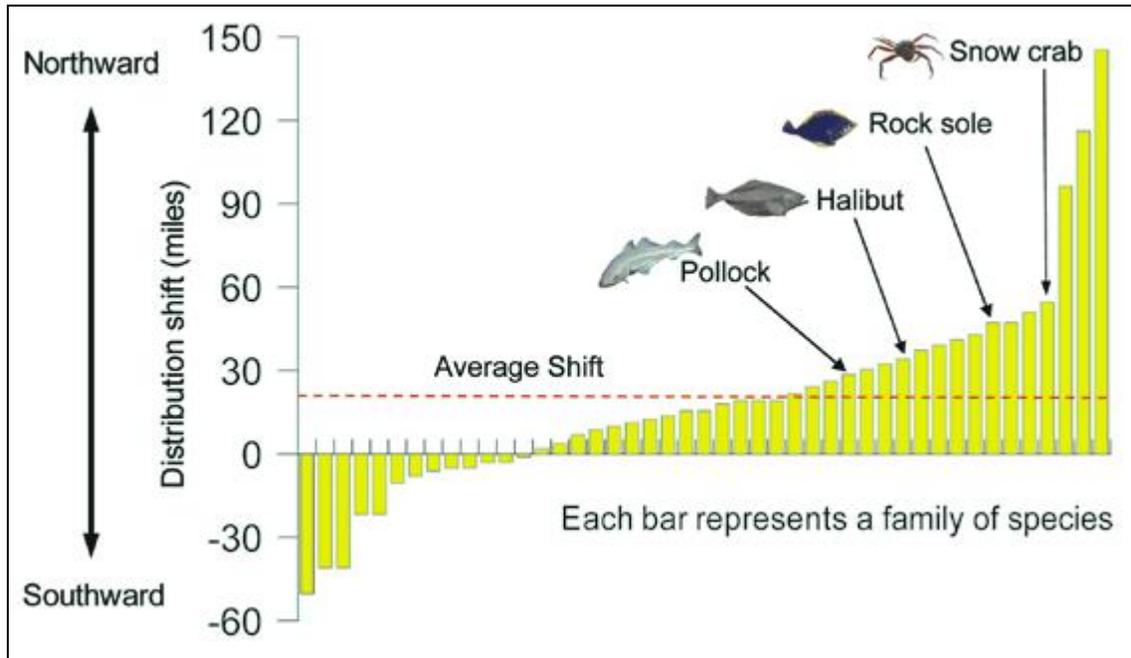


Figure 20. Marine Species Shifting Northward: As air and water temperatures rise, marine species are moving northward, affecting fisheries, ecosystems, and coastal communities that depend on the food source. On average, by 2006, the center of the range for the examined species moved nineteen miles north of their 1982 locations. *Source: Reproduced from Karl, Melillo, and Peterson. (2009, p. 144) by authors of this report.*

⁹⁶¹ Verbatim or nearly verbatim from Papiez. (2009, p. 13). The author cites Jackson (2008), Matson (2008), Morganroth III (2008) as the elders interviewed. The author cites Dickerson (2008), B. Johnson (2008), G. Johnson (2008), and Payne (2008) as the LEK interviewees. The author cites Moon (2008), Ratcliff (2008), and J. Schumack (2008) as the tribal fishermen interviewed. The author cites Geyer (2008) and Northcut (2008) as the natural resource staff interviewed.

⁹⁶² Verbatim or nearly verbatim from Papiez. (2009, p. 13). The author cites interviews with Moon (2008), Morganroth III (2008), and Payne (2008) for this information.

⁹⁶³ Verbatim or nearly verbatim from Papiez. (2009, p. 13)

⁹⁶⁴ Verbatim or nearly verbatim from Papiez. (2009, p. 13). The author cites interviews with Geyer (2008), Moon (2008), Morganroth III (2008), and Penn Jr. (2008) for this information.

⁹⁶⁵ Verbatim or nearly verbatim from Papiez. (2009, p. 16). The author cites Black III (2008), Moon (2008), Morganroth III (2008), Ratcliff (2008), Sampson (2008), and Williams (2008) as the Quileute and Hoh fishermen interviewed.

⁹⁶⁶ Verbatim or nearly verbatim from Papiez. (2009, p. 16)

Box 17. Indigenous science, and traditional and local ecological knowledge.

Traditional knowledge (also known as indigenous science), as a way of knowing, is similar to Western science in that it is based on an accumulation of observations, but it is different from Western science in some fundamental ways. Interest in traditional ecological knowledge (TEK) has grown in recent years, partly due to a recognition that such knowledge can contribute to the conservation of biodiversity, rare species, protected areas, ecological processes, and to sustainable resource use in general. Cajete provides a working definition of indigenous science and TEK:

Indigenous science is that body of traditional environmental and cultural knowledge that is unique to a group of people and that has served to sustain those people through generations of living within a distinct bioregion. This is founded on a body of practical environmental knowledge learned and transformed through generations through a form of environmental and cultural education unique to them. Indigenous science may also be termed “traditional environmental knowledge” (TEK), since a large proportion of this knowledge served to sustain Indigenous communities and ensure their survival within the environmental contexts in which they were situated.

Local ecological knowledge (LEK), on the other hand, is knowledge based on a shorter timescale than TEK. Both Native and non-Native inhabitants of an area may hold LEK. Their residence and occupations may bring them into close proximity with the environment. Natural resources staff and land managers, particularly those who have studied the area for longer periods of time, often hold LEK.

Many of the prescriptions of traditional knowledge and practice are generally consistent with adaptive management as an integrated method for resource and ecosystem management. It is adaptive because it acknowledges that environmental conditions will always change, requiring societies to respond by adjusting and evolving. In fact, some scholars caution against overemphasizing the differences between Western science and traditional knowledge. However, others argue TEK and Western science cannot be integrated and cannot be bridged. For more information on climate change adaptation planning for natural systems, please see *Chapter VIII. Sources: Papież (2009); Berkes, Colding, and Folke (2000); Wall (2009).*

Future Projections

Global

Information needed.

Gulf of Alaska LME and California Current

Climate change may have a large impact on the distribution of maximum catch potential – a proxy for potential fisheries productivity – by 2055.⁹⁶⁷ Redistribution of catch potential is driven by projected shifts in species’ distribution ranges and by the change in total primary production within the species’ exploited range.⁹⁶⁸ Ocean warming and the retreat of sea ice in high-latitude regions opens up new habitat for lower

⁹⁶⁷ Verbatim or nearly verbatim from Cheung et al. *Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change.* (2010, p. 31)

⁹⁶⁸ Verbatim or nearly verbatim from Cheung et al. *Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change.* (2010, p. 31). The authors cite Sarmiento et al. (2004) and Cheung et al. (2008a) for this information.

latitude species and thus may result in a net increase in catch potential.⁹⁶⁹ In subtropical and temperate regions, cold-water species are replaced by warm-water species, rendering the trend in catch potential changes in these regions generally weaker than in tropical, high-latitude and polar regions.⁹⁷⁰

Based on an empirical model published by Cheung et al. (2008), Cheung et al. (2010) project:

- Both increases and decreases in the ten-year average maximum catch potential in 2055, relative to 2005, in the NPLCC region (A1B scenario; Figure 21).⁹⁷¹
- In general, decreases of five to thirty-one percent are projected for the coastal waters, with the exception of southeast Alaska, which ranges from small decreases (<6%) to >100% increases.⁹⁷²
- In offshore areas, increases of >100% are projected for the northern and southeastern Gulf of Alaska, while decreases of five to thirty-one percent interspersed with increases of up to thirty percent are projected farther south.⁹⁷³

In the CCE, generally warmer ocean conditions will cause a northward shift in the distribution of most species, and possibly the creation of reproductive populations in new regions.⁹⁷⁴ Existing faunal boundaries (i.e., zones of rapid changes in species composition, e.g. the waters between Cape Blanco, OR and Cape Mendocino, CA) are likely to remain as strong boundaries, but their resiliency to shifts in ocean conditions due to global climate change is not known.⁹⁷⁵

Information Gaps

Information is needed on observed changes in the Gulf of Alaska LME as well as in other areas of the California Current Ecosystem. More specific future projections are needed throughout the NPLCC region, e.g. for particular species and communities.

⁹⁶⁹ Verbatim or nearly verbatim from Cheung et al. (2010, p. 31)

⁹⁷⁰ Verbatim or nearly verbatim from Cheung et al. (2010, p. 31)

⁹⁷¹ Cheung et al. (2010, Fig. 1, p. 28)

⁹⁷² Cheung et al. (2010, Fig. 1, p. 28)

⁹⁷³ Cheung et al. (2010, Fig. 1, p. 28)

⁹⁷⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 55)

⁹⁷⁵ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 55)

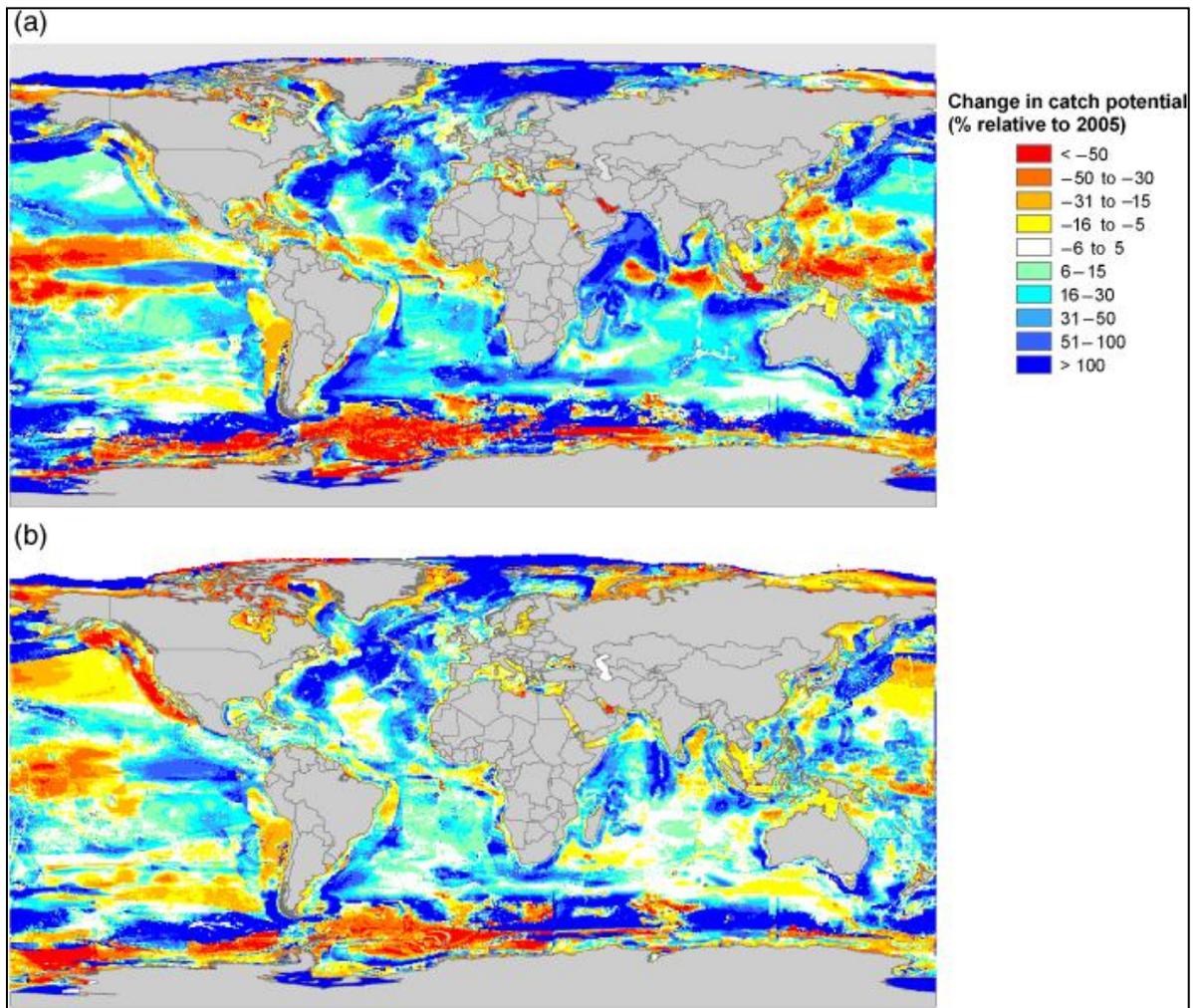


Figure 21. Change in maximum catch potential (10-year average) from 2005 to 2055 in each 30' x 30' cell under climate change scenarios: (a) Special Report on Emission Scenarios A1B and (b) stabilization at 2000 level.
Source: Reproduced from Cheung et al. (2010, Fig. 1, p. 28) by authors of this report.

2. ALTERED PHENOLOGY AND DEVELOPMENT

Observed Trends

Global

In a meta-analysis of the effects of ocean acidification on marine organisms, Kroeker et al. (2010) conclude that ocean acidification had a significant negative effect on survival, calcification, growth and reproduction in marine organisms, but no significant effect on photosynthesis.⁹⁷⁶ Results for survival are found in the next section, results for calcification are found in Chapter VII.4 (Shellfish), and results for photosynthesis are found in Chapter IV.2 (Altered ocean productivity). Results for growth and developmental stages are reported here:

- **Growth:** The effect of ocean acidification on growth varied between calcifying organisms and non-calcifying organisms as well as amongst taxonomic groups.⁹⁷⁷ Ocean acidification had a significant negative mean effect on the growth of calcifiers, but a significant effect on non-calcifiers was not detected.⁹⁷⁸ Within calcifiers, ocean acidification had a significant negative mean effect on calcifying algae and corals, and a non-significant negative mean effect on coccolithophores, molluscs and echinoderms.⁹⁷⁹ There was a significant positive mean effect on fish and fleshy algae, and a non-significant positive effect on crustaceans.⁹⁸⁰
- **Developmental Stages:** No differences were detected amongst developmental stages in any of the response variables besides survival.⁹⁸¹ However, significant differences were detected amongst developmental stages within specific taxonomic groups (molluscs, echinoderms and crustaceans).⁹⁸² For molluscs, there was a larger negative effect for larvae than adults regarding survival.⁹⁸³ For echinoderms, there was a larger negative effect for juveniles than larvae in growth responses.⁹⁸⁴ For crustaceans, there was a larger negative effect for adults than juveniles in survival.⁹⁸⁵

Gulf of Alaska LME

Information needed.

⁹⁷⁶ Verbatim or nearly verbatim from Kroeker et al. *Meta-analysis reveals negative yet variable effects on ocean acidification on marine organisms*. (2010, p. 1424). The authors refer the reader to Fig. 1 in the cited report.

⁹⁷⁷ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 2 & 3 in the cited report and provide statistics for results for growth ($Q_M = 14.5$, d.f. = 1, $P = 0.004$) and taxonomic groups ($Q_M = 56.09$, d.f. = 7, $P < 0.001$).

⁹⁷⁸ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424-1425)

⁹⁷⁹ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425)

⁹⁸⁰ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425)

⁹⁸¹ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 4 in the cited report.

⁹⁸² Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 6 in the cited report.

⁹⁸³ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 6 in the cited report and provide statistics for this result: $Q_M = 2.92$, d.f. = 2, $P = 0.05$.

⁹⁸⁴ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 6 in the cited report and provide statistics for this result: $Q_M = 8.03$, d.f. = 1, $P = 0.05$.

⁹⁸⁵ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 6 in the cited report and provide statistics for this result: $Q_M = 0.36$, d.f. = 1, $P = 0.01$.

California Current Ecosystem

In the Pacific Northwest the summer of 2005 was characterized by a three-month delay to the start of the upwelling season resulting in a lack of significant plankton production until August (rather than the usual April-May time period).⁹⁸⁶ Delayed lower trophic level production was accompanied by:

- A failure of many rockfish species to recruit,
- Low survival of coho and Chinook salmon,
- Complete nesting failure by the sea bird, Cassin's Auklet,
- Widespread deaths of other seabirds such as common murre and sooty shearwaters,⁹⁸⁷ and
- Organisms such as whiting, sardines, shearwaters, and blue and humpback whales that migrate within the CC to take advantage of feeding opportunities associated with the seasonal cycle of production, encountered poor feeding conditions upon their arrival in spring 2005.⁹⁸⁸

Thus fish, birds and mammals that relied upon plankton production occurring at the normal time experienced massive recruitment failure.⁹⁸⁹ Peterson and Scwhing (2008) note similar mismatches have occurred in recent years in which upwelling began early (as in 2006 and 2007) but was interrupted at a critical time (May-June).⁹⁹⁰ The summer of 2006 had some of the strongest upwelling winds on record yet many species again experienced recruitment failure, in part because there was a one-month period of no winds (mid-May to mid-June) that occurred at the time when many bird and fish species are recruiting:⁹⁹¹

- Marine organisms that had come to exploit expected production peaks found little food.⁹⁹² The organisms which seem to be the most affected by delayed upwelling include juvenile salmon that were just entering the coastal ocean in April/May, whiting that were migrating northward, seabirds which are nesting at that time and all other animals that migrate to the northern California Current in summer to feed.⁹⁹³
- Both salmon and seabirds experienced increased mortality in 2006 and 2007, attributed to poor ocean conditions over a relatively short period in late spring.⁹⁹⁴

As summarized by Somero (2010), Kuo and Sanford (2009) recently reported that populations of the whelk *Nucella canaliculata* from intertidal sites along the Eastern Pacific coastline from central Oregon to central California differed significantly in upper lethal temperature.⁹⁹⁵ This patterning of thermal tolerance is a clear illustration of how heat stress varies across latitude as a consequence of interactions

⁹⁸⁶ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 45)

⁹⁸⁷ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 54)

⁹⁸⁸ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 54). The authors cite Sydeman et al. (2006), Mackas et al. (2006), Schwing et al. (2006), and Kosro et al. (2006) for information on these trends.

⁹⁸⁹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 45)

⁹⁹⁰ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 45)

⁹⁹¹ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 45)

⁹⁹² Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 54)

⁹⁹³ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 54)

⁹⁹⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 54)

⁹⁹⁵ Verbatim or nearly verbatim from Somero. *The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers'*. (2010, p. 914). The authors refer the reader to Fig. 2 in the cited report.

between temperature *per se* and the timing of the tidal cycle.⁹⁹⁶ The most heat-tolerant populations came from sites in central Oregon (Fogarty Creek, Strawberry Hill and Cape Arago) where midday low tides in summer expose the snails to more extreme heat stress than is encountered by populations in northern and central California sites, where summer low tides occur during cooler periods of the day.⁹⁹⁷

Future Projections

Global

Reduced developmental times may result in phenological (i.e. timing of biological events such as breeding) mismatches between developing larval organisms and the availability of suitable food, similar to phenological mismatches reported for terrestrial systems.⁹⁹⁸

Gulf of Alaska LME

Sigler et al. (2008) state the North Pacific Ocean is a sentinel region for the biological impacts of ocean acidification.⁹⁹⁹ As described in Chapter III.1 (Ocean acidification) of this report, it will be one of the first regions affected by decreasing ocean pH because the depth below which the water is undersaturated in calcium carbonate (the “calcium carbonate saturation horizon”) is relatively shallow and the saturation horizon is projected to reach the surface during this century.¹⁰⁰⁰ At that point, a wide range of North Pacific species will be exposed to seawater undersaturated with respect to calcium carbonate and may be unable, or have difficulty, forming the carbonate structures needed for their shells or other body components.¹⁰⁰¹ For example, cold-water scleractinian corals build their skeletons from the more soluble form of calcium carbonate known as aragonite.¹⁰⁰² As the world’s oceans become less saturated over time, corals are expected to build weaker skeletons (a process similar to osteoporosis in humans) and/or experience slower growth rates.¹⁰⁰³ A study by Guinotte et al. (2006) projects:

- Of 410 locations where deep ocean waters were saturated with aragonite in pre-industrial times, seventy percent are projected to be in undersaturated waters by 2099,¹⁰⁰⁴ as the aragonite saturation horizon (the depth boundary between waters saturated and undersaturated with aragonite) moves shallower over time.¹⁰⁰⁵

⁹⁹⁶ Verbatim or nearly verbatim from Somero. (2010, p. 914). The authors cite Helmuth et al. (2002), Helmuth et al. (2006), and Helmuth (2009) for this information.

⁹⁹⁷ Verbatim or nearly verbatim from Somero. (2010, p. 914)

⁹⁹⁸ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Durant et al. (2007) for information on developmental times and phenological mismatches between larval organisms and food availability. The authors cite Walther et al. (2002) for information on terrestrial systems.

⁹⁹⁹ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 71)

¹⁰⁰⁰ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 71-72). See, for example, Feely et al. (2004) and Orr et al. (2005).

¹⁰⁰¹ Verbatim or nearly verbatim from Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 72)

¹⁰⁰² Verbatim or nearly verbatim from Guinotte et al. *Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals?* (2006, p. 142)

¹⁰⁰³ Verbatim or nearly verbatim from Guinotte et al. (2006, p. 142-143)

¹⁰⁰⁴ Verbatim or nearly verbatim from Guinotte et al. (2006, p. 141)

¹⁰⁰⁵ Verbatim or nearly verbatim from Guinotte et al. (2006, p. 142)

- Although the impacts of undersaturated waters are still being determined, the upward migration of the aragonite saturation horizon has the potential to alter the global distribution of deep-sea scleractinian corals and the organisms that depend on them.¹⁰⁰⁶

California Current Ecosystem

Animals (such as whiting, sardines, shearwaters, leatherback turtles, and blue whales) that migrate both to and within the CCE to take advantage of feeding opportunities associated with the seasonal cycle of production, and time their spawning, breeding or nesting with peaks in the seasonal cycles of production, may have to make adjustments in the timing of such activities.¹⁰⁰⁷

Information Gaps

Information on observed changes in the Gulf of Alaska LME is needed, as well as information on future projections for a wider range of species and communities. Additional information on the California Current Ecosystem is needed, as results from a single study are presented here. Additional information on observed changes and future projections in phenology and development are also needed, as results for from single studies are presented here.

¹⁰⁰⁶ Verbatim or nearly verbatim from Guinotte et al. (2006, p. 146)

¹⁰⁰⁷ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 53)

3. SHIFTS IN COMMUNITY COMPOSITION, COMPETITION, & SURVIVAL

Observed Trends

Global

Kroeker et al.'s (2010) meta-analysis of the effects of ocean acidification on marine organisms concluded a comparison could not be made between the effect of ocean acidification on survival between calcifiers and non-calcifiers because the experiments were dominated by those examining the responses of calcifiers.¹⁰⁰⁸ Additionally, the researchers could not detect a difference amongst taxonomic groups.¹⁰⁰⁹ However, the effect of ocean acidification on survival varied amongst developmental stages.¹⁰¹⁰ The effect size for larvae was the most negative, but this effect was not significant.¹⁰¹¹

Ward and Lafferty (2004) conducted an analysis that revealed that disease for some groups of marine species is increasing while others are not.¹⁰¹² Turtles, corals, mammals, urchins, and mollusks all showed increasing trends of disease, while none were detected for seagrasses, decapods, or sharks/rays.¹⁰¹³ The effects of increasing temperature on disease are complex, and can increase or decrease disease depending on the pathogen.¹⁰¹⁴

Gulf of Alaska LME

Two alternate stable states have been observed repeatedly in Pacific and Atlantic Subarctic/boreal continental shelf ecosystems; switches between “crustacean/small pelagic fish” communities and “groundfish” communities have been observed in the Gulf of Alaska and elsewhere.¹⁰¹⁵

- A study by Litzow (2006) investigating climate regime shifts and community reorganization in the Gulf of Alaska reports that following the 1976/1977 PDO regime shift (to a positive state), catch per unit effort data for representative taxa showed either rapid decline (capelin, pink shrimp) or rapid increase (arrowtooth flounder, Pacific cod, jellyfish).¹⁰¹⁶
- Survey catch composition strongly responded to local climate at lags of two and four years (using non-linear regression).¹⁰¹⁷

¹⁰⁰⁸ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 2 in the cited report.

¹⁰⁰⁹ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 3 in the cited report and provide statistics for this result: $Q_m = 7.81$, d.f. = 2, $P = 0.015$.

¹⁰¹⁰ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 4 in the cited report and provide statistics for this result: $\text{LnRR} = -1.24$, 95% bias-corrected confidence interval $\text{val} = -3.4$ to 0.01.

¹⁰¹¹ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424)

¹⁰¹² Verbatim or nearly verbatim from Janetos et al. (2008, p. 168). Janetos et al. are summarizing the work of Ward and Lafferty (2004).

¹⁰¹³ Verbatim or nearly verbatim from Janetos et al. (2008, p. 168)

¹⁰¹⁴ Verbatim or nearly verbatim from Janetos et al. (2008, p. 168). The authors cite Ward and Lafferty (2004) for this information.

¹⁰¹⁵ Verbatim or nearly verbatim from Litzow. *Climate regime shifts and community reorganization in the Gulf of Alaska: how do recent shifts compare with 1976/1977*. (2006, p. 1395). The author cites Anderson and Piatt (1999) for information on the Gulf of Alaska.

¹⁰¹⁶ Verbatim or nearly verbatim from Litzow. (2006, p. 1390)

¹⁰¹⁷ Verbatim or nearly verbatim from Litzow. (2006, p. 1386)

- Consistent with the view that the 1998/1999 climate regime shift did not represent a reversion to a negative PDO state, the analysis failed to detect the 1998/1999 regime shift in local climate, or in survey or commercial catches.¹⁰¹⁸

Switches between the two states are apparently modulated by the relative strength of demersal and pelagic secondary production, and the strength of top-down ecosystem control.¹⁰¹⁹

California Current Ecosystem

Between 1998 and 2002, after an intense 1997 El Niño and a prolonged La Niña (summer 1998-2002), species composition of pelagic nekton shifted from a community dominated by southern predatory species (mackerels and hake) to one dominated by northern species (smelts, squid and salmonids).¹⁰²⁰

Near Tatoosh Island (WA), Wootton, Pfister and Forester (2008) observed complex interactions between species under acidified ocean conditions.¹⁰²¹ As described in Chapter III.1 (Ocean acidification), the model includes all variables that are currently suggested to have a large impact on ocean pH.¹⁰²² Of these, only atmospheric CO₂ exhibits a consistent change that can explain the persistent decline in pH.¹⁰²³

The abundance and mean size of the dominant species in the system, the California mussel (*Mytilus californianus*), declined with declining pH, as did the blue mussel (*Mytilus trossulus*) and the goose barnacle (*Pollicipes polymerus*).¹⁰²⁴ In contrast, the abundance of acorn barnacles (*Balanus glandula*, *Semibalanus cariosus*) and fleshy algae (*Halosaccion glandiforme*, *ephemeral algae*, *filamentous red algae*, and *foliose red algae*) increased with declining pH.¹⁰²⁵ Prior evidence suggests the acorn barnacles, noncalcareous fleshy algae, and calcareous coralline algae (*Corallina vancouveriensis*) are strongly impacted by competition with the dominant calcareous sessile species, whose performance declined with lower pH, as well as by reduced predation and grazing by consumers with calcareous shells, which might also be impacted by lower pH.¹⁰²⁶

Along the central Oregon coast in a rocky intertidal area, Sanford (2002) studied rates of seastar density and predation on mussels and found they were reduced during cold-water upwelling events.¹⁰²⁷ The sensitivity of starfish predation to small changes in water temperature was surprising because it occurred in the middle of the seastar's thermal tolerance range.¹⁰²⁸ Seastars maintain diversity on the lower reef by

¹⁰¹⁸ Verbatim or nearly verbatim from Litzow. (2006, p. 1386)

¹⁰¹⁹ Verbatim or nearly verbatim from Litzow. (2006, p. 1395). The author cites Hunt et al. (2002) and Choi et al. (2004) for information on secondary production, and Worm and Myerst (2003) and Frank et al. (2005) for information on top-down ecosystem control.

¹⁰²⁰ Verbatim or nearly verbatim from ISAB. (2007, p. 69). The authors cite Emmett and Brodeur (2000) and Brodeur et al. (2005) for this information.

¹⁰²¹ Wootton, Pfister and Forester. (2008)

¹⁰²² Verbatim or nearly verbatim from Wootton et al. (2008, p. 18851). The authors cite Solomon et al. (2007), Dore et al. (2003), Pelejero et al. (2005), and Feely et al. (2008) for this information.

¹⁰²³ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18851)

¹⁰²⁴ Wootton, Pfister and Forester. (2008)

¹⁰²⁵ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18849)

¹⁰²⁶ Verbatim or nearly verbatim from Wootton, Pfister and Forester. (2008, p. 18851)

¹⁰²⁷ Sanford. *Community responses to climate change: links between temperature and keystone predation in a rocky intertidal system*. (2002)

¹⁰²⁸ Verbatim or nearly verbatim from Sanford. (2002, p. 183)

feeding on the competitively dominant mussel, thereby preventing the dominant mussel from overgrowing and smothering less competitive sessile organisms.¹⁰²⁹

In Bodega Harbor (CA), the dominance of invasive species has approximately doubled over the last forty years, as sea temperatures have increased.¹⁰³⁰ A study by Sorte, Williams and Zerebecki (2010) concluded that introduced species of sessile (permanently attached to a surface) invertebrates were more tolerant of higher temperatures than native species: three of four non-native species were likely to become more abundant as a critical temperature threshold was reached, while a native species declined in abundance, in part due to high mortality.¹⁰³¹ The researchers suggest that the effects of climate change on communities can occur via both direct impacts on the diversity and abundance of native species and indirect effects due to increased dominance of introduced species.¹⁰³²

Climate change has been implicated in recent variation in the prevalence and severity of disease outbreaks within marine ecosystems.¹⁰³³ These influences are likely to be a consequence of several factors, including the expansion of pathogen ranges in response to warming, changes to host susceptibility as a result of increasing environmental stress, and the expansion of potential vectors.¹⁰³⁴ Two recent studies explore the links between climate and disease in the California Current Ecosystem:

- In a study by Rogers-Bennett et al. (2010), red abalone with Rickettsiales-like-prokaryote also exposed to warm water developed the disease Withering Syndrome and did not produce any mature gametes (reproductive cells, e.g. sperm and eggs).¹⁰³⁵ Normal sperm and egg production was found in red abalone testing positive for Rickettsiales-like-prokaryote in cool water.¹⁰³⁶
 - *Note: Rickettsiales-like-prokaryote, or RLP, is the agent of Withering Syndrome, which is a disease of the digestive tract that inhibits production of digestive enzymes, leading to muscle atrophy, starvation, and death in abalone. Vibrio tubiashii is a pathogen of larval bivalve mollusks, causing both toxigenic (i.e. producing a toxin or toxic effect) and invasive disease.*¹⁰³⁷
- During 2006 and 2007, Elston et al. (2008) report that losses of larval and juvenile bivalves were linked to *V. tubiashii* blooms in the coastal environment of western North America.¹⁰³⁸ Losses were associated with the apparent mixing of unusually warm surface seawater and intermittently upwelled cooler, nutrient- and *Vibrio* spp.- enriched seawater.¹⁰³⁹

¹⁰²⁹ Verbatim or nearly verbatim from Sanford. (2002, p. 175)

¹⁰³⁰ Verbatim or nearly verbatim from Sorte, Williams and Zerebecki. *Ocean warming increases threat of invasive species in a marine fouling community*. (2010, p. 2203)

¹⁰³¹ Verbatim or nearly verbatim from Sorte, Williams and Zerebecki. (2010, p. 2200-2201)

¹⁰³² Verbatim or nearly verbatim from Sorte, Williams and Zerebecki. (2010, p. 2198)

¹⁰³³ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1527). The authors cite Harvell et al. (2009) for this information.

¹⁰³⁴ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1527)

¹⁰³⁵ Verbatim or nearly verbatim from Rogers-Bennett et al. *Response of red abalone production to warm water, starvation, and disease stressors: implications of ocean warming*. (2010, p. 599)

¹⁰³⁶ Verbatim or nearly verbatim from Rogers-Bennett et al. (2010, p. 599)

¹⁰³⁷ Verbatim or nearly verbatim from Hasegawa et al. *The extracellular metalloprotease of Vibrio tubiashii is a major virulence factor for Pacific oyster (Crassostrea gigas) larvae*. (2008, p. 4101)

¹⁰³⁸ Verbatim or nearly verbatim from Elston et al. *Re-emergence of Vibrio tubiashii in bivalve shellfish aquaculture: severity, environmental drivers, geographic extent and management*. (2008, p. 119)

¹⁰³⁹ Verbatim or nearly verbatim from Elston et al. (2008, p. 119)

Future Projections

Global

One of the inevitable outcomes of differing tolerances for changes in the environment among marine organisms is the development of novel assemblages of organisms in the near future.¹⁰⁴⁰ Such communities will have no past or contemporary counterparts and consequently are likely to present serious challenges to marine resource managers and policy makers.¹⁰⁴¹

With regard to competition among species, the winners under low oxygen conditions seem to be smaller specimens that outcompete larger ones due to their advantageous body-mass-oxygen-consumption ratio.¹⁰⁴² The decline of fish stocks due to an extending hypoxia could enhance pCO₂ in the upper water layers and thus make organisms more vulnerable to hypoxia, resulting in a self-sustaining negative loop.¹⁰⁴³

According to the IPCC AR4, there is *medium confidence* that approximately twenty to thirty percent of species assessed so far are *likely* to be at increased risk of extinction if increases in global average warming exceed 2.7 to 4.5°F (1.5 to 2.5°C; relative to 1980-1999).¹⁰⁴⁴ As global average temperature increase exceeds about 3.5°C, model projections suggest significant extinctions (40 to 70% of species assessed) around the globe.¹⁰⁴⁵

Results from Kroeker et al.'s (2010) meta-analysis suggest the effects of ocean acidification will be negative for most calcifying organisms, but that variation in life history characteristics will prove some organisms more resilient than others.¹⁰⁴⁶ For example, the echinoderm *Echinus esculentus* larvae had high mortality under ocean acidification, while the echinoderm *Strongylocentrotus droebachiensis* larvae showed increased developmental success.¹⁰⁴⁷

Gulf of Alaska LME

Transition back to a crustacean/small pelagic fish state is an unlikely result in the Gulf of Alaska, because dominant taxa in this state, such as capelin and pandalid shrimp, are associated with cold temperatures.¹⁰⁴⁸ A more likely possibility is a transition to a community containing more temperate/warm-water species.¹⁰⁴⁹

¹⁰⁴⁰ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1526). The authors cite Williams and Jackson (2007) for information on past and contemporary counterparts in novel assemblages.

¹⁰⁴¹ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1526-1527)

¹⁰⁴² Verbatim or nearly verbatim from Ekau et al. (2010, p. 1690). The authors cite Burleson et al. (2001) for this information.

¹⁰⁴³ Verbatim or nearly verbatim from Ekau et al. (2010, p. 1691)

¹⁰⁴⁴ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 54)

¹⁰⁴⁵ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Synthesis Report*. (2007c, p. 54)

¹⁰⁴⁶ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1427)

¹⁰⁴⁷ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1429-1430). The authors cite Dupont and Thorndyke (2009) for this information.

¹⁰⁴⁸ Verbatim or nearly verbatim from Litzow. (2006, p. 1395). The author cites Rose (2005) and Wieland (2005) for this information.

¹⁰⁴⁹ Verbatim or nearly verbatim from Litzow. (2006, p. 1395)

With regard to species survival, in coastal basins and fjords whose basin waters are rejuvenated with periodic replacement from the ocean, declining oxygen levels in the subarctic Pacific could lead to serious hypoxia resulting in widespread mortality of benthic species.¹⁰⁵⁰

California Current Ecosystem

Over time, the trends described for the marine community near Tatoosh Island (WA) may result in significant changes to the composition of the coastal environment: in the study, fleshy macroalgae and seagrasses became dominant.¹⁰⁵¹ This result supports earlier predictions that calcifiers (particularly corals and crustose coralline algae) harmed by ocean acidification and environmental damage may give way to more aquatic vegetation and herbivores, creating future marine ecosystems that are significantly different from today's.¹⁰⁵²

Along the central Oregon coast in a rocky intertidal area, sustained increases in cold-water upwelling may allow the dominant mussel to move down the shore, which may dramatically decrease the diversity of species occupying low zone rock surfaces.¹⁰⁵³ Other impacts may mitigate (e.g. ocean acidification, harvesting) or exacerbate (e.g. reduced harvest) the effect.¹⁰⁵⁴

Information Gaps

Information is needed on observed changes and future projections for both the Gulf of Alaska LME and California Current Ecosystem, as results from one or two studies for each ecosystem are presented here. Kroeker et al. (2010) state their results do not support the hypothesis that more soluble forms of calcium carbonate (CaCO_3) will be more sensitive to ocean acidification, and the resilience of crustaceans and coralline algae requires further experimentation to understand the mechanisms for their responses.¹⁰⁵⁵

¹⁰⁵⁰ Verbatim or nearly verbatim from Whitney, Freeland and Robert. (2007, p. 191)

¹⁰⁵¹ Verbatim or nearly verbatim from Cooley, Kite-Powell and Doney. *Ocean acidification's potential to alter global marine ecosystem services*. (2009, p. 173).

¹⁰⁵² Verbatim or nearly verbatim from Cooley, Kite-Powell and Doney. (2009, p. 173). The authors cite Anthony et al. (2008) for information on harm to calcifiers and Hoegh-Guldberg et al. (2007) for information on the transition to aquatic vegetation and herbivores.

¹⁰⁵³ Verbatim or nearly verbatim from Sanford. (2002, p. 189-190). The author cites Paine (1966, 1969, 1974) regarding decreases to the diversity of species occupying low zone rock surfaces.

¹⁰⁵⁴ Comment from reviewer, June 2011.

¹⁰⁵⁵ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1429)

4. ALTERED INTERACTION WITH NON-NATIVE & INVASIVE SPECIES

Over the past several hundred years, the movement of ships and other transport vehicles around the globe has enabled the spread of a large number of marine species.¹⁰⁵⁶ Successful establishment, however, depends on conditions at the destination matching the tolerance range of invading organisms.¹⁰⁵⁷

Both invasive species and climate change are major ecosystems stressors.¹⁰⁵⁸ Climate change will have direct and second order impacts that facilitate the introduction, establishment, and/or spread of invasive species.¹⁰⁵⁹ Climate change may enhance environmental conditions for some species in some locations with the following consequences:

- New species are now able to survive in new or existing locations,
- Known invasive species expand their range into new territories, and
- Species that currently are not considered invasive may become invasive and cause significant impacts.¹⁰⁶⁰

Climate change impacts, such as warming temperatures and changes in CO₂ concentrations, are likely to increase opportunities for invasive species because of their adaptability to disturbance and to a broader range of biogeographic conditions and environmental controls.¹⁰⁶¹ Recent accelerated warming of high-latitude environments has increased the chances that species being transported from lower latitudes are able to establish themselves and spread.¹⁰⁶² Warmer air and water temperatures may also facilitate movement of species along previously inaccessible pathways of spread, both natural and human-made.¹⁰⁶³ Further, a rising number of species are expanding their ranges, often with large-scale impacts on

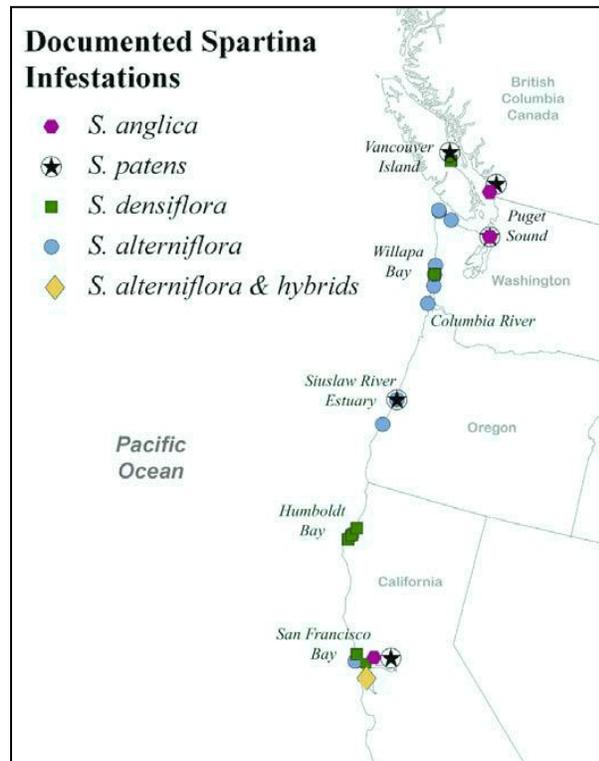


Figure 22. Distribution of non-native *Spartina* species on the Pacific Coast of North America. (courtesy of Portland State University, 2009). *Source: Reproduced from (Boe, et al. 2010, Fig. 1, p. 9) by authors of this report.*

¹⁰⁵⁶ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1527)

¹⁰⁵⁷ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1527)

¹⁰⁵⁸ Verbatim or nearly verbatim from U. S. EPA. (2008b, p. 4-1)

¹⁰⁵⁹ Verbatim or nearly verbatim from Burgiel and Muir. *Invasive species, climate change and ecosystem-based adaptation: Addressing multiple drivers of global change.* (2010, p. 5)

¹⁰⁶⁰ Verbatim or nearly verbatim from U.S. EPA. *Effects of Climate Change on Aquatic Invasive Species and Implications for Management and Research [EPA/600/R-08/014].* (2008, p. 2-14)

¹⁰⁶¹ Verbatim or nearly verbatim from Burgiel and Muir. (2010, p. 4)

¹⁰⁶² Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1527). The authors cite Stachowicz et al. (2002) for this information.

¹⁰⁶³ Verbatim or nearly verbatim from Burgiel and Muir. (2010, p. 4)

ecosystems at the destination.¹⁰⁶⁴ The impacts of those invasive species may be more severe as they increase both in numbers and extent, and as they compete for diminishing resources such as water.¹⁰⁶⁵

Invasive species can compromise the ability of intact ecosystems to sequester carbon which helps offset greenhouse gas emissions.¹⁰⁶⁶ Thus, invasive species can increase the vulnerability of ecosystems to other climate-related stressors and also reduce their potential to sequester greenhouse gases.¹⁰⁶⁷

*Note: Given the multitude of invasive and non-native species in the NPLCC region and the need for a more in-depth discussion of which species are of most significant concern due to climate change, this chapter compiles information on the three species most often cited by interviewees and reviewers. They are: cordgrass (*Spartina spp*), Japanese eelgrass (*Zostera japonica*), and New Zealand mudsnail (*Potamopyrgus antipodarum*).*



Figure 23. Two blades of *Zostera japonica* (Japanese eelgrass) are pictured with one blade of *Z. marina* (common eelgrass). Credit: Mary Jo Adams (used with permission). <http://www.beachwatchers.wsu.edu/ezidweb/seagrasses/Zosterajaponica3.htm> (accessed 4.13.2011).

Observed Trends

Global

Information needed.

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Commonly known as cordgrass, *Spartina spp* (*Spartina anglica*, *S. patens*, *S. densiflora*, *S. alterniflora*, hybrids) is a non-native estuarine grass that is widely considered a noxious weed (e.g., Figure 22).¹⁰⁶⁸ The impacts of *Spartina* species include: conversion of mudflats to monoculture stands, loss of habitat to waterbirds and fish, accretion of sediments, and modification of drainage patterns.¹⁰⁶⁹ For example, intertidal areas in Washington dominated by *Spartina* have exhibited large declines in the abundance of shorebirds and waterfowl.¹⁰⁷⁰

¹⁰⁶⁴ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1527)

¹⁰⁶⁵ Verbatim or nearly verbatim from Burgiel and Muir. (2010, p. 4)

¹⁰⁶⁶ Verbatim or nearly verbatim from Burgiel and Muir. (2010, p. 8)

¹⁰⁶⁷ Verbatim or nearly verbatim from Burgiel and Muir. (2010, p. 5)

¹⁰⁶⁸ Verbatim or nearly verbatim from Tulalip Tribes. *The Tulalip Spartina Control Project: 1998 Annual Report (website)*. (2002). *Spartina foliosa* is the only native *Spartina* species on the North American Pacific coast (see Boe et al. 2010. pp. 12 for this information)

¹⁰⁶⁹ Verbatim or nearly verbatim from Ducks Unlimited Canada. *British Columbia Spartina Eradication Program: 2009 Progress Report (pdf)*. (2009, p. 5)

¹⁰⁷⁰ Verbatim or nearly verbatim from Ducks Unlimited Canada. (2009, p. 5)

Native to Japan and the West Pacific, Japanese eelgrass (*Zostera japonica*, Figure 23) was first reported on the West Coast of the U.S. in 1957.¹⁰⁷¹ The range of Japanese eelgrass in the Pacific Northwest extends from bays and inlets on Vancouver Island and Cortes Island (about 160 km north of Vancouver) in B.C. south through Washington and Oregon.¹⁰⁷² The species was also reported in Humboldt Bay, CA.¹⁰⁷³ In Washington there is debate about the non-native vs. invasive characterization for Japanese eelgrass; a 2007 report by WA Department of Natural Resources describes *Z. japonica* as non-native.¹⁰⁷⁴ Tallis (2006) notes Japanese eelgrass can invade areas that are naturally barren of plant growth and hence is a pioneering species, as is the native eelgrass (*Zostera marina*).¹⁰⁷⁵ By moving into barren areas, the invasive alters habitat structure, changing water flow and sediment deposition, making the sediments finer grained and richer in organics.¹⁰⁷⁶ Shafer et al. (2008) tested temperature effects on growth and production of *Z. japonica* in its North American range, and showed southern populations were better adapted to high temperatures than northern populations.¹⁰⁷⁷

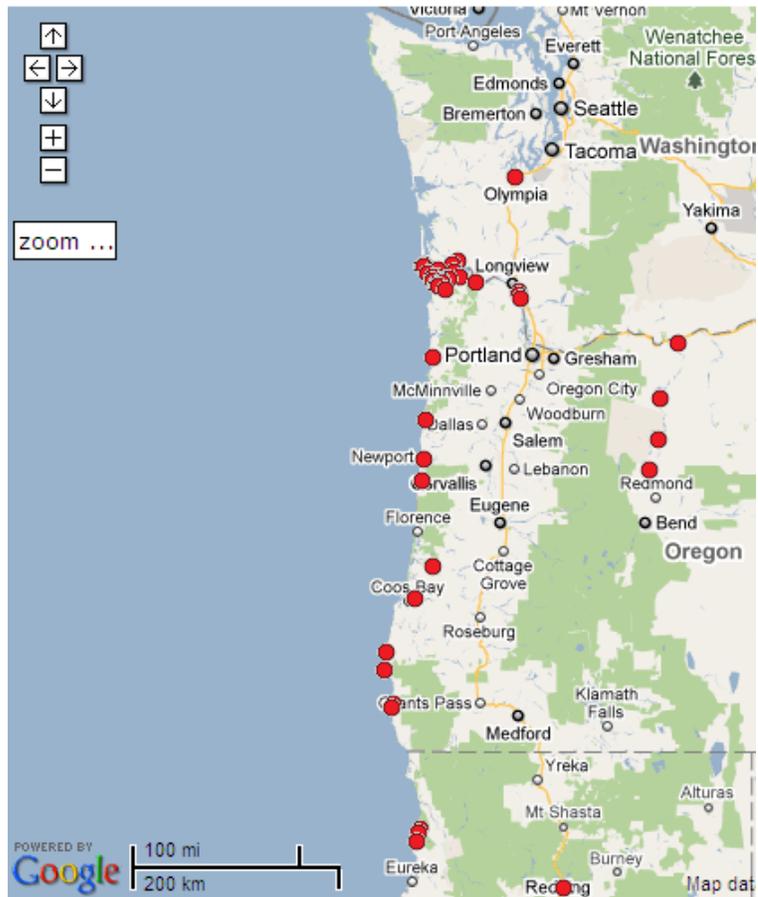


Figure 24. Compilation of confirmed New Zealand mudsnail sighting reports in the United States and Canada from 1987 through 2011, updated daily. For the NPLCC region, one sighting in a waterway in Port Alberni, Vancouver Island, British Columbia is not shown. Source: Benson, A. J. 2011. *New Zealand mudsnail sightings distribution*. Retrieved from newzealandmudsnaildistribution.aspx, 4.14.2011.

The New Zealand mud snail (*Potamopyrgus antipodarum*; Figure 24) is a common invasive species in fresh and brackish water ecosystems in Europe, Australia, Japan, and North America.¹⁰⁷⁸ In some invaded

¹⁰⁷¹ Verbatim or nearly verbatim from Tallis. *Invasive Species in the Pacific Northwest: Japanese Eelgrass*. (2006, p. 27)

¹⁰⁷² Verbatim or nearly verbatim from Tallis. (2006, p. 26)

¹⁰⁷³ Verbatim or nearly verbatim from Tallis. (2006, p. 26)

¹⁰⁷⁴ Comments from reviewers, January and April 2011; WA DNR. *Eelgrass Stressor-Response Report: 2005-2007 Report*. (2007). See, for example, p. 19.

¹⁰⁷⁵ Verbatim or nearly verbatim from Tallis. (2006, p. 26)

¹⁰⁷⁶ Verbatim or nearly verbatim from Tallis. (2006, p. 26)

¹⁰⁷⁷ Verbatim or nearly verbatim from Mach, Wyllie-Echeverria and Rhode Ward. *Distribution and potential effects of a non-native seagrass in Washington State: Zostera japonica workshop (pdf)*. (2010, p. 24)

habitats, *P. antipodarum* can reach high densities (over 500,000 snails per m²) and dominate the biomass of the benthos, leading to detrimental impacts to native biota and changes in ecosystem dynamics.¹⁰⁷⁹ *P. antipodarum* was found recently in thirteen fresh and brackish water systems adjacent to the Pacific coast of North America including a new northern range for *P. antipodarum*: Port Alberni, Vancouver Island, British Columbia, Canada (49.2479°, -124.8395°).¹⁰⁸⁰

Future Projections

Global

Information needed.

Gulf of Alaska LME and California Current Ecosystem

As sea level rises and marshes and mudflats migrate inland, invasive *Spartina* will have an opportunity to colonize new areas.¹⁰⁸¹ While invasive *Spartina* may protect marshes and mudflats from sea level rise, the value of these *Spartina* monocultures for other plants and wildlife would be very low.¹⁰⁸² Unless invasive *Spartina* is eradicated before these large-scale disturbances to marshes take place, a rapid and large scale loss of native marsh may occur.¹⁰⁸³ Minimizing other stresses on indigenous marsh species, such as competition from invasive *Spartina*, is critical to increase their ability to cope with climate change.¹⁰⁸⁴

Japanese eelgrass's (*Z. japonica*) response to predicted climatic changes in Puget Sound (WA) and the outer coast of Washington is likely to be either a neutral change or an increase in biomass.¹⁰⁸⁵

Loo et al. (2007) project New Zealand mud snail (*P. antipodarum*) might be distributed in areas many kilometers north of Port Alberni due to its wide range of temperature and salinity tolerance.¹⁰⁸⁶

Information Gaps

Information is needed on observed trends globally and for the Gulf of Alaska LME. Information is also needed on the projected distribution of non-native and invasive marine species in the NPLCC region under a changing climate.

¹⁰⁷⁸ Verbatim or nearly verbatim from Davidson et al. *Northern range expansion and coastal occurrences of the New Zealand mud snail Potamopyrgus antipodarum* (Gray, 1843) in the northeast Pacific. (2008, p. 349)

¹⁰⁷⁹ Verbatim or nearly verbatim from Davidson et al. (2008, p. 349)

¹⁰⁸⁰ Verbatim or nearly verbatim from Davidson et al. (2008, p. 349)

¹⁰⁸¹ Verbatim or nearly verbatim from Boe et al. *West Coast Governor's Agreement on Ocean Health Spartina Eradication Action Coordination Team Work Plan* (pdf). (2010, p. 14)

¹⁰⁸² Verbatim or nearly verbatim from Boe et al. (2010, p. 14)

¹⁰⁸³ Verbatim or nearly verbatim from Boe et al. (2010, p. 14)

¹⁰⁸⁴ Verbatim or nearly verbatim from Boe et al. (2010, p. 14)

¹⁰⁸⁵ Verbatim or nearly verbatim from Mach, Wyllie-Echeverria and Rhode Ward. (2010, p. 24)

¹⁰⁸⁶ Verbatim or nearly verbatim from Davidson et al. (2008, p. 351)

VII. IMPLICATIONS FOR KEY FISH, WILDLIFE, PLANTS, PLANKTON, & SHELLFISH

Based on a search of peer-reviewed studies, government reports, and publications from non-governmental organizations, sufficient information is available to discuss observed trends and future projections in the NPLCC region for:

1. Sea and shorebirds
2. Pacific lamprey
3. Pacific salmon
4. Shellfish
5. Eelgrass
6. Plankton

The following structure will be used to present information on the implications of climate change for the NPLCC region's fish, wildlife, plants, plankton, and shellfish:

- **Observed Trends** – observed changes for the Gulf of Alaska Large Marine Ecosystem (LME) and the California Current Ecosystem (CCE).
- **Future Projections** – projected direction and/or magnitude of change for the Gulf of Alaska LME and the CCE.
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

1. SEA AND SHOREBIRDS

According to an assessment of relative vulnerability of U.S. bird species by the North American Bird Conservation Initiative (NABCI), across all habitats species of conservation concern showed higher levels of vulnerability to climate change than species not threatened by other factors.¹⁰⁸⁷ Vulnerability to climate change may hasten declines or prevent recovery.¹⁰⁸⁸ At the same time, increased conservation concern may be warranted for groups of birds, such as waterfowl and aerial insect-eating birds that are abundant now but that will be increasingly stressed as climate change impacts intensify.¹⁰⁸⁹

Observed Trends

Region-wide

Of the sixty-seven ocean birds assessed by NABCI, all have medium to high vulnerability to climate change; forty-three are at the highest level of vulnerability (Figure 26).¹⁰⁹⁰ For example, Reed et al. (2009) studied breeding and development timing in the common guillemot (also known as the common murre) on southeast Farallon Island (about twenty-seven miles off the California coast), concluding:

- Egg laying date responded to environmental variability in non-extreme years, suggesting that guillemots were able to maintain high breeding success across most of the range of environmental conditions by adjusting laying dates in line with cues.¹⁰⁹¹
- Breeding was earlier in years where SSTs were low and the Northern Oscillation Index (NOI, a large-scale atmospheric phenomenon) was positive.¹⁰⁹²
- Enhanced upwelling of cold, nutrient-rich water from depth in such years would have made the seas around Southeast Farallon Island more productive, which likely influenced the availability and/or timing of fish prey.¹⁰⁹³

Of the eighty-four coastal species assessed by the NABCI, the majority (74 of 84, or 88%) have medium or high vulnerability to climate change (Figure 25).¹⁰⁹⁴ Many of the coastal species that show medium or high vulnerability to climate change are coastal seabirds such as the Aleutian Tern and Kittlitz's Murrelet.¹⁰⁹⁵ These species are vulnerable to climate change because they rely on marine food webs and because they have low reproductive potential.¹⁰⁹⁶

¹⁰⁸⁷ Verbatim or nearly verbatim from North American Bird Conservation Initiative (NABCI). *The State of the Birds 2010 Report on Climate Change, United States*. (2010, p. 4). The vulnerability assessment was based on five biological aspects of sensitivity to climate change, as well as the exposure of each species' habitat to climate change in the near future.

¹⁰⁸⁸ Verbatim or nearly verbatim from NABCI. (2010, p. 4)

¹⁰⁸⁹ Verbatim or nearly verbatim from NABCI. (2010, p. 4)

¹⁰⁹⁰ NABCI. (2010, p. 6)

¹⁰⁹¹ Verbatim or nearly verbatim from Reed et al. *Timing is everything: flexible phenology and shifting selection in a colonial seabird*. (2009, p. 384)

¹⁰⁹² Verbatim or nearly verbatim from Reed et al. (2009, p. 384)

¹⁰⁹³ Verbatim or nearly verbatim from Reed et al. (2009, p. 384)

¹⁰⁹⁴ NABCI. (2010, p. 8)

¹⁰⁹⁵ Verbatim or nearly verbatim from NABCI. (2010, p. 8)

¹⁰⁹⁶ Verbatim or nearly verbatim from NABCI. (2010, p. 8)

Observed trends for coastal birds include:

- Kittlitz's murrelet (*Brachyramphus brevirostris*) has been reported to be experiencing an annual estimated decline of around eighteen percent, attributed primarily to climate change, although the specific causes of its decline have not been determined.¹⁰⁹⁷ Kittlitz's murrelet feeds in waters around tidewater glaciers and is considered a critically endangered species as glaciers recede.¹⁰⁹⁸
- Recently published data confirms marbled murrelets (*Brachyramphus marmoratus*) are susceptible to domoic acid poisoning.¹⁰⁹⁹ During a *Pseudo-nitzschia* bloom in California in 1998, domoic acid poisoning was documented as the cause of death of two of seventeen radio-tagged murrelets.¹¹⁰⁰ In addition, Peery et al. (2006b, p.83) showed murrelet survival was reduced in years with a *Pseudo-nitzschia* bloom.¹¹⁰¹ McShane et al (2004) acknowledged that biotoxins will affect murrelets in the near future.¹¹⁰²
- Beach-nesting black oystercatchers are among the most vulnerable coastal birds because they rely heavily on limited, low-elevation coastal habitats.¹¹⁰³ Please see Chapter V.3 for further information on Habitat loss, degradation, and conversion due to climate change.
- Black and western High Arctic brant of the Pacific Flyway are dependent on *Zostera* (eelgrass), and are undergoing a shift in winter distribution that is likely related to climate change and its associated effects on *Zostera* dynamics.¹¹⁰⁴ Between 1980 and 2000 and during a period of population stability for black brant, inventories showed a negative trend in numbers of black brant wintering in Mexico ($R^2 = 0.35$, $F_{2,20} = 10.59$, $P < 0.01$) and a positive trend in numbers in the United States and Canada ($R^2 = 0.69$, $F_{2,20} = 44.71$, $P < 0.01$).¹¹⁰⁵ Brant reductions in Mexico have largely occurred at the southern wintering sites where *Z. marina* reaches the southern extent of its range in the northern hemisphere and air and sea surface temperatures already limit *Z. marina* growth to low intertidal and subtidal areas.¹¹⁰⁶
- Variation in breeding propensity of Black Brant associated with winter location and climate strongly suggests that food abundance on the wintering grounds directly affects reproductive performance in these geese.¹¹⁰⁷ In summer, salt marshes, especially those containing *Carex* (sedges) and *Puccinellia* (common saltmarsh grass), are key habitats for raising young.¹¹⁰⁸ Availability and abundance of salt marshes has a direct effect on growth and recruitment of

¹⁰⁹⁷ Verbatim or nearly verbatim from Haufler, Mehl and Yeats. *Climate change: anticipated effects on ecosystem services and potential actions by the Alaska Region, U.S. Forest Service.* (2010, p. 17)

¹⁰⁹⁸ Verbatim or nearly verbatim from Haufler, Mehl and Yeats. (2010, p. 17)

¹⁰⁹⁹ Verbatim or nearly verbatim from U.S. Fish and Wildlife Service (FWS). *Marbled Murrelet (Brachyramphus marmoratus): 5-Year Review (Final)*. (June 12, 2009, p. 38)

¹¹⁰⁰ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 38). The authors cite Peery et al. (2006b, p. 83-84) for this information.

¹¹⁰¹ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 38)

¹¹⁰² Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 38)

¹¹⁰³ Verbatim or nearly verbatim from NABCI. (2010, p. 8)

¹¹⁰⁴ Verbatim or nearly verbatim from Ward et al. *North American Brant: effects of changes in habitat and climate on population dynamics.* (2005, p. 869)

¹¹⁰⁵ Verbatim or nearly verbatim from Ward et al. (2005, p. 876). The authors refer the reader to Fig. 4a and 4b for black brant in Mexico and the U.S./Canada, respectively.

¹¹⁰⁶ Verbatim or nearly verbatim from Ward et al. (2005, p. 876). The authors refer the reader to Fig. 4a in the cited report and cite Meling-López & Ibarra-Obando (1999) and Cabello-Pasini et al. (2003) for this information.

¹¹⁰⁷ Verbatim or nearly verbatim from Ward et al. (2005, p. 869)

¹¹⁰⁸ Verbatim or nearly verbatim from Ward et al. (2005, p. 869)

goslings (young geese) and ultimately, plays an important role in regulating size of local brant populations.¹¹⁰⁹

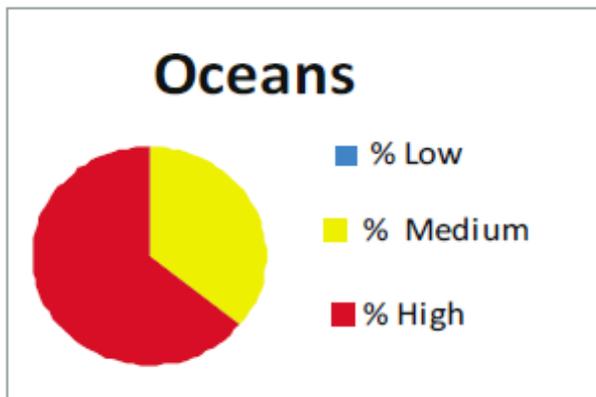


Figure 26. The 67 ocean birds assessed have medium to high vulnerability to climate change; 43 are at the highest level.

Source: Reproduced from NABCI (2010, p. 6) by authors of this report.

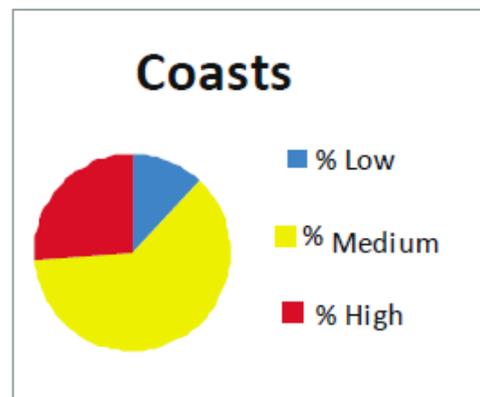


Figure 25. The great majority of coastal species (74 of 84 assessed) have medium or high vulnerability to climate change.

Source: Reproduced from NABCI (2010, p. 8) by authors of this report.

Future Projections

Region-wide

NABCI (2010) states ocean birds are slow to adapt or recover from adverse conditions and are vulnerable to climate change because of their low reproductive potential (advanced age of first breeding, production of one egg each year or every other year, and the high mortality rate for young birds).¹¹¹⁰ Many seabirds forage over vast areas of ocean and are highly sensitive to the availability of marine food.¹¹¹¹ This sensitivity is especially pronounced during breeding, when providing food for chicks can place enormous physiological strain on the parents.¹¹¹² In fact, reproductive failure of seabirds resulting from changes in marine productivity is a documented natural occurrence, such as when Pacific Coast seabird chicks starve during El Niño years (when sea surface temperatures are warmer than usual).¹¹¹³ If catastrophic events become more frequent, intense, or longer as a result of climate change, population recovery is less likely.¹¹¹⁴

In the California Current region, significant ocean climate change is projected for the foraging range of Cassin's auklet by 2100, including a large increase in SST (~3.6°F, ~2°C) year-round and an intensification of spring upwelling followed by an overall decrease in summer and winter upwelling (using a mid-level emissions scenario and well-validated regional climate model for the California

¹¹⁰⁹ Verbatim or nearly verbatim from Ward et al. (2005, p. 869)

¹¹¹⁰ Verbatim or nearly verbatim from NABCI. (2010, p. 6)

¹¹¹¹ Verbatim or nearly verbatim from NABCI. (2010, p. 6)

¹¹¹² Verbatim or nearly verbatim from NABCI. (2010, p. 6)

¹¹¹³ Verbatim or nearly verbatim from NABCI. (2010, p. 6)

¹¹¹⁴ Verbatim or nearly verbatim from NABCI. (2010, p. 6-7)

Current region).¹¹¹⁵ Because breeding success of Farallon Island auklets covaries with population parameters of other important predators in the California Current Ecosystem (i.e. return rates of Sacramento River fall Chinook salmon), climate change-related impacts to auklet populations may be harbingers of effects on other plankton predators in this system.¹¹¹⁶ For example:

- The Cassin's auklet population growth rate at one breeding site on Farallon Island is projected to experience an absolute decline of 11–45% by the end of the century, which would lead to rapid population extirpation.¹¹¹⁷

Warmer waters have apparently led to decreases in the abundance of fish in Prince William Sound, the Gulf of Alaska, and the California Current region, which is likely to reduce the abundance of fish-eating birds.¹¹¹⁸ In the future, seabirds such as Common Murres (also known as Common Guillemot) that time their breeding based on temperature cues may fail to raise any young if their chicks hatch at the wrong time, missing the window when food is abundant.¹¹¹⁹ Climate change may also cause prey to shift ranges, leading to declines in bird populations if the birds are unable to follow.¹¹²⁰

For coastal birds, losses of habitat and food sources due to climate change are the largest concerns.¹¹²¹ Some researchers suggest that, overall, sea level rise is expected to have minor impacts on waterfowl habitats along much of the Pacific Coast because of the abrupt topography of the coastline and continuing tectonic movements that counteract sea level rise.¹¹²² However, researchers have also noted the combined effects of habitat change on shorebird breeding areas and intertidal habitat loss at their wintering and migratory staging sites could, potentially, have even more severe effects than could be brought about by any one factor.¹¹²³ Where landform or human development prevent the shoreward movement of coastal wetlands, the threat of loss is greater.¹¹²⁴ Future projections by the U.S. Fish and Wildlife Service (2009) for the marbled murrelet include:

- Within the marine environment, effects on the murrelet food supply (amount, distribution, quality) provide the most likely mechanism for climate change impacts to murrelets.¹¹²⁵ The murrelet diet is not well studied, which hampers assessment of climate change effects related to prey, but effects on nutrient levels, and primary productivity are of concern, as are effects on prey abundances, quality, and distribution.¹¹²⁶

¹¹¹⁵ Verbatim or nearly verbatim from Wolf et al. *Predicting population consequences of ocean climate change for an ecosystem sentinel, the seabird Cassin's auklet.* (2010, p. 1930)

¹¹¹⁶ Verbatim or nearly verbatim from Wolf et al. (2010, p. 1931). The authors cite (Roth et al., 2007) for information on return rates of Sacramento River fall Chinook salmon.

¹¹¹⁷ Verbatim or nearly verbatim from Wolf et al. (2010, p. 1930)

¹¹¹⁸ Verbatim or nearly verbatim from NABCI. (2010, p. 7)

¹¹¹⁹ Verbatim or nearly verbatim from NABCI. (2010, p. 7)

¹¹²⁰ Verbatim or nearly verbatim from NABCI. (2010, p. 7)

¹¹²¹ Verbatim or nearly verbatim from NABCI. (2010, p. 8)

¹¹²² Verbatim or nearly verbatim from The Wildlife Society. *Global climate change and wildlife in North America: Technical review 04-2.* (2004, p. 14). The authors cite Shaw et al. (1998) for this information.

¹¹²³ Verbatim or nearly verbatim from Galbraith et al. (2005, p. 1121)

¹¹²⁴ Verbatim or nearly verbatim from The Wildlife Society. (2004, p. 14). The authors cite Boesch et al. (2000) for this information.

¹¹²⁵ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 42)

¹¹²⁶ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 42)

- While murrelets have likely adapted to occasional adverse ocean conditions, should strong El Niño events continue to be more frequent, the cumulative effects of repeated El Niño events in a short period with other threats “could contribute to serious population declines or extirpations” (emphasis in original).¹¹²⁷ As noted in Chapter IV.2 (Altered ocean productivity), it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change.¹¹²⁸
- Given uncertainty about future variability in California Current ocean conditions (e.g., how increased upwelling and increased stratification will interact), positive changes (for murrelet food supply) appear rare in forecasts, with the possible exception of increased upwelling.¹¹²⁹ While upwelling is generally associated with increased productivity, at some level increased winds and upwelling could negatively affect the coastal marine ecosystems, by reducing the concentration of marine organisms, through increased mixing and transport seaward of surface water and organisms (out of the murrelet’s near-shore environment).¹¹³⁰
- The negative impacts of increased acidity on plankton may cause negative impacts on many other species which are important food-sources for murrelet and their prey.¹¹³¹

For further information on projected changes to the quantity of tidal marsh, mudflat, and other habitat types important for sea and shorebirds in specific locations throughout the geographic extent of the NPLCC, please see Section 3 in Chapter V (Habitat loss, degradation, and conversion).

Information Gaps

Information is needed on impacts to sea and shorebirds in the NPLCC region, including information on the effects of climate change on feeding, breeding, migration, socialization, interspecies interactions, and other factors.

¹¹²⁷ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 43). The authors cite USFWS (1997, p. 78-19) for the quoted information.

¹¹²⁸ Verbatim or nearly verbatim from Collins et al. *The impact of global warming on the tropical Pacific Ocean and El Nino.* (2010, p. 391)

¹¹²⁹ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 44)

¹¹³⁰ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 44). The authors cite Snyder et al. (2003, p. 4) for this information.

¹¹³¹ Verbatim or nearly verbatim from U.S. FWS. (June 12, 2009, p. 45). The authors cite Ruckelshaus and McClure (2007, p. 55) for this information.

2. PACIFIC LAMPREY (*LAMPETRA TRIDENTATA*)

Observed Trends

Gulf of Alaska LME

Information needed.

California Current Ecosystem

In recent decades, anadromous Pacific lampreys (*Lampetra tridentata*) along the west coast of North America, have experienced broad-based population declines and regional extirpations.¹¹³² These declines parallel those of Pacific salmonids (*Oncorhynchus spp.*), perhaps because the two groups share widely sympatric (i.e. occurring in the same or overlapping geographic areas) distributions and similar anadromous life histories.¹¹³³ In light of these similarities, the Columbia River Inter-Tribal Fish Commission is conducting a preliminary assessment of climate change impacts on the estuarine habitat for salmon and lamprey as derived from “filtering” simulations of Columbia River flow scenarios.¹¹³⁴

Along the coasts of Oregon, southern Washington, and northern California, threats to lamprey are, overall, moderate to severe.¹¹³⁵ Population decline over the last three generations (27 years) has been observed throughout the region:

- Up to seventy percent decline in two Puget Sound watersheds and the North Coast of Oregon, and
- A ten to thirty percent decline in some areas of coastal California, the Lower Columbia River region, and other areas of coastal Oregon.¹¹³⁶

Future Projections

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Climate change may exacerbate many existing threats to lamprey, especially water flow, ocean conditions, water quality, disease, predation, and stream conditions.¹¹³⁷

Information Gaps

Research on Pacific lamprey marine life stages, including projected effects of climate change, is needed.

¹¹³² Verbatim or nearly verbatim from Keefer et al. *Variability in migration timing of adult Pacific lamprey (Lampetra tridentata) in the Columbia River, U.S.A.* (2009, p. 254). The authors cite Beamish and Northcote (1989), Kostow (2002), and Moser and Close (2003) for this information.

¹¹³³ Verbatim or nearly verbatim from Keefer et al. (2009, p. 254). The authors cite Scott and Crossman (1973), Simpson and Wallace (1978), and Moyle (2002) for information on sympatric distributions, and McDowall (2001) and Quinn and Myers (2004) for information on Anadromous life histories.

¹¹³⁴ Pers. Comm. with Laura Gephart. (June 2011). Contact information: (503) 238-0667, gepl@critfc.org

¹¹³⁵ Verbatim or nearly verbatim from U.S. Fish and Wildlife Service. *Pacific Lamprey (Lampetra tridentata) Draft Assessment and Template for Conservation Measures.* (2010, p. 42). This information is obtained from Figure 4-6b. Data for the Puget Sound region is not available. Data from California are incomplete.

¹¹³⁶ U.S. Fish and Wildlife Service. (2010, p. 41, 43, 46, 48, 55)

¹¹³⁷ Verbatim or nearly verbatim from U.S. Fish and Wildlife Service. (2010, p. 23)

3. PACIFIC SALMON (*ONCORHYNCHUS* SPP.)

Pacific salmon have complex life histories that span diverse environments across the Pacific Rim.¹¹³⁸ Pacific salmon (*Oncorhynchus* spp) are an important ecological and economic species complex in the North Pacific Ocean.¹¹³⁹ Their natural distribution extends from San Francisco Bay in California, northwards along the Canadian and Alaskan coasts to North American and Russian rivers draining into the Arctic Ocean, and southwards along the Asian coastal areas of Russia, Japan, and Korea.¹¹⁴⁰

Pacific salmon spawn in fall in fresh water and their embryos incubate in the gravel during the winter and emerge in spring.¹¹⁴¹ Juveniles then spend days to years in habitats ranging from small creeks to large rivers, and small ponds to large lakes.¹¹⁴² Most juveniles then migrate downriver, through estuaries and coastal waters, to the ocean.¹¹⁴³ These “anadromous” individuals spend anywhere from a few months to as much as seven years at sea, before migrating back to spawn and die at their natal sites in fresh water.¹¹⁴⁴

This great diversity of environments and behaviors suggests that climate change could influence selection on multiple traits in multiple phases of the life cycle.¹¹⁴⁵ Changes in the ocean associated with warming will affect salmonids and their ecosystems, both directly and indirectly.¹¹⁴⁶ Physical changes associated with warming include: increases in ocean temperature, increased stratification of the water column, and changes in the intensity and timing of coastal upwelling.¹¹⁴⁷ These changes in climate forcing will alter both primary and secondary productivity and the structure of marine communities, and in turn, the growth, productivity, survival and migrations of salmonids.¹¹⁴⁸ Nearshore ecosystems also play critical roles for salmon and steelhead, many of which use coastal marshes for feeding and refuge as they transition from freshwater to the ocean.¹¹⁴⁹

Observed Trends

Region-wide

At the scale of the Pacific Coast of North America, salmon production is strongly influenced by decadal-scale changes in the phase of the PDO.¹¹⁵⁰ For example, the PDO can change the timing and distribution

¹¹³⁸ Verbatim or nearly verbatim from Crozier et al. *Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon*. (2008, p. 253). The authors cite Groot and Margolis (1991) and Quinn (2005) for this information.

¹¹³⁹ Verbatim or nearly verbatim from Irvine and Fukuwaka. *Pacific salmon abundance trends and climate change*. (2011, p. 1122)

¹¹⁴⁰ Verbatim or nearly verbatim from Irvine and Fukuwaka. (2011, p. 1122). The authors cite Groot and Margolis (1991) for this information.

¹¹⁴¹ Verbatim or nearly verbatim from Crozier et al. (2008, p. 253)

¹¹⁴² Verbatim or nearly verbatim from Crozier et al. (2008, p. 253-254)

¹¹⁴³ Verbatim or nearly verbatim from Crozier et al. (2008, p. 254)

¹¹⁴⁴ Verbatim or nearly verbatim from Crozier et al. (2008, p. 254)

¹¹⁴⁵ Verbatim or nearly verbatim from Crozier et al. (2008, p. 254)

¹¹⁴⁶ Verbatim or nearly verbatim from ISAB. (2007, p. 57)

¹¹⁴⁷ Verbatim or nearly verbatim from ISAB. (2007, p. 57)

¹¹⁴⁸ Verbatim or nearly verbatim from ISAB. (2007, p. 57)

¹¹⁴⁹ Verbatim or nearly verbatim from Martin and Glick. *A great wave rising: solutions for Columbia and Snake River salmon in the age of global warming*. (2008, p. 15). The authors cite Bottom et al. (2005) for this information.

¹¹⁵⁰ Verbatim or nearly verbatim from Hare, Mantua and Francis. *Inverse production regimes: Alaska and West Coast Pacific Salmon*. (1999, p. 7)

of salmon predators such as Pacific mackerel, which are drawn to the region's coastal waters by warmer sea surface temperatures.¹¹⁵¹

Pacific salmon production in Alaska is inversely related to that on the West Coast (i.e., Washington, Oregon, California) and is climate-driven.¹¹⁵² The loadings on the British Columbia Pacific salmon catches suggest that those stocks occupy a transitional region, with Chinook and coho salmon of the same sign as the southern stocks and the three other species (sockeye, pink, chum) of the same sign, but in a smaller magnitude as do the Alaska stocks.¹¹⁵³ For example, in the Pacific Northwest, the cool PDO years of 1947-1976 coincided with high returns of Chinook and coho salmon to Oregon rivers.¹¹⁵⁴ Conversely, during the warm PDO cycle that followed (1977-1998), salmon numbers declined steadily.¹¹⁵⁵

Irvine and Fukuwaka (2011) estimated Pacific salmon abundance in the eastern North Pacific during five time periods:

- **1925-1946 and 1947-1976:** Mean catches declined between 1925-1946 and 1947-1976 for pink, chum, and sockeye salmon.¹¹⁵⁶
- **1977-1988:** Sockeye, pink, and coho salmon abundances increased; mean abundances for these species, as well as chum salmon, were higher in this period than in 1947-1976.¹¹⁵⁷
- **1989-1998:** Chum and pink salmon were more abundant in 1989-1998 than in 1977-1988.¹¹⁵⁸ Chum salmon abundances increased, whereas sockeye and coho decreased.¹¹⁵⁹
- **1999-2009:** Chinook salmon were less abundant than in earlier years and abundances declined. In general, differences during this time period were inconsistent.¹¹⁶⁰

Gulf of Alaska LME

Information needed.

¹¹⁵¹ Verbatim or nearly verbatim from Martin and Glick. (2008). The authors cite Percy, W.G. (1992) for this information.

¹¹⁵² Verbatim or nearly verbatim from Hare, Mantua and Francis. (1999, p. 7)

¹¹⁵³ Verbatim or nearly verbatim from Hare, Mantua and Francis. (1999, p. 10)

¹¹⁵⁴ Verbatim or nearly verbatim from Peterson et al. *Ocean conditions and salmon survival in the northern California Current*. (2006, p. 3). The authors cite Mantua et al. (1997) for this information.

¹¹⁵⁵ Verbatim or nearly verbatim from Peterson et al. (2006, p. 3). The authors cite Mantua et al. (1997) for this information.

¹¹⁵⁶ Verbatim or nearly verbatim from Irvine and Fukuwaka. (2011, p. 1126-1127)

¹¹⁵⁷ Verbatim or nearly verbatim from Irvine and Fukuwaka. (2011, p. 1127)

¹¹⁵⁸ Verbatim or nearly verbatim from Irvine and Fukuwaka. (2011, p. 1127)

¹¹⁵⁹ Verbatim or nearly verbatim from Irvine and Fukuwaka. (2011, p. 1127)

¹¹⁶⁰ Verbatim or nearly verbatim from Irvine and Fukuwaka. (2011, p. 1127)

California Current Ecosystem

In the Pacific Northwest, salmonid species use the nearshore marine and estuarine environment throughout their life cycle (Table 21 and Figure 27).¹¹⁶¹ There is evidence that the growth rate of Chinook salmon in Washington, Oregon, and California is influenced by the environment, and that the relationship is region- and life-history specific.¹¹⁶²

- Wells et al. (2008) found that growth of Puget Sound (WA) salmon with ocean-type behavior was negatively related to a stronger California Current.¹¹⁶³ Specifically, ocean-type Puget Sound fish were negatively related to the Northern Oscillation Index and upwelling.¹¹⁶⁴
- On the other hand, a strong, productive California Current promoted growth among California Chinook salmon.¹¹⁶⁵ Specifically, growth of California Chinook was enhanced by cool temperatures, increased upwelling, a stronger North Pacific high pressure system, and reduced sea level height.¹¹⁶⁶
- In Oregon, Logerwell et al. (2003) found that cooler sea surface temperature during the winter prior to smolt migration contributes to higher survival of coho salmon.¹¹⁶⁷ The mechanism for this link is suggested by correlations between ocean and atmospheric variables: relatively weak downwelling (poleward) winds in the winter, due to a weaker Aleutian Low, result in less onshore transport of warm oceanic water, and reduced upper ocean stratification the following spring.¹¹⁶⁸ Cooler sea surface temperature during the winter following smolt migration also contribute to high coho survival.¹¹⁶⁹ The mechanism may involve either improved feeding conditions or reduced predation.¹¹⁷⁰
- A later transition between winter downwelling and spring upwelling season appears to contribute to relatively poor coho survival in Oregon, perhaps due to a temporal mismatch between arrival of smolts to the sea and seasonal increases in ocean food production in the nearshore upwelling habitat.¹¹⁷¹
- Lower spring sea level anomalies (below a threshold of around -100 mm) are correlated with higher coho survival in Oregon.¹¹⁷² The processes responsible for the anomalies are expected to result in enhanced feeding conditions due to the transport of nutrients from depth to the euphotic zone, and/or the equatorward transport of nutrients and boreal copepod species from subarctic waters.¹¹⁷³

¹¹⁶¹ Verbatim or nearly verbatim from Glick, Clough and Nunley. (2007, p. 13)

¹¹⁶² Verbatim or nearly verbatim from Wells et al. *Relationships between oceanic conditions and growth of Chinook salmon (*Oncorhynchus tshawytscha*) from California, Washington, and Alaska, USA.* (2008, p. 120)

¹¹⁶³ Verbatim or nearly verbatim from Wells et al. (2008, p. 121)

¹¹⁶⁴ Verbatim or nearly verbatim from Wells et al. (2008, p. 121)

¹¹⁶⁵ Verbatim or nearly verbatim from Wells et al. (2008, p. 101)

¹¹⁶⁶ Verbatim or nearly verbatim from Wells et al. (2008, p. 122)

¹¹⁶⁷ Verbatim or nearly verbatim from Logerwell et al. *Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (*Oncorhynchus kisutch*) marine survival.* (2003, p. 564)

¹¹⁶⁸ Verbatim or nearly verbatim from Logerwell et al. (2003, p. 564-565)

¹¹⁶⁹ Verbatim or nearly verbatim from Logerwell et al. (2003, p. 565)

¹¹⁷⁰ Verbatim or nearly verbatim from Logerwell et al. (2003, p. 565)

¹¹⁷¹ Verbatim or nearly verbatim from Logerwell et al. (2003, p. 565)

¹¹⁷² Verbatim or nearly verbatim from Logerwell et al. (2003, p. 565)

¹¹⁷³ Verbatim or nearly verbatim from Logerwell et al. (2003, p. 565). The authors cite Chelton et al. (1982), Chelton and Davis (1982), Simpson (1984), and Huyer and Smith (1985) for this information.

In 2009, the decline of sockeye salmon stocks in the Fraser River in British Columbia led to the closure of the fishery for the third consecutive year, despite favorable pre-season estimates of the number of sockeye salmon expected to return to the river.¹¹⁷⁴ The 2009 return marked a steady decline that could be traced back two decades.¹¹⁷⁵ Although the two-decade decline in Fraser sockeye stocks has been steady and profound, in 2010 Fraser sockeye experienced an extraordinary rebound, demonstrating their capacity to produce at historic levels.¹¹⁷⁶ A qualitative assessment by Hinch and Martins (2011) of the likelihood that life-stage-specific survival of Fraser River sockeye salmon has been undergoing a trend in the past 20 years due to the recent trends in climate, particularly in temperature, concluded for the marine environment:¹¹⁷⁷

- Survival of immatures in the ocean has *possibly* decreased; and,
- Survival of returning adults has *very likely* decreased (but not in all stocks).¹¹⁷⁸

A number of studies have identified the loss of wetlands in the lower Columbia River estuary due to reduced freshwater flows, diking, and other problems as limiting factors in recovery of Columbia and Snake River Basin salmon.¹¹⁷⁹ As described in Chapter V.3 (Habitat loss, degradation, and conversion), Ducks Unlimited project a two percent loss of low tidal areas, nineteen percent loss of saltmarsh, eleven percent loss of freshwater tidal areas, and a 160% gain in transitional areas.¹¹⁸⁰ The Lower Columbia River may be resilient to climate-induced changes to habitat because losses to low tidal, saltmarsh, and freshwater tidal habitats are minimized, while gains in transitional areas are substantial (Figure 19).¹¹⁸¹

Future Projections

Region-wide

If the regional impacts of global warming are expressed in El Niño-like or PDO-like ways, warmer waters due to global warming are likely to promote increased production of salmon in Alaskan waters, at least initially, provided primary and secondary production does not decline, while promoting decreased salmon production for salmon populations in the Pacific Northwest region (and throughout the California Current System).¹¹⁸² A key uncertainty here is how global warming will influence the characteristics of atmospheric surface pressure and wind fields over the North Pacific because of the prominent role that wind forcing plays in structuring the upper ocean.¹¹⁸³

¹¹⁷⁴ Verbatim or nearly verbatim from Hinch and Martins. *A review of potential climate change effects on survival of Fraser River sockeye salmon and an analysis of interannual trends in en route loss and pre-spawn mortality*. (2011, Preface)

¹¹⁷⁵ Verbatim or nearly verbatim from Hinch and Martins. (2011, Preface)

¹¹⁷⁶ Verbatim or nearly verbatim from Hinch and Martins. (2011, Preface)

¹¹⁷⁷ Verbatim or nearly verbatim from Hinch and Martins. (2011, p. 2)

¹¹⁷⁸ Verbatim or nearly verbatim from Hinch and Martins. (2011, p. 3)

¹¹⁷⁹ Verbatim or nearly verbatim from Martin and Glick. (2008). The authors cite Fresh et al. (2005) for this information.

¹¹⁸⁰ DU. (2010b)

¹¹⁸¹ DU. (2010b)

¹¹⁸² Verbatim or nearly verbatim from ISAB. (2007, p. 64)

¹¹⁸³ Verbatim or nearly verbatim from ISAB. (2007, p. 64)

Gulf of Alaska LME

Under a doubling of CO₂, models predict that Pacific salmon would experience a range decline as they move northward into the Bering Sea and the Arctic.¹¹⁸⁴ Many habitats used by juvenile coho salmon in the lower Taku River, Alaska would likely be inundated with a modest (3 ft, 0.9 m) increase in sea level.¹¹⁸⁵ Rising sea levels will flood low elevation habitats converting freshwater habitats into brackish or saline environments.¹¹⁸⁶ Habitats above the immediate effects of flooding will become intertidal and subject to periodic tidal flooding and pulses of saline water and will no longer provide viable freshwater habitat for juvenile Coho salmon.¹¹⁸⁷ Predicted effects of climate change on pink salmon growth in the Gulf of Alaska are that a ten percent increase in water temperature will lead to a three percent drop in mature salmon body weight (physiological effect) and a ten percent decrease in pteropod production will lead to a twenty percent drop in mature salmon body weight (prey limitation).¹¹⁸⁸

California Current Ecosystem

Recent analyses of the potential effects of future climate change on Fraser River (BC) sockeye salmon all point to reduced survival and lower productivity if the climate continues to warm.¹¹⁸⁹ Although there is some potential for tolerance to warm temperatures to evolve in Pacific salmon, further evolutionary change may already be restricted in populations that have historically experienced high temperatures, such as summer-run Fraser River sockeye salmon.¹¹⁹⁰ Phenological (i.e. timing of events such as seaward migration and return migration) changes are likely to be one of the major responses of Pacific salmon to climate change.¹¹⁹¹

Most climate models project the 21st century will feature greater annual precipitation in the Pacific Northwest, extreme winter precipitation events in California, and a more rapid spring melt leading to a shorter, more intense spring period of river flow and freshwater discharge.¹¹⁹² This will greatly alter coastal stratification and mixing, riverine plume formation and evolution, and the timing of transport of anadromous populations to and from the ocean.¹¹⁹³ Likely impacts of climate change on Pacific salmon such as the salmon that use the Columbia, Klamath, and Sacramento River systems include the following:

- Altered stream flow and warmer temperatures will reduce the available habitat, life history diversity, and freshwater survival rates for juvenile salmon;

¹¹⁸⁴ Verbatim or nearly verbatim from Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1*.

¹¹⁸⁵ Verbatim or nearly verbatim from Kelly et al. (2007, p. 58). The authors cite Murphy et al. (1989) for this information.

¹¹⁸⁶ Verbatim or nearly verbatim from Kelly et al. (2007, p. 59)

¹¹⁸⁷ Verbatim or nearly verbatim from Kelly et al. (2007, p. 59)

¹¹⁸⁸ Verbatim or nearly verbatim from Sigler et al. (2008, p. 7). The authors cite Aydin et al. (2005) for this information.

¹¹⁸⁹ Verbatim or nearly verbatim from Hinch and Martins. (2011, p. 3)

¹¹⁹⁰ Verbatim or nearly verbatim from Hinch and Martins. (2011, p. 3)

¹¹⁹¹ Verbatim or nearly verbatim from Hinch and Martins. (2011, p. 3)

¹¹⁹² Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 50). The authors refer the reader to Figure 3 in the cited report.

¹¹⁹³ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 50)

- Altered air temperatures will increase heating of mainstem reservoirs and affect juvenile and adult salmon survival and passage timing through sections of regulated rivers such as the Columbia, Klamath, and Sacramento; and,
- Changes in coastal ocean habitat quality due to changes in productivity and seasonal cycles of production, and food chain bioenergetics.¹¹⁹⁴

With less productive coastal waters and modifications in timing of ocean entry, early ocean survival rates for Columbia River salmon will likely decline, and as observed in past periods of poor ocean conditions, declines in adult return rates may be exacerbated by large releases of hatchery fish.¹¹⁹⁵

Scientists believe that historical loss of nearshore marine and estuary habitats regionwide has already contributed to the decline in salmon populations.¹¹⁹⁶ In the Puget Sound, the general picture of climate change – increased winter flooding and decreased summer and fall stream flows, along with elevated warm season stream and estuary temperatures – would be especially problematic for instream and estuarine habitat for salmon.¹¹⁹⁷ Juvenile chum and fall Chinook salmon, considered to be the most estuary-dependent species, are at special risk:

- A recent analysis in the Skagit Delta of Puget Sound estimates that the rearing capacity in marshes for threatened juvenile Chinook salmon would decline by 211,000 and 530,000 fish, respectively, for an 18- and 32-inch (0.45 m and 0.81 m) sea level rise.¹¹⁹⁸

In conclusion, it is unknown whether the predicted rapid rate of change of new selective forces induced by climate change on salmonids will allow natural selection to produce evolutionary responses that will ameliorate impacts and retain the viability of populations.¹¹⁹⁹ Such changes have occurred: for example, in less than a century, ocean-type Chinook introduced to New Zealand colonized rivers and evolved significant differences in heritable traits.¹²⁰⁰ The advanced spawning times of hatchery reared salmon is another example of evolutionary change, in this case from artificial selection.¹²⁰¹ In any event, the future will depend on adequate freshwater spawning and rearing habitats, the chain of habitats in the life histories of anadromous salmonids, and maintenance of populations with diverse life histories and phenotypic and genetic variability to provide resilience to future changes.¹²⁰²

Information Gaps

Information is needed on observed trends particular to the Gulf of Alaska LME. Information is also needed on future projections throughout the NPLCC region. For example, information is needed to

¹¹⁹⁴ Verbatim or nearly verbatim from Peterson, W. & Schwing, F. (2008, p. 50)

¹¹⁹⁵ Verbatim or nearly verbatim from ISAB. (2007, p. 72). The authors cite Levin et al. (2001) for this information.

¹¹⁹⁶ Verbatim or nearly verbatim from Martin and Glick. (2008, p. 15). The authors cite William and Thom (2001) for this information.

¹¹⁹⁷ Verbatim or nearly verbatim from Snover et al. (2005, p. 30)

¹¹⁹⁸ Verbatim or nearly verbatim from Martin and Glick. (2008, p. 15). The authors cite Hood, W.G. (2005) for this information.

¹¹⁹⁹ Verbatim or nearly verbatim from ISAB. (2007, p. 72)

¹²⁰⁰ Verbatim or nearly verbatim from ISAB. (2007, p. 72). The authors cite Quinn et al. (2001) and Quinn (2005) for this information.

¹²⁰¹ Verbatim or nearly verbatim from ISAB. (2007, p. 72)

¹²⁰² Verbatim or nearly verbatim from ISAB. (2007, p. 72)

understand the genetic adaptation and phenotypic plasticity of salmonids in response to climate change, and the consequences for abundance, distribution, and survival.

Table 21. Nearshore marine and estuarine habitat use by salmonid species in Pacific Northwest.

Species	Nearshore Marine and Estuary Use		
	Adult Residence	Adult and Juvenile Migration	Juvenile Rearing
Chinook Salmon	Extensive Use	Extensive Use	Extensive Use
Chum Salmon	Little or Unknown	Extensive Use	Extensive Use
Coho Salmon	Some Use	Extensive Use	Some Use
Sockeye Salmon	Little or Unknown	Extensive Use	Little or Unknown
Pink Salmon	Little or Unknown	Extensive Use	Extensive Use
Cutthroat Trout	Extensive Use	Extensive Use	Extensive Use
Steelhead	Little or Unknown	Extensive Use	Some Use
Bull Trout	Extensive Use	Extensive Use	Extensive Use

Source: Williams, G.D. and R.M. Thom. 2001. *Marine and Estuarine Shoreline Modification* (Sequim, WA: Battelle Marine Sciences Laboratory/Pacific Northwest National Laboratory, p. 14. Available online at http://www.ser.org/sernw/pdf/WDFW_marine_shoreline_white_paper.pdf (accessed 12.13.2010)

Note: Table reproduced from Glick et al. (2007), Table 3, p. 13 by authors of this report.

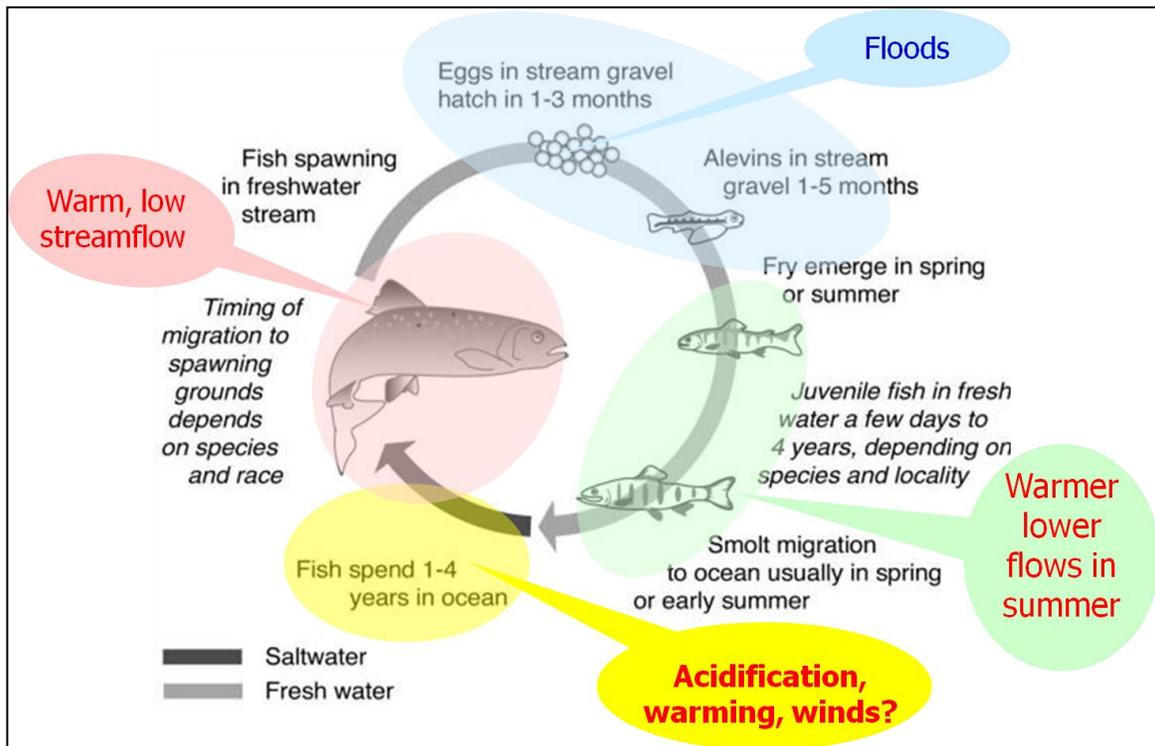


Figure 27. Climate change effects on the salmon life cycle. Reproduced with permission from Nathan Mantua.

4. SHELLFISH

Observed Trends

Global

Kroeker et al. (2010) conducted a meta-analysis of the biological effects of ocean acidification on marine organisms. Calcification was the most sensitive process, and their analyses suggest calcifying organisms are more susceptible to ocean acidification across other response variables.¹²⁰³ This pattern was also highlighted in the differences in taxonomic groups, where survival and growth were negatively affected across most calcifiers.¹²⁰⁴ With the exception of crustaceans, these results suggest the effects of ocean acidification will be negative for most calcifying organisms, but that variation in life history characteristics will prove some organisms more resilient than others.¹²⁰⁵ Specific findings include:

- Calcifying organisms generally exhibited larger negative responses than noncalcifying organisms across numerous response variables, with the exception of crustaceans, which calcify but were not negatively affected.¹²⁰⁶
 - Ocean acidification had significant negative mean effects on calcification in corals, and similar magnitude but non-significant negative mean effects on calcifying algae, coccolithophores and molluscs.¹²⁰⁷
 - Ocean acidification had a significant positive mean effect on calcification on crustaceans, and a non-significant positive effect on calcification on echinoderms.¹²⁰⁸
- The mean effect of ocean acidification on calcification varied amongst organisms with different mineral forms of calcium carbonate (CaCO₃):¹²⁰⁹
 - Organisms using aragonite and low-magnesium (low-Mg) calcite were negatively affected by ocean acidification, whereas organisms utilizing high-magnesium (high-Mg) calcite were not significantly affected.¹²¹⁰
 - These results are in contrast to the hypothesis that organisms utilizing high-Mg calcite will be more sensitive to ocean acidification because both crustaceans and coralline algae (which made up most of the calcifying algae category) utilize high-Mg calcite for calcified structures.¹²¹¹ This hypothesis, based on the solubility of the pure mineral forms in seawater, may fail to predict the sensitivity of marine organisms to ocean acidification because it does not account for biogenic calcification processes.¹²¹²

¹²⁰³ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1427)

¹²⁰⁴ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1427)

¹²⁰⁵ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1427)

¹²⁰⁶ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1419)

¹²⁰⁷ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424)

¹²⁰⁸ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 3 in the cited report.

¹²⁰⁹ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 5 in the cited report and provide statistics for this result: $Q_M = 9.91$, d.f. = 2, $P = 0.05$.

¹²¹⁰ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424)

¹²¹¹ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1428-1429)

¹²¹² Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1429). The authors cite Pörtner (2008) for this information.

- The effect of ocean acidification on calcification did not differ significantly amongst taxonomic groups.¹²¹³

Ries, Cohen, and McCorkle (2009) conducted sixty-day laboratory experiments in which they investigated the effects of CO₂-induced ocean acidification on calcification in eighteen benthic marine organisms.¹²¹⁴ They observed variable responses among benthic marine species to acidified conditions:

- Ten of eighteen benthic marine species exhibited reduced rates of net calcification and, in some cases, net dissolution under elevated *p*CO₂ (partial pressure of carbon dioxide. At the air-sea interface, *p*CO₂ values indicate whether CO₂ will be absorbed by the ocean or emitted to the air).¹²¹⁵
- However, in seven species, net calcification increased under the intermediate and/or highest levels of *p*CO₂ and one species showed no response at all.¹²¹⁶
- A combination of factors, including the organisms' ability to regulate pH at the site of calcification, the extent of organic-layer coverage of their external shell, their biomineral solubility, and whether they utilize photosynthesis, may contribute to the disparity of these response patterns.¹²¹⁷

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Some oyster hatcheries in the Pacific Northwest region have experienced mass mortalities of oyster larvae in association with a combination of circumstances including unusually saline surface waters and the upwelling of cold, CO₂- and nutrient-rich waters, which contained high concentrations of the pathogenic bacteria, *Vibrio tubiashii*, and would also have low pH and aragonite saturation values.¹²¹⁸ In Puget Sound, as may be the case for other coastal embayments and estuaries of the Pacific Northwest and elsewhere, Feely et al. (2010) note the impacts of lowered seawater pH and hypoxia may have a synergistic or compounding impact on organisms.¹²¹⁹

During central Oregon's severe hypoxic event in summer 2002, significant mortality of Dungeness crab was observed.¹²²⁰ Rates of crab mortality varied by location, from less than twenty-five percent loss in most pots within two of four regions and greater than seventy-six percent loss in most pots in another

¹²¹³ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 3 in the cited report and provide statistics for this result: $Q_M = 16.24$, d.f. = 5, $P = 0.1$.

¹²¹⁴ Verbatim or nearly verbatim from Ries, Cohen and McCorkle. *Marine calcifiers exhibit mixed responses to CO₂-induced ocean acidification*. (2009, p. 1132)

¹²¹⁵ Verbatim or nearly verbatim from Ries, Cohen and McCorkle. (2009, p. 1132)

¹²¹⁶ Verbatim or nearly verbatim from Ries, Cohen and McCorkle. (2009, p. 1132)

¹²¹⁷ Verbatim or nearly verbatim from Ries, Cohen and McCorkle. (2009, p. 1132)

¹²¹⁸ Verbatim or nearly verbatim from Feely et al. *The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary*. (2010, p. 447). The authors cite Elston et al. (2008) for information on the pathogenic bacteria, and Feely et al. (2008) for the information on low pH and aragonite saturation.

¹²¹⁹ Verbatim or nearly verbatim from Feely et al. (2010, p. 447).

¹²²⁰ Verbatim or nearly verbatim from Grantham et al. (2004, p. 750)

region.¹²²¹ During Oregon's anoxic event in 2006, surveys revealed the complete absence of all fish from rocky reefs that normally serve as habitats for diverse rockfish communities that are of current fishery management concern.¹²²² Near-complete mortality of macroscopic benthic invertebrates was also observed.¹²²³

Recent abundance observations have not indicated any significant decrease in California Current System pteropod population size,¹²²⁴ whereas the Pacific oyster *Crassostrea gigas* exhibited recruitment failure during four consecutive years (2005–2008).¹²²⁵ *C. gigas* has an aragonitic larval stage, making it exceptionally vulnerable to decreasing aragonite saturation states.¹²²⁶

Rogers-Bennett et al. (2010) examined the impacts of warm water, starvation, and disease on reproduction in red abalone (*Haliotis rufescens*; a harvested species).¹²²⁷ Wild abalone were gathered from sites in northern and southern California and subjected to a series of laboratory experiments.¹²²⁸

Rogers-Bennett et al. concluded both male and female red abalone responded negatively to warm water, starvation, and disease stressors, with declines in sperm formation among males and declines in egg production and quantity among females:¹²²⁹

- At temperatures above 60.8°F (16°C) lasting for one year, total reproductive failure was observed in males irrespective of food treatment.¹²³⁰
- Females exposed to 64.4°F (18°C) water for six months had diminished egg quantity, while those exposed to starvation did not produce any mature eggs.¹²³¹

Future Projections

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Hauri et al. (2009) state secondary producers in the California Current System (CCS) can be affected both directly as a result of a change in seawater chemistry, and also indirectly by changes in food quality, prey disappearance, and altered timing of phytoplankton blooms.¹²³² Limited experiments available today

¹²²¹ Grantham et al. (2004, p. 750). Figure 1b displays crab mortality rates within four regions of the hypoxic zone. For example, in the region shown at top, crab mortality in most pots was recorded as one to twenty-five percent.

¹²²² Verbatim or nearly verbatim from Chan et al. (2008, p. 920)

¹²²³ Verbatim or nearly verbatim from Chan et al. (2008, p. 920)

¹²²⁴ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68). The authors cite Ohman and Lavaniegos (2008) for this information.

¹²²⁵ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68). The authors cite Elston et al. (2008) for this information.

¹²²⁶ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68). The authors cite Elston et al. (2008) for this information.

¹²²⁷ Verbatim or nearly verbatim from Rogers-Bennett et al. *Response of red abalone production to warm water, starvation, and disease stressors: implications of ocean warming.* (2010, p. 599)

¹²²⁸ Rogers-Bennett et al. (2010)

¹²²⁹ Rogers-Bennett et al. (2010)

¹²³⁰ Verbatim or nearly verbatim from Rogers-Bennett et al. (2010, p. 599)

¹²³¹ Verbatim or nearly verbatim from Rogers-Bennett et al. (2010, p. 599)

¹²³² Verbatim or nearly verbatim from Hauri et al. (2009, p. 67)

suggest that the aragonite-shelled pteropods, foraminifera, and planktonic life stages of bivalves and echinoderms are affected directly by ocean acidification as they experience either rapid shell dissolution and reduced calcification ability or larvae develop with a temporal delay, build abnormal asymmetry, and often die before metamorphosis in aragonite undersaturated waters.¹²³³ However, one study points out that such negative responses are species specific, so that the primary effect in a future, more acidic ocean is likely to be a shift in species composition rather than the complete disappearance of an entire class of organisms.¹²³⁴ The recent meta-analysis by Kroeker et al. (2010), described previously, provides further insight on these topics.

Benthic organisms appear to be among those that will be most affected by the continuing acidification of the California Current System.¹²³⁵ Benthic organisms will be exposed to the lowest pH and aragonite saturation states in the nearshore, shallow areas, and many of them appear to be sensitive to ocean acidification.¹²³⁶ Moreover, their ability to migrate is limited.¹²³⁷ However, given limited understanding, this conclusion should be viewed as a preliminary assessment rather than a final conclusion.¹²³⁸ More accurate projections require special consideration of the integrated effects of ocean acidification, ocean warming, decreasing oxygen levels, and other processes that are expected with global change.¹²³⁹

Information Gaps

Information is needed on the Gulf of Alaska LME, both observed trends and future projections. For the California Current Ecosystem, additional experiments and quantitative future projections are needed. Kroeker et al. (2010) note the resilience of crustaceans and coralline algae requires further experimentation to understand the mechanisms for their responses.¹²⁴⁰

¹²³³ Verbatim or nearly verbatim from Hauri et al. (2009, p. 67-68). The authors cite Orr et al. (2005), Fabry et al. (2008), Kurihara et al. (2008), Dupont and Thorndyke (2009), and Lebrato et al. (in press) for this information.

¹²³⁴ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68). The authors cite Dupont and Thorndyke (2009) for this information.

¹²³⁵ Verbatim or nearly verbatim from Hauri et al. (2009, p. 61)

¹²³⁶ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68)

¹²³⁷ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68)

¹²³⁸ Verbatim or nearly verbatim from Hauri et al. (2009, p. 68)

¹²³⁹ Verbatim or nearly verbatim from Hauri et al. (2009, p. 61)

¹²⁴⁰ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1429)

5. EELGRASS

Eelgrass is a flowering plant adapted to the marine environment that roots in sand or mud in shallow waters typically less than ten meters deep where waves and currents are not too severe.¹²⁴¹ It is critical spawning and fertilization ground for Pacific herring eggs in southern British Columbia waters, which in turn is central to the marine food web, contributing thirty to seventy percent to the summer diets of Chinook salmon, Pacific cod, lingcod, and harbor seals in the area.¹²⁴² A report from the Washington Department of Natural Resources (2007; WA DNR) provides additional detail on the role of eelgrass in the nearshore ecosystem: in greater Puget Sound, *Z. marina* also provides spawning grounds for Pacific herring (*Clupea harengus pallasii*), out-migrating corridors for juvenile salmon (*Oncorhynchus* spp.), and important feeding and foraging habitats for waterbirds such as the black brant (*Branta bernicla*) and great blue heron (*Ardea herodias*).¹²⁴³ Similarly, forty-two species of fish (mostly juvenile and including chum salmon and Pacific herring), as well as juvenile shrimp, hermit crabs, and juvenile Dungeness crabs, were found during nearshore habitat sampling in the City and Borough of Juneau, Alaska from 2004 to 2007.¹²⁴⁴

Observed Trends

Gulf of Alaska LME

Information needed.

California Current Ecosystem

At several sites in Willapa and Coos Bay (located in Washington and Oregon, respectively), Thom et al. (2003) observed plant density of eelgrass was positively correlated with summer estuarine salinity and inversely correlated with water temperature gradients in the estuaries from 1998 to 2001.¹²⁴⁵ Warmer periods can cause drying that concentrates mineral salts to levels that are stressful or toxic.¹²⁴⁶ Warmer winters and cooler summers associated with the transition from El Niño to La Niña ocean conditions during the study period corresponded with a substantial increase in eelgrass abundance and flowering in Willapa Bay, and less so in Coos Bay.¹²⁴⁷ The results suggest profound effects of climate variation on the abundance and flowering of eelgrass in Pacific Northwest coastal estuaries.¹²⁴⁸

¹²⁴¹ Verbatim or nearly verbatim from Mumford. *Kelp and eelgrass in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-05.* (2007, p. v)

¹²⁴² Verbatim or nearly verbatim from Wright. *Eelgrass conservation for the B.C. coast: a discussion paper.* (2002, p. 3)

¹²⁴³ WA DNR. *Eelgrass Stressor-Response Report: 2005-2007 Report.* (2007, p. 4). The authors cite Phillips (1984) and Simenstad (1994) for information on juvenile salmon, Wilson and Atkinson (1995) for information on black brant, and Butler (1995) for information on great blue heron.

¹²⁴⁴ Verbatim or nearly verbatim from Harris et al. *Eelgrass habitat and faunal assemblages in the City and Borough of Juneau, Alaska.* (2008, p. iii)

¹²⁴⁵ Verbatim or nearly verbatim from Thom et al. *Factors influencing spatial and annual variability in eelgrass (*Zostera marina* L.) meadows in Willapa Bay, Washington and Coos Bay, Oregon, Estuaries.* (2003, p. 1117)

¹²⁴⁶ Thom et al. *The influence of climate variation and change on structure and processes in nearshore vegetated communities of Puget Sound and other northwest estuaries.* (2001)

¹²⁴⁷ Verbatim or nearly verbatim from Thom et al. (2003, p. 1117)

¹²⁴⁸ Verbatim or nearly verbatim from Thom et al. (2003, p. 1117)

Non-native and invasive exotic plants, such as cordgrass *Spartina* spp, the brown algae *Sargassum muticum*, or the Japanese eelgrass *Zostera japonica* crowd and displace native plants.¹²⁴⁹ However, in most cases in the Pacific Northwest region, there is little opportunity for direct competition between the two *Zostera* species because they occupy different niches in the intertidal zone.¹²⁵⁰ Where they do overlap, neither species is clearly competitively dominant, since biomass and density of both species are reduced in the presence of the other.¹²⁵¹

Future Projections

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Previous short term studies demonstrated that carbon enrichment can sustain eelgrass growth under light limitation.¹²⁵² Eelgrass has been projected to possibly benefit from acidification – in this case due to an enhancement of photosynthesis from an increased abundance of dissolved carbon dioxide.¹²⁵³ However, these benefits may be ultimately offset by water quality decline, and may have an upper threshold.¹²⁵⁴ Increased water temperature in rivers, for example, can harm or kill eelgrass close to the river mouth.¹²⁵⁵ In the Pacific Northwest, eelgrass variation may be related to sea level and temperature changes such that a decline under warmer, drier conditions would be expected.¹²⁵⁶

Kroeker et al. (2010) suggest another rationale for observed differences in seagrass response to ocean acidification and light: species-specific differences in response to ocean acidification may be more pronounced within certain taxonomic groups, and are likely responsible for the inability to detect strong effects of ocean acidification in photosynthesis in seagrasses (e.g., eelgrass).¹²⁵⁷ Some species of seagrass significantly increase photosynthesis under reduced pH, whereas other species are relatively immune to the changes due to differences in their carbon-concentrating mechanisms.¹²⁵⁸

Palacios and Zimmerman (2007) show that long-term CO₂ enrichment derived from the flue gas of an electric power plant enhances the performance of eelgrass growing under natural light conditions over a year, resulting in significantly higher reproductive output, below-ground biomass and vegetative

¹²⁴⁹ Verbatim or nearly verbatim from Puget Sound Water Quality Action Team (PSWQAT). *Sound Facts: Eelgrass (pdf)*. (2001, p. 2)

¹²⁵⁰ Verbatim or nearly verbatim from Mach, Wyllie-Echeverria and Ward. *Distribution and potential effects of a non-native seagrass in Washington State: Zostera japonica workshop*. (2010, p. 8). The authors cite Shafer (2007) for this information.

¹²⁵¹ Verbatim or nearly verbatim from Mach, Wyllie-Echeverria and Ward. (2010, p. 8)

¹²⁵² Verbatim or nearly verbatim from Palacios and Zimmerman. *Response of eelgrass Zostera marina to CO₂ enrichment: possible impacts of climate change and potential for remediation of coastal habitats*. (2007, p. 1)

¹²⁵³ Guinotte and Fabry. *Ocean acidification and its potential effects on marine ecosystems*. (2008); Thom. *CO₂-Enrichment effects on eelgrass (Zostera marina L.) and bull kelp (Nereocystis luetkeana (Mert.) P. & R.)*. (1996)

¹²⁵⁴ Verbatim or nearly verbatim from Thom. (1996, p. 88).

¹²⁵⁵ Verbatim or nearly verbatim from PSWQAT. (2001, p. 2)

¹²⁵⁶ Thom et al. (2001)

¹²⁵⁷ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1430)

¹²⁵⁸ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1430). The authors cite Invers et al. (1997) for this information.

proliferation of new shoots.¹²⁵⁹ Three concentrations of carbon dioxide in solution [CO₂(aq)] were used, representing current values (16 μM CO₂(aq), pH 8.1) and three scenarios of higher concentration: pH 7.75 in 2100 (36 μM CO₂(aq)), pH 7.5 in 2200 (85 μM CO₂(aq)), and pH 6.2 (1123 μM CO₂(aq)), which triples the light-saturated photosynthesis rate of eelgrass.¹²⁶⁰ Their findings include:

- **Shoot size and biomass accumulation:** Shoots growing at 36 μM CO₂(aq) were 25% larger than those in the unenriched treatment [16 μM CO₂ (aq)], at 85 μM CO₂ (aq) shoots were 50% larger than those in the unenriched treatment and at 1123 μM CO₂(aq) shoots were almost twice as large as those in the unenriched treatment.¹²⁶¹
- **Flowering shoot production:** The proliferation of flowering shoots responded positively to CO₂(aq) enrichment in the light-replete treatments.¹²⁶² Flowering shoots appeared earlier in the year and matured more quickly in proportion to [CO₂(aq)].¹²⁶³ At 1123 μM CO₂(aq) in May 2001, 22% of the shoots differentiated into flowers, more than twice the flowering output of the other treatments at this light level.¹²⁶⁴
- **Vegetative shoot abundance:** Shoot abundance was stable in the 16, 36, and 85 μM CO₂(aq) treatments under light-replete conditions through summer 2001.¹²⁶⁵ Abundance in the 1123 μM treatment dropped in late spring as flowering shoots matured and then died.¹²⁶⁶ However, the shoot population of this highest CO₂(aq) treatment recovered subsequently through late spring and summer as a result of vegetative proliferation.¹²⁶⁷ Shoot numbers declined in all treatments in winter.¹²⁶⁸

Information Gaps

Information is needed on studies testing eelgrass under various environmental conditions in the NPLCC region to determine its potential reaction to the changing climate, including studies of interspecies interaction with other native and nonnative plant species. Information is also needed on observed trends in the Gulf of Alaska LME.

¹²⁵⁹ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 1)

¹²⁶⁰ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 6). The authors cite Zimmerman et al. (1997) for the photosynthetic rate.

¹²⁶¹ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 6). The authors refer the reader to Fig. 4a in the cited report.

¹²⁶² Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 8). The authors refer the reader to Table 3 and Fig. 7a in the cited report.

¹²⁶³ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 8).

¹²⁶⁴ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 8). The authors refer the reader to Fig. 8 in the cited report.

¹²⁶⁵ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 8). The authors refer the reader to Fig. 9a in the cited report.

¹²⁶⁶ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 8)

¹²⁶⁷ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 8)

¹²⁶⁸ Verbatim or nearly verbatim from Palacios and Zimmerman. (2007, p. 8)

6. PLANKTON

Despite their microscopic size, marine phytoplankton are responsible for about half of the global primary production and represent the basis of the marine food web.¹²⁶⁹ This diverse group of organisms drives important biogeochemical cycles, exporting massive amounts of carbon to deep waters and sediments, and strongly influencing ocean-atmosphere gas exchanges.¹²⁷⁰ The distribution and abundance of

Plankton are microscopic aquatic organisms that drift or swim weakly. Phytoplankton are the basis of the entire marine food web and are the dominant plants in the sea. These single-celled organisms are the principle agents of photosynthetic carbon fixation in the ocean. Zooplankton are the animal forms of plankton. They consume phytoplankton or other zooplankton.

Source: Parry et al. (2007); Rost, Zondervan, & Wolf-Gladrow. (2008)

phytoplankton communities throughout the world, as well as their phenology and productivity, are changing in response to warming, acidifying, and stratifying oceans.¹²⁷¹ The annual primary production of the world's oceans has decreased by at least six percent since the early 1980s (no end date provided), with nearly seventy percent of this decline occurring at higher latitudes and with large relative decreases occurring within Pacific and Indian ocean gyres.¹²⁷² Overall, changes in the primary production of the oceans have profound implications for the marine biosphere, carbon sinks, and biogeochemistry of Earth.¹²⁷³ In the case of phytoplankton, these factors include nutrients and iron availability, temperature, light, and predation, and other factors.¹²⁷⁴ Essential fatty acids are produced exclusively by marine phytoplankton and transferred up the food chain to

fish through their zooplankton prey.¹²⁷⁵ Some of these lower trophic members such as coccolithophores, foraminifera, and pteropods may be particularly vulnerable to ocean acidification as calcium carbonate forms their biological structure.¹²⁷⁶ Changes in the production rates and community composition of phytoplankton and zooplankton could lead to changes in the fatty acid composition of prey that might not contain the essential fatty acids needed for optimal growth and survival of larval and juvenile fishes.¹²⁷⁷

¹²⁶⁹ Verbatim or nearly verbatim from Rost, Zondervan and Wolf-Gladrow. *Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions.* (2008, p. 227)

¹²⁷⁰ Verbatim or nearly verbatim from Rost, Zondervan and Wolf-Gladrow (2008, p. 227)

¹²⁷¹ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Doney et al. (2009) and Polovina et al. (2008) for this information.

¹²⁷² Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Gregg et al. (2003) for information about higher latitudes and Polovina et al. (2008) for information about the Pacific and Indian oceans.

¹²⁷³ Verbatim or nearly verbatim from Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Falkowski et al. (2000) for this information.

¹²⁷⁴ Verbatim or nearly verbatim from Hauri et al. (2009, p. 66-67). The authors cite Hare et al. (2007) and Tortell et al. (1997, 2008) for this information.

¹²⁷⁵ Verbatim or nearly verbatim from Sigler et al. (2008, p. 12)

¹²⁷⁶ Verbatim or nearly verbatim from Sigler et al. (2008, p. 12)

¹²⁷⁷ Verbatim or nearly verbatim from Sigler et al. (2008, p. 12)

Observed Trends

Global

Declining ocean pH affects plankton, particularly those with calcium carbonate shells.¹²⁷⁸ These changes are likely to be important to the food web, but in ways scientists cannot entirely predict.¹²⁷⁹ Kroeker et al.'s (2010) meta-analysis of 251 unique experiments on the biological response of marine organisms revealed that ocean acidification had a significant negative effect on survival, calcification, growth, and reproduction, but no significant effect on photosynthesis.¹²⁸⁰ The negative effect of ocean acidification was most pronounced for calcification and survival.¹²⁸¹ There was significant heterogeneity in the calcification and growth responses, but not for the other response variables.¹²⁸² The results of this study are addressed in further detail in other sections of this report: for calcification, see Section 4 (Shellfish) in this Chapter; for survival, see Chapter VI.3 (Shifts in community composition, competition, & survival); for growth and developmental stages, see Chapter VI.2 (Altered phenology and development); and for photosynthesis, see Chapter IV.2 (Altered ocean productivity).

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Along rocky intertidal zones of the Oregon coast, a study by Menge et al. (2009) of the influence of climatic variation on phytoplankton abundance and mussel recruitment found that the North Pacific Gyre Oscillation had the strongest relationships with both phytoplankton and recruitment, while relationships between these factors and ENSO and PDO were weak.¹²⁸³ Despite the strong relationship between climate variation, phytoplankton concentration, and mussel recruitment, intertidal community dynamics have changed only in relatively subtle ways, suggesting a role for local ecological interactions in dampening the effects of dominant modes of climate forcings in coastal ecosystems.¹²⁸⁴

Future Projections

Gulf of Alaska LME

With increasing SST, a northward shift by end-of-century of a region in the North Pacific that shows large seasonal cycles in phytoplankton and herbivore concentrations, roughly between 150°E and 140°W, 50°N and 60°N is projected.¹²⁸⁵ This is accompanied by a decrease in springtime primary productivity, which is

¹²⁷⁸ Verbatim or nearly verbatim from Snover et al. (2005, p. 27)

¹²⁷⁹ Verbatim or nearly verbatim from Snover et al. (2005, p. 27)

¹²⁸⁰ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 1 in the cited report.

¹²⁸¹ Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424)

¹²⁸² Verbatim or nearly verbatim from Kroeker et al. (2010, p. 1424). The authors provide statistics for heterogeneity in calcification ($Q_T = 116.33$, d.f. = 62, $P < 0.0001$) and growth responses ($Q_T = 224.76$, d.f. = 85, $P < 0.0001$).

¹²⁸³ Verbatim or nearly verbatim from Menge et al. *Climatic variation alters supply-side ecology: impact of climate patterns on phytoplankton and mussel recruitment.* (2009, p. 379)

¹²⁸⁴ Verbatim or nearly verbatim from Menge et al. (2009, p. 379)

¹²⁸⁵ Verbatim or nearly verbatim from Pierce. *Future changes in biological activity in the North Pacific due to anthropogenic forcing of the physical environment.* (2004, p. 412). This region is bounded approximately by an east-

partially counteracted by an increase in wintertime productivity.¹²⁸⁶ Changes in mixed layer temperature and depth account for almost all the changes in productivity; model-predicted changes in surface insolation (a measure of solar energy over a given surface and time period) and large-scale upwelling have little impact.¹²⁸⁷

California Current Ecosystem

In the California Current System (CCS), a preliminary assessment by Hauri et al. (2009) suggests that ocean acidification will cause a species shift in open ocean phytoplankton, with diatoms possibly profiting at the expense of calcifying phytoplankton.¹²⁸⁸ However, any conclusions about future phytoplankton compositions in the CCS remain speculative because factors such as nutrients and iron availability, temperature, light, and predation might change in parallel in the future, and because there is a lack of experiments that cover a combination of all factors.¹²⁸⁹

Information Gaps

Studies that specifically assess the current or potential response of planktonic species to climate change such as studies on potential changes to the occurrence and quantity of species, interspecies interactions, and food web interactions, are needed.

west line through Strathcona Provincial Park on Vancouver Island (BC) in the south, a north-south line passing through Yakutat (AK) in the east, a north-south line through the east coast of Australia in the west, and an east-west line through Seward AK in the north.

¹²⁸⁶ Verbatim or nearly verbatim from Pierce. (2004, p. 412)

¹²⁸⁷ Verbatim or nearly verbatim from Pierce. (2004, p. 389)

¹²⁸⁸ Verbatim or nearly verbatim from Hauri et al. (2009, p. 67)

¹²⁸⁹ Verbatim or nearly verbatim from Hauri et al. (2009, p. 67)

VIII. ADAPTING TO THE EFFECTS OF CLIMATE CHANGE IN THE MARINE & COASTAL ENVIRONMENT

This section presents adaptation actions culled from peer-reviewed studies, government reports, publications from non-governmental organizations, and interviews with experts.

In this report, “adaptation” refers to the IPCC’s definition: “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.”¹²⁹⁰

Climate change is now widely acknowledged as a global problem that threatens marine and coastal conservation, management, and policy.¹²⁹¹ Adaptation is one of two major ways in which climate-related risks can be managed (the other is mitigation, which includes strategies to reduce greenhouse gas sources and emissions, and enhance greenhouse gas sinks).¹²⁹² Even if global greenhouse gas emissions were to be stabilized near their current levels, atmospheric concentrations would increase throughout the 21st century, and might well continue to increase slowly for several hundred years after that.¹²⁹³ Thus, mitigation can reduce climate-related risks only in the longer term.¹²⁹⁴ Adaptation has emerged as a necessary response to and preparation for the unavoidable impacts of global climate change.¹²⁹⁵

Adaptation is in its infancy and the field is developing in a rapid and *ad hoc* fashion.¹²⁹⁶ However, general and specific approaches to adaptation action are emerging, as are common tenets of adaptation action.¹²⁹⁷ Along with these, existing conservation activities are being applied to climate change adaptation, and new activities are also being developed.¹²⁹⁸ The states, provinces, and tribal governments of the NPLCC region are developing climate change adaptation strategies. Each of these topics is covered in turn:

- **Framework for Adaptation Actions:** A general approach and specific planning and management approaches to adaptation action, derived from published and grey literature.
- **Common Tenets of Adaptation Action:** Adaptation principles derived from the literature.
- **Climate Adaptation Actions:** Adaptation actions are organized into five broad categories, including information gathering and capacity building; monitoring and planning; infrastructure and development; governance, policy, and law; and, conservation, restoration, protection and natural resource management. The actions described represent the range of ideas suggested by the scientific literature on climate change adaptation. They are not intended as recommendations.

¹²⁹⁰ Verbatim or nearly verbatim from IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Introduction*. (2007b, p. 6)

¹²⁹¹ Verbatim or nearly verbatim from Gregg et al. *The State of Marine and Coastal Adaptation in North America: A Synthesis of Emerging Ideas (Final Report)*. (2011, p. 30)

¹²⁹² Asian Development Bank (ADB). *Climate Proofing: A risk-based approach to adaptation*. (2005, p. 7); Information on mitigation available from Parry et al. (2007, p. 878)

¹²⁹³ Verbatim or nearly verbatim from ADB. (2005, p. 7)

¹²⁹⁴ ADB. (2005, p. 7)

¹²⁹⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 30)

¹²⁹⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 30)

¹²⁹⁷ ADB (2005); Gregg et al. (2011); Heller and Zavaleta (2009); NOAA. *Adapting to Climate Change: A Planning Guide for State Coastal Managers*. (2010)

¹²⁹⁸ See, for example, Baron et al. (2009); Heller and Zavaleta (2009); Mawdsley, O’Malley, and Ojima (2009); NOAA. (2010); U.S. EPA. (2009).

- **Status of Adaptation Strategies and Plans:** Brief descriptions of the development and implementation of state, provincial, and selected tribal adaptation strategies in the NPLCC region.

1. FRAMEWORK FOR ADAPTATION ACTIONS

General Approach to Adaptation Action

Adaptation actions are undertaken either to avoid or take advantage of actual and projected climate change impacts either by decreasing a system's vulnerability or increasing its resilience.¹²⁹⁹ Glick et al. (2011a) note this may entail reprioritizing current efforts as well as identifying new goals and objectives to reduce overall ecosystem vulnerability to climate change.¹³⁰⁰ The former – reprioritizing current efforts – is known as a “bottom-up” or “project-based” approach and involves integrating climate change considerations into existing management and program structures.¹³⁰¹ The latter – identifying new goals and objectives – is known as a “top-down” or “landscape-based” approach and is particularly useful for broad-scale efforts, such as those conducted at regional, state, or national levels for one or more sectors.¹³⁰²

General approaches to and principles of adaptation action in both human and natural systems have been addressed in past reports.¹³⁰³ A review of these reports indicates the approaches and adaptation principles are consolidated typically into four broad steps:

1. **Assess current and future climate change impacts and conduct a vulnerability assessment.**¹³⁰⁴ Gregg et al. (2011) suggest the vulnerability assessment may focus on a species, place, program, community, or anything else of concern to those doing the assessment, and should include exposure (the nature and degree to which a system is exposed to significant climatic variations), sensitivity (the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli), and adaptive capacity (ability of the system to respond effectively), as well as interactions with other factors, such as existing stressors or possible changes in human resource use patterns.¹³⁰⁵ In all cases, the assessment should begin with the overall goal of those carrying it out (e.g. sustainable fisheries management, coastal habitat protection).¹³⁰⁶ Further information on conducting vulnerability assessments is provided in Section 3 of this Chapter.
2. **Select conservation targets and course of action.**¹³⁰⁷ This step includes identifying, designing, prioritizing, and implementing management, planning, or regulatory actions and policies that reduce the vulnerabilities and/or climate change effects identified in Step 1.¹³⁰⁸ *Note that Steps 1 and 2 are interchanged in some reports (CIG 2007; Heller & Zavaleta 2009), and are considered iterative by others (Glick et al. 2009).*

¹²⁹⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 29). The authors cite ADB (2005), Levin & Lubchenco (2008), Lawler (2009). Pew Center (2009).

¹³⁰⁰ Verbatim or nearly verbatim from Glick et al. (2011a, p. 7)

¹³⁰¹ Glick et al. (2011a, p. 7); Glick et al. (2011b, Box 1.1, p. 13)

¹³⁰² Glick et al. (2011a, p. 8); Glick et al. (2011b, Box 1.1, p. 13)

¹³⁰³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 30)

¹³⁰⁴ Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010); U.S. AID (2009); CIG (2007); ADB (2005); Pew Center. (2009)

¹³⁰⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 30)

¹³⁰⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 30)

¹³⁰⁷ Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010); U.S. AID (2009); CIG (2007); Pew Center. (2009)

¹³⁰⁸ Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010); U.S. AID (2009); CIG (2007)

3. **Measure, evaluate, and communicate progress** through the design and implementation of monitoring programs that assess changes in the chosen parameters of management and/or policy effectiveness.¹³⁰⁹
4. **Create an iterative process to reevaluate and revise the plan, policy, or program**, including assumptions.¹³¹⁰

In some reports, a wider planning process and team-building activities precede Step 1 above. For example, the process outlined in NOAA’s *Adapting to Climate Change: A Planning Guide for State Coastal Managers* (2010) begins with a planning process that includes scoping the level of effort and responsibility; assessing resource needs and availability; assembling a planning team and establishing responsibilities; and, educating, engaging & involving stakeholders.¹³¹¹ The Climate Impacts Group *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* (2007) includes similar steps: scope climate change impacts in major sectors; build and maintain support to prepare for climate change by identifying a “champion” and audience, and developing and spreading a message; and, build a climate change preparedness team.¹³¹² The Asian Development Bank’s (2005) approach begins with capacity building and provision, enhancement, and application of data, tools, and knowledge.¹³¹³

Specific Planning and Management Approaches to Adaptation Action

Two of many approaches to adaptation planning and management in the coastal and marine environment are:

- **The U.S. EPA’s National Estuary Program – Climate Ready Estuaries**

There are five critical elements in an adaptation plan that earns recognition as a “Climate Ready Estuary:”

- *Assessment of vulnerability to climate change*, which includes a description of the specific effects from climate change (and interactions of climate change with existing stressors) that are likely to affect key management goals, the timeframe for the predicted effects, and consideration of uncertainty or other factors needed to set planning priorities.¹³¹⁴
- *Summary of considerations used to set priorities and select actions*, including the timing and severity of projected impacts, the probability of occurrence of different impacts, the economic or social value of endpoints in concern, and the capacity of the community to undertake the action compared to the scale of impacts.¹³¹⁵

¹³⁰⁹ Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010); U.S. AID (2009); CIG (2007); ADB (2005)

¹³¹⁰ Gregg et al. (2011); Glick et al. (2009); NOAA (2010); U.S. AID (2009); CIG (2007); ADB (2005)

¹³¹¹ NOAA. (2010)

¹³¹² CIG. (2007)

¹³¹³ ADB. (2005, p. 95)

¹³¹⁴ Verbatim or nearly verbatim from U.S. EPA. *Adaptation Planning for the National Estuary Program*. (2009, p. 2)

¹³¹⁵ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 3)

- ***Description of specific adaptation actions for implementation***, which is a limited set of essential actions and a preliminary schedule and approach to achieving those actions.¹³¹⁶ The crucial need is to select realistic actions to address known risks and identify the needs to implement those actions.¹³¹⁷ In the style of adaptive management, the plan should recognize the need to proceed without complete information and acknowledge the need to revisit and update the plan.¹³¹⁸
- ***Plan for communicating with stakeholders and decision-makers***, which may include new communication techniques and strategies to address unfamiliar concerns in addition to existing communications strategies.¹³¹⁹
- ***Plan for monitoring and evaluating results***, that outlines the process that will be used to periodically monitor and evaluate (1) climate-driven changes in the estuary, and (2) the effectiveness of adaptation actions in lessening the negative impacts of those climate-driven changes.¹³²⁰

- **The U.S. NOAA’s Planning Guide for State Coastal Managers**

This document is structured to help guide managers through the planning process from establishing the planning team to implementing the plan.¹³²¹ The major components of developing a plan are:

- ***The planning process***, which involves scoping the level of effort and responsibility of those involved, assessing resource needs and availability, assembling the planning team and establishing responsibilities, and educating, engaging, and involving stakeholders.¹³²²
- ***The vulnerability assessment***, in which climate change phenomena, impacts, and consequences are identified, the sensitivity, exposure, and adaptive capacity of systems is assessed, scenarios are developed to simulate changes, and focus areas are identified.¹³²³
- ***Developing the adaptation strategy***, which includes setting goals, identifying actions, evaluating, selecting, and prioritizing actions, and writing the action plan.¹³²⁴
- ***Implementing and maintaining the plan***, which includes adopting and implementing the plan, integrating the plan into other state planning efforts and programs, tracking, evaluating, and communicating progress, and updating the plan.¹³²⁵

¹³¹⁶ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 4)

¹³¹⁷ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 4)

¹³¹⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 4)

¹³¹⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 5)

¹³²⁰ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 6)

¹³²¹ Verbatim or nearly verbatim from NOAA. *Adapting to Climate Change: A Planning Guide for State Coastal Managers*. (2010, p. 4)

¹³²² Verbatim or nearly verbatim from NOAA. (2010, p. 16-25)

¹³²³ Verbatim or nearly verbatim from NOAA. (2010, p. 26-44)

¹³²⁴ Verbatim or nearly verbatim from NOAA. (2010, p. 45-101)

¹³²⁵ Verbatim or nearly verbatim from NOAA. (2010, p. 102-106)

2. COMMON TENETS OF ADAPTATION ACTION

No single element or component of adaptation is a solution on its own, and there is no universally best set of solutions.¹³²⁶ Gregg et al. (2011) note that successfully adapting to climate change relies on a mixture of approaches as well as perpetual review and modification as new information comes to light, new ideas are generated, and additional changes take place.¹³²⁷ Scientists are increasingly emphasizing the concepts of maintaining or improving ecosystem resistance and resilience,¹³²⁸ as well as enabling or facilitating the ability of a species or ecosystem to change,¹³²⁹ e.g. via response or realignment.¹³³⁰ A review of the published and grey literature indicates the following are common tenets of adaptation action:

- Remove other threats and reduce non-climate stressors that interact negatively with climate change or its effects.¹³³¹
- Establish or increase habitat buffer zones and corridors, including adjustments to protected area design and management such as expanding reserve networks.¹³³²
- Increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management (Box 18 and Box 19).¹³³³

Four additional tenets were also found in the literature, although they were not cited universally:

- Manage for ecological function and protection of biological diversity, including restoration of habitat and system dynamics.¹³³⁴
- Implement proactive management and restoration strategies, which may include translocations.¹³³⁵
- Reduce local and regional climate change, e.g. via restoration, planting vegetation.¹³³⁶
- Reduce greenhouse gas emissions.¹³³⁷

¹³²⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 30)

¹³²⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 30)

¹³²⁸ Verbatim or nearly verbatim from Glick et al. (2009, p. 12)

¹³²⁹ Verbatim or nearly verbatim from Glick et al. (2009, p. 13)

¹³³⁰ Verbatim or nearly verbatim from U.S. Fish and Wildlife Service. *Rising to the urgent challenge: strategic plan for responding to accelerating climate change (pdf)*. (2010, Sec1:16). The authors cite Millar et al. (2007) for information on realignment.

¹³³¹ Gregg et al. (2011); Lawler (2009); Glick et al. (2009)

¹³³² Gregg et al. (2011); Lawler (2009); Glick et al. (2009)

¹³³³ Gregg et al. (2011); Lawler (2009); Glick et al. (2009)

¹³³⁴ Glick et al. (2009); Lawler (2009)

¹³³⁵ Glick et al. (2009); Lawler (2009)

¹³³⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 32)

¹³³⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 33)

Box 18. Managing uncertainty: Scenario-based planning and adaptive management.

Scenario-based planning: Scenario planning is a concept developed by Peterson, Cumming, & Carpenter (2003).¹³³⁸ It is a systematic method for thinking creatively about possible complex and uncertain futures.¹³³⁹ The central idea of scenario planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome.¹³⁴⁰ In this context, the scenarios are not predictions or forecasts but, rather, a set of *plausible* alternative future conditions.¹³⁴¹ Scenario planning is appropriate for systems in which there is a lot of uncertainty that is not controllable.¹³⁴² This approach is used by the IPCC (see Box 2 for an explanation).

Adaptive management: Adaptive management is a systematic approach for improving resource management by learning from management outcomes.¹³⁴³ It puts management actions into an experimental framework, specifying what information is needed to evaluate management success and how and when it will be used to adjust management actions.¹³⁴⁴ In theory, adaptive management allows for the management of highly uncertain systems.¹³⁴⁵ It is useful not only when the future is uncertain, but when there is uncertainty about which management approach is best or how the system being managed functions even under today's conditions.¹³⁴⁶ It may be particularly useful in cases where immediate action is required to address short-term and/or potentially catastrophic long-term consequences or where management actions are likely to have no regrets near-term benefits.¹³⁴⁷ While it is a common complaint that current environmental rules and regulations lack the flexibility needed for true adaptive management, the U.S. Department of the Interior's technical guide to adaptive management provides both suggestions for and examples of effective adaptive management in the federal context.¹³⁴⁸

¹³³⁸ Glick et al. (2009, p. 18)

¹³³⁹ Verbatim or nearly verbatim from Peterson, Cumming and Carpenter. *Scenario planning: a tool for conservation in an uncertain world*. (2003, p. 359)

¹³⁴⁰ Peterson, Cumming and Carpenter. (2003, p. 359)

¹³⁴¹ Glick et al. (2009, p. 18)

¹³⁴² Verbatim or nearly verbatim from Peterson, Cumming and Carpenter. (2003, p. 365)

¹³⁴³ Williams et al. *Adaptive Management: The U.S. Department of the Interior Technical Guide*. (2009, p. 1). The authors cite Sexton et al. (1999) for this information.

¹³⁴⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 32)

¹³⁴⁵ Lawler. (2009, p. 85)

¹³⁴⁶ Verbatim or nearly verbatim from Glick et al. *Restoring the Great Lakes' Coastal Future: Technical Guidance for the Design and Implementation of Climate-Smart Restoration Projects*. (2011a, p. 39)

¹³⁴⁷ Verbatim or nearly verbatim from Glick et al. (2011a, p. 39). The authors cite Ojima and Corell (2009) and Climate Change Wildlife Action Plan Working Group (2008) for this information.

¹³⁴⁸ Verbatim or nearly verbatim from Glick et al. *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment*. (2011b, Box 1.2, p. 15). The authors cite Williams et al. (2007) for the technical guide.

Box 19. Adaptation and Adaptive Management: Complementary but Distinct Concepts.

Adaptation and adaptive management are distinct concepts that are frequently confused with one another.¹³⁴⁹ As described earlier, adaptation refers to strategies designed to prepare for and cope with the effects of climate change.¹³⁵⁰ In contrast, adaptive management is one particular approach to management in the face of uncertainty, and is not necessarily tied to climate change (see Box 18)¹³⁵¹

Adaptation to climate change is characterized by making decisions in the face of uncertainty.¹³⁵² Because of the uncertainties associated with predicting the effects of future climates on species and ecosystems, flexible management will almost certainly be a component of well-designed adaptation strategies.¹³⁵³ However, while the adaptive management framework is structured to enable managers to act in the face of uncertainty, Glick et al. (2011b) note other management approaches and philosophies are also designed to address different levels of uncertainty (e.g. scenario-based planning).¹³⁵⁴

To summarize, adaptive management can be an important component of adaptation efforts, but not all adaptive management is climate change adaptation, nor is all climate change adaptation necessarily adaptive management.¹³⁵⁵

¹³⁴⁹ Verbatim or nearly verbatim from Glick et al. (2011b, Box 1.2, p. 15)

¹³⁵⁰ Verbatim or nearly verbatim from Glick et al. (2011b, Box 1.2, p. 15)

¹³⁵¹ Verbatim or nearly verbatim from Glick et al. (2011b, Box 1.2, p. 15)

¹³⁵² Verbatim or nearly verbatim from Glick et al. (2011b, Box 1.2, p. 15)

¹³⁵³ Verbatim or nearly verbatim from Glick et al. (2011b, Box 1.2, p. 15)

¹³⁵⁴ Verbatim or nearly verbatim from Glick et al. (2011b, Box 1.2, p. 15)

¹³⁵⁵ Verbatim or nearly verbatim from Glick et al. (2011b, Box 1.2, p. 15)

3. CLIMATE ADAPTATION ACTIONS – INFORMATION GATHERING AND CAPACITY BUILDING

Building capacity in organizations, managers, practitioners, decision-makers, and the public can increase the ability to plan, develop, and implement adaptation strategies.¹³⁵⁶ Gregg et al. (2011) list multiple factors that can affect capacity to engage in adaptation, including generic factors such as economic resources and more specific factors such as quality and quantity of information, and training and technological resources.¹³⁵⁷ The sections below describe components of information gathering and capacity building.

Conduct/gather additional research, data, and products

Gregg et al. (2011) state gathering research, data, and products on actual and projected climate change impacts is critical to supporting adaptation action.¹³⁵⁸ Models and research products have predicted a range of plausible scenarios; as these tools are refined, many indicate that the extent and magnitude of climate impacts may be greater than previously thought.¹³⁵⁹ Incorporating the best available science, traditional ecological knowledge, and citizen science efforts may improve climate adaptation decisions.¹³⁶⁰ For example, the U.S. Agency for International Development (2009) notes the general maintenance and restoration of wetlands in a changing climate may benefit from:

- *Mapping intact coastal wetland systems in the region* using field surveys, together with remote sensing imagery (where available) to distinguish salt-tolerant species from freshwater species.¹³⁶¹
- *Analyzing the vulnerability of the wetland to storms and sea level rise* to establish priorities for protection and restoration.¹³⁶² Post-storm evaluation of wetlands and adjacent land impacts provides valuable information on the resilience of wetlands and their storm buffer capacities.¹³⁶³
- *Determining freshwater flow requirements* and potential climate change impacts on freshwater flows to support the maintenance of brackish water wetlands.¹³⁶⁴

Create/enhance technological resources

In their synthesis of adaptation strategies for marine and coastal ecosystems, Gregg et al. (2011) state technological resources can make adaptation action easier and more accessible.¹³⁶⁵ These resources include the tools that can support information exchange, modeling of vulnerability and risk, and decision-making.¹³⁶⁶ These resources can help planners, managers, scientists, and policy makers to identify priority

¹³⁵⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 46)

¹³⁵⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 46)

¹³⁵⁸ Verbatim or nearly verbatim from Gregg et al. (2011, p. 53)

¹³⁵⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 53)

¹³⁶⁰ Verbatim or nearly verbatim from Gregg et al. (2011, p. 53)

¹³⁶¹ Verbatim or nearly verbatim from U.S. AID (2009, p. 76)

¹³⁶² Verbatim or nearly verbatim from U.S. AID (2009, p. 76)

¹³⁶³ Verbatim or nearly verbatim from U.S. AID (2009, p. 76)

¹³⁶⁴ Verbatim or nearly verbatim from U.S. AID (2009, p. 76)

¹³⁶⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 70)

¹³⁶⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 70)

species and areas for conservation, generate inundation and hazard maps, and ascertain organizations and communities that have successfully implemented adaptation strategies.¹³⁶⁷

Conduct vulnerability assessments and studies

Vulnerability assessments help practitioners evaluate potential effects of climatic changes on ecosystems, species, human communities, and other areas of concern.¹³⁶⁸ Vulnerability assessments and studies can identify impacts of concern, a range of scenarios that depend on the frequency and magnitude of changes, who and what is at risk from these impacts, and what can be done to reduce vulnerability and increase resilience.¹³⁶⁹ Specifically, climate change vulnerability assessments provide two essential components to adaptation planning:

- Identifying *which* species or ecosystems are likely to be most strongly affected by projected changes; and
- Understanding *why* these resources are likely to be vulnerable, including the interaction between climate shifts and existing stressors.¹³⁷⁰

Determining *which* resources are most vulnerable enables managers to better set priorities for conservation action, while understanding *why* they are vulnerable provides a basis for developing appropriate management and conservation responses.¹³⁷¹ In other words, they can provide a factual underpinning for differentiating between species and systems likely to decline and likely to thrive, but do not in themselves dictate adaptation strategies and management responses.¹³⁷²

Vulnerability is a function of exposure and sensitivity to change as well as adaptive capacity, which can all vary greatly depending on geography, genetic or species diversity, resources, and other factors.¹³⁷³ Vulnerability assessments are, therefore, structured around assessments of these distinct components.¹³⁷⁴ The key steps and associated actions for assessing vulnerability to climate change are listed in Table 22.

The EPA's Climate Ready Estuaries program compiled best practices and lessons learned for vulnerability assessment efforts including:

- Recognize that non-climate drivers, such as development, pollution, and population growth, often exacerbate climate change vulnerabilities.¹³⁷⁵
- When working with limited data, use readily available scientific best professional judgment to help support decision-making.¹³⁷⁶ Surveying both local and regional experts and stakeholders can assist in building knowledge, as they have access to some of the most up-to-date information and research.¹³⁷⁷

¹³⁶⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 70)

¹³⁶⁸ Verbatim or nearly verbatim from Gregg et al. (2011, p. 54)

¹³⁶⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 54)

¹³⁷⁰ Verbatim or nearly verbatim from Glick et al. (2011b, p. 1)

¹³⁷¹ Verbatim or nearly verbatim from Glick et al. (2011b, p. 1)

¹³⁷² Verbatim or nearly verbatim from Glick et al. (2011b, p. 3)

¹³⁷³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 54)

¹³⁷⁴ Verbatim or nearly verbatim from Glick et al. (2011b, p. 2)

¹³⁷⁵ Verbatim or nearly verbatim from U.S. EPA. *Lessons Learned from the Climate Ready Estuaries Program*. (2011, p. 2)

¹³⁷⁶ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 2)

¹³⁷⁷ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 2)

- Focus on emergency and disaster management, which is one area National Estuary Programs can work with local and state governments to incorporate climate change issues.¹³⁷⁸ *For further information on emergency and disaster management, please see “Increase organizational capacity” in this section and “Develop a disaster preparedness plan” in Section 6 of this Chapter.*
- Collaborate with and use local partners, such as universities, non-profits, Sea Grants, and National Estuarine Research Reserves to fill information gaps.¹³⁷⁹
- Determine scope – vulnerability assessments do not necessarily have to be broad in scope.¹³⁸⁰ Focusing on the vulnerability of a specific resource may generate momentum for adaptation.¹³⁸¹ This lesson is echoed by Glick et al.’s “landscaped-based” and “project-based” approach to climate-smart conservation, described previously (see Section 1 in this Chapter).¹³⁸²

Table 22. Key Steps for Assessing Vulnerability to Climate Change	
<i>Key Steps</i>	<i>Associated Actions</i>
Determine objectives and scope	<ul style="list-style-type: none"> • Identify audience, user requirements, and needed products • Engage key internal and external stakeholders • Establish and agree on goals and objectives • Identify suitable assessment targets • Determine appropriate spatial and temporal scales • Select assessment approach based on targets, user needs, and available resources
Gather relevant data and expertise	<ul style="list-style-type: none"> • Review existing literature on assessment targets and climate impacts • Reach out to subject experts on target species or systems • Obtain or develop climatic projections, focusing on ecologically relevant variables and suitable spatial and temporal scales • Obtain or develop ecological response projections
Assess components of vulnerability	<ul style="list-style-type: none"> • Evaluate climate sensitivity of assessment targets • Determine likely exposure of targets to climatic/ecological change • Consider adaptive capacity of targets that can moderate potential impact • Estimate overall vulnerability of targets • Document level of confidence or uncertainty in assessments
Apply assessment in adaptation planning	<ul style="list-style-type: none"> • Explore why specific targets are vulnerable to inform possible adaptation responses • Consider how targets might fare under various management and climatic scenarios • Share assessment results with stakeholders and decision-makers • Use results to advance development of adaptation strategies and plans
<i>Source: Modified from Glick et al. (2011b, Box 2.1, p. 19) by authors of this report.</i>	

Conduct scenario planning exercises

Scenario planning involves the creation of a series of scenarios specifically for the planning process in question, as well as narratives to accompany those scenarios.¹³⁸³ It also involves the use of those scenarios

¹³⁷⁸ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 2)

¹³⁷⁹ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 2)

¹³⁸⁰ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 2)

¹³⁸¹ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 2)

¹³⁸² Glick et al. (2011a, p. 7)

¹³⁸³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 59)

for evaluating policy/management options.¹³⁸⁴ Scenario planning allows participants to identify actions that work well across multiple scenarios, to discover options for dealing with uncertainty, and can improve adaptive management.¹³⁸⁵ Please see Box 18 for additional information on scenario planning.

Increase organizational capacity

Sufficient organizational capacity is needed to support adaptation activities at all levels of government.¹³⁸⁶ This strategy includes improving the resources, tools, knowledge, and institutional support required to increase organizational capacity.¹³⁸⁷ Gregg et al. (2011) identify several specific strategies for increasing organizational capacity:

- **Coordinate planning and management across institutional boundaries:** Many climate change impacts will affect multiple jurisdictions at once whether the effects are felt at local, regional, national, or international scales.¹³⁸⁸ Because climatic variability is not confined by political or social boundaries, cross-jurisdictional coordination of planning and management can improve adaptation efforts.¹³⁸⁹ Increased cooperation may include information sharing, improved communication, and establishing formal partnerships to share resources, funds, and knowledge.¹³⁹⁰
- **Create new institutions (training staff, establishing committees):** Creating committees and advisory bodies and having properly trained staff can institutionalize climate change considerations within an organization.¹³⁹¹ Technical experts, scientists, and other staff can contribute important knowledge and recommendations to support governmental decision-making on climate adaptation.¹³⁹²
- **Invest in/enhance emergency services planning and training:** Climate change is expected to increase risks to public health and safety throughout North America.¹³⁹³ Flooding, erosion, and sea level rise will affect low-lying coastal communities by short- and long-term displacement of people and communities, salinization of potable water, and infrastructure damage.¹³⁹⁴ Warmer temperatures and changes in precipitation patterns will likely increase incidences of wildfires and drought, pests and diseases, and intense heat waves.¹³⁹⁵ Integrating climate change concerns into emergency services planning and training, including police, fire and rescue, and emergency medical services, will be important to limit public health and safety risks.¹³⁹⁶

¹³⁸⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 59)

¹³⁸⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 59). The authors cite Peterson (2003) for this information.

¹³⁸⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 48)

¹³⁸⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 48)

¹³⁸⁸ Verbatim or nearly verbatim from Gregg et al. (2011, p. 49)

¹³⁸⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 49)

¹³⁹⁰ Verbatim or nearly verbatim from Gregg et al. (2011, p. 49)

¹³⁹¹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 46)

¹³⁹² Verbatim or nearly verbatim from Gregg et al. (2011, p. 46)

¹³⁹³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 50)

¹³⁹⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 50)

¹³⁹⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 50)

¹³⁹⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 50)

Increase job training and retraining

Gregg et al. (2011) identify two strategies for increasing job training and retraining:

- ***Create/host adaptation training and planning workshops:*** While many researchers, conservation practitioners, and resource managers understand the reality of climate change, they are often still challenged by what actions to take.¹³⁹⁷ As a result, the conservation and resource management community needs assistance developing its thinking on dealing with climate change, finding the information or data it needs to make informed decisions, and finding people to interact with on this topic as individuals develop their own approaches.¹³⁹⁸ Training and planning workshops can provide context, guidance, and practical examples of how adaptation is being addressed on-the-ground.¹³⁹⁹
- ***Provide new job training for people whose livelihoods are threatened by climate change:*** This strategy directly addresses the potential economic consequences of global climate change.¹⁴⁰⁰ Increased water temperatures and ocean acidification will severely impact fisheries, aquaculture, and ecotourism and recreation based on natural resources.¹⁴⁰¹

Create stakeholder engagement processes

As mentioned by Gregg et al. (2011), gaining public buy-in for adaptation can be critical to ensuring the effectiveness of any strategy.¹⁴⁰² Engaging stakeholders can occur in a variety of ways; for example, participating in meetings and workshops, one-on-one interactions, and websites, among others.¹⁴⁰³ Activities like interactive, participatory discussions, problem solving sessions, and role-playing exercises have been used to engage stakeholders in climate adaptation.¹⁴⁰⁴ The EPA's Climate Ready Estuaries program compiled best practices and lessons learned for stakeholder engagement efforts including:

- Leverage existing efforts.¹⁴⁰⁵
- Focus on local issues.¹⁴⁰⁶ Presenting local evidence of climate change (e.g., changes in seasonal events or animal behavior, local projections of wetland loss) to local officials and the general public is often a useful approach to build support for adaptation.¹⁴⁰⁷
- Link climate change adaptation messages to clean water supply and stormwater drainage.¹⁴⁰⁸ This can be an effective way to engage local decision-makers, as constituents are increasingly concerned about these issues.¹⁴⁰⁹

¹³⁹⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 56)

¹³⁹⁸ Verbatim or nearly verbatim from Gregg et al. (2011, p. 56)

¹³⁹⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 56)

¹⁴⁰⁰ Verbatim or nearly verbatim from Gregg et al. (2011, p. 55)

¹⁴⁰¹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 55)

¹⁴⁰² Verbatim or nearly verbatim from Gregg et al. (2011, p. 57)

¹⁴⁰³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 57)

¹⁴⁰⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 57)

¹⁴⁰⁵ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴⁰⁶ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴⁰⁷ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴⁰⁸ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴⁰⁹ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

- Target entities most responsible for construction and maintenance of public infrastructure (e.g., municipalities, counties or regional authorities) first to encourage greater willingness to engage on the impacts of sea level rise due to the significant fiscal implication of infrastructure loss or damage.¹⁴¹⁰
- Conduct meetings or phone calls with key stakeholders to help identify what stakeholders are already working on and their key needs for undertaking climate change adaptation.¹⁴¹¹

Increase/improve public awareness, education, and outreach efforts

This strategy, identified by Gregg et al. (2011) in their synthesis of marine and coastal adaptation strategies, relates to improving the links between science, management, decision-making, and public awareness.¹⁴¹² These efforts may be in the form of presentations and workshops, print and internet media, steering and advisory committees, and traditional educational venues.¹⁴¹³ More interactive approaches tend to be better at ensuring a two-way flow of information, recognizing that scientists must learn from managers, policy makers, and the public as well as vice-versa.¹⁴¹⁴ Enabling managers and decision-makers to incorporate climate adaptation into practice requires that the appropriate science be available in useable forms when needed.¹⁴¹⁵ The broader public also needs to be engaged in climate adaptation and be made aware of the potential ways that climate change may affect the economy, natural resources, livelihoods, health, and well-being.¹⁴¹⁶ Gaining public buy-in may increase political and social capital to support climate adaptation action at local, regional, national, and international levels.¹⁴¹⁷

¹⁴¹⁰ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴¹¹ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴¹² Verbatim or nearly verbatim from Gregg et al. (2011, p. 51)

¹⁴¹³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 51)

¹⁴¹⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 51)

¹⁴¹⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 51)

¹⁴¹⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 51-52)

¹⁴¹⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 52)

4. CLIMATE ADAPTATION ACTIONS – MONITORING AND PLANNING

The sections below describe components of monitoring and planning.

Develop climate change indicators

The U.S. EPA’s Climate Ready Estuaries Program notes that the development of climate change indicators for estuaries is still an evolving field, but there have already been a number of lessons learned from the Climate Ready Estuaries partners.¹⁴¹⁸ They include:

- Identify desired climate change information outputs prior to the beginning of the indicator selection process.¹⁴¹⁹
- Consider conducting a climate change vulnerability assessment prior to developing climate change indicators.¹⁴²⁰ A vulnerability assessment may be useful in order to ensure that the candidate list of indicators is comprehensive and to identify variables that are indicative of consequences rather than drivers.¹⁴²¹ *For further information on conducting vulnerability assessments, please see “Conduct vulnerability assessments and studies” in Section 3 of this Chapter.*
- Explore the development of conceptual ecological models of climate change prior to developing indicators.¹⁴²² These models are organized in a hierarchical way among drivers, stressors, ecological effects, key attributes, and measures.¹⁴²³ The measures point the way to key indicators of climate change.¹⁴²⁴
- Draw up a universe of candidate indicators from which to consider.¹⁴²⁵ Identify any factors that are uncertain (such as the direct tie to climate change or available monitoring), as these factors will be important to consider later.¹⁴²⁶
- Obtain as much public and scientific input as possible on selecting a subset of indicators for more intense review.¹⁴²⁷ *For further information on stakeholder engagement, please see “Create stakeholder engagement processes” in Section 3 of this Chapter.*
- Recognize that regional efforts that cross state lines often require additional involvement from government agencies and other key stakeholders.¹⁴²⁸ The involvement of key local, state, and regional organizations will be important to discuss during the initial stages of any indicator development process.¹⁴²⁹

¹⁴¹⁸ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴¹⁹ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²⁰ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²¹ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²² Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²³ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²⁴ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²⁵ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²⁶ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²⁷ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²⁸ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

¹⁴²⁹ Verbatim or nearly verbatim from U.S. EPA. (2011, p. 3)

Evaluate existing monitoring programs for wildlife and key ecosystem components

Monitoring systems provide information that managers can use to adjust or modify their activities through the process of adaptive management.¹⁴³⁰ This approach, described by the Heinz Center (2008) in their report on strategies for managing climate change effects on wildlife and ecosystems, would evaluate the current state of the systems that collect, analyze, and interpret environmental information.¹⁴³¹ It would determine how programs will need to be modified to provide management-relevant information on the effects of climate change and what new monitoring systems will need to be established in order to address gaps in knowledge of climate effects.¹⁴³² The costs to adapt existing monitoring systems and develop new monitoring systems are likely to be high.¹⁴³³ In many cases this will probably require new legislation and regulations, and possibly new tools and approaches to monitoring.¹⁴³⁴ It will also require better integration and coordination across existing monitoring programs.¹⁴³⁵

Incorporate predicted climate change impacts into species and land management

Information about actual and potential climate change impacts can be of benefit to land and natural resource managers in making decisions and taking actions.¹⁴³⁶ Climate change is not addressed in many existing natural resource plan documents.¹⁴³⁷ This strategy would use existing natural resource planning mechanisms to inform decision-making on a broad spectrum of natural resource management topics.¹⁴³⁸ Many existing natural resource plans already contain provisions for updates and revisions, which could provide a mechanism for incorporating information about climate change effects and adaptation strategies.¹⁴³⁹ The Heinz Center (2008) notes the problems with this approach are mainly practical at present: there is a definite cost associated with revisiting and revising management plans; in practice, many resource management plans are updated infrequently.¹⁴⁴⁰ Also, detailed predictions of potential climate change effects are currently only available for a small subset of species and areas,¹⁴⁴¹ as shown by the Information Gaps identified throughout this report.

¹⁴³⁰ Verbatim or nearly verbatim from Heinz Center (2008, p. 29). The authors cite Walters (1986), Margoluis and Salafsky (1998), and Williams, Szaro, and Shapiro (2007) for this information.

¹⁴³¹ Verbatim or nearly verbatim from Heinz Center (2008, p. 29). The authors cite Walters (1986), Margoluis and Salafsky (1998), and Williams, Szaro, and Shapiro (2007) for this information.

¹⁴³² Verbatim or nearly verbatim from Heinz Center (2008, p. 29)

¹⁴³³ Verbatim or nearly verbatim from Heinz Center (2008, p. 30)

¹⁴³⁴ Verbatim or nearly verbatim from Heinz Center (2008, p. 30)

¹⁴³⁵ Verbatim or nearly verbatim from Heinz Center (2008, p. 30). The authors cite The Heinz Center (2006) for this information.

¹⁴³⁶ Verbatim or nearly verbatim from Heinz Center (2008, p. 30)

¹⁴³⁷ Verbatim or nearly verbatim from Heinz Center (2008, p. 30). The authors cite Hannah, Midgley and Millar (2002) for information on existing natural resource plan documents, and Mawdsley (unpublished data) for information on endangered species recovery plans and State Wildlife Action Plans.

¹⁴³⁸ Verbatim or nearly verbatim from Heinz Center (2008, p. 30)

¹⁴³⁹ Verbatim or nearly verbatim from Heinz Center (2008, p. 30)

¹⁴⁴⁰ Verbatim or nearly verbatim from Heinz Center (2008, p. 30-31)

¹⁴⁴¹ Verbatim or nearly verbatim from Heinz Center (2008, p. 31). The authors cite The Heinz Center (2007) for this information.

Develop dynamic landscape conservation plans

Dynamic landscape conservation plans include information on fixed and dynamic spatial elements, along with management guidelines for target species, genetic resources, and ecosystems within the planning areas.¹⁴⁴² Fixed spatial elements include protected areas where the land use is fully natural.¹⁴⁴³ Dynamic spatial elements include all other areas within the landscape matrix, where land use may change over time.¹⁴⁴⁴ The plan includes a desired future condition for each element, based on predicted shifts in distribution of species and other ecosystem components, as well as any intermediate steps that may be necessary to transition between current and future condition.¹⁴⁴⁵ The management guidelines suggest mechanisms and tools for management (such as land acquisition, riparian plantings, or other wildlife-friendly farming practices) and specific government agencies responsible for implementation.¹⁴⁴⁶ The actual planning activities required to develop these plans are likely to be compatible with other local or regional-scale planning projects such as State Wildlife Action Plans or watershed management plans.¹⁴⁴⁷ However, planning efforts can be resource-intensive.¹⁴⁴⁸ Recommendations such as suggesting that certain spatial elements (i.e., areas of land or water) will need to be converted from human uses to “natural” management are likely to prove controversial.¹⁴⁴⁹

Changes to land use planning and zoning

This may include restricting or prohibiting development in erosion zones, redefining riverine flood hazard zones, or increasing shoreline setbacks.¹⁴⁵⁰ Restricting development in erosion zones allows for more land available to protect estuaries, but will not help areas already developed.¹⁴⁵¹ It

Case Study 1. Ecosystem-Based Management and Climate Change Adaptation in Humboldt Bay, CA.

Climate stressors addressed: Ocean acidification. Increased sea surface temperature. Altered hydrology and ocean currents. Increased frequency and severity of storms. Sea level rise. Coastal erosion, upwelling, hypoxia and anoxia.

In the NPLCC region, the San Juan Initiative (WA), Port Orford Ocean Resource Team (OR), and Humboldt Bay Initiative (CA) represent three of six community-based initiatives comprising the West Coast EBM network, which is a partnership focused on the successful implementation of EBM along the coasts of Washington, Oregon, and California. The Humboldt Bay Initiative (HBI) is currently planning a coordinated response to climate change for the Humboldt Bay ecosystem. In early 2010, HBI organized a meeting of local, state and federal agencies, along with public stakeholders, to identify and inventory all climate change activities underway in Humboldt Bay in order to leverage common approaches, address gaps, and avoid redundancy in research and management efforts.

Source: West Coast EBM Network (2010)

¹⁴⁴² Verbatim or nearly verbatim from Heinz Center (2008, p. 31). The authors cite Hannah and Hansen (2005) for this information.

¹⁴⁴³ Verbatim or nearly verbatim from Heinz Center (2008, p. 31).

¹⁴⁴⁴ Verbatim or nearly verbatim from Heinz Center (2008, p. 31).

¹⁴⁴⁵ Verbatim or nearly verbatim from Heinz Center (2008, p. 31).

¹⁴⁴⁶ Verbatim or nearly verbatim from Heinz Center (2008, p. 31).

¹⁴⁴⁷ Verbatim or nearly verbatim from Heinz Center (2008, p. 31).

¹⁴⁴⁸ Verbatim or nearly verbatim from Heinz Center (2008, p. 31).

¹⁴⁴⁹ Verbatim or nearly verbatim from Heinz Center (2008, p. 31).

¹⁴⁵⁰ Verbatim or nearly verbatim from U.S. EPA. *Synthesis of Adaptation Options for Coastal Areas*. (2009, p. 14)

¹⁴⁵¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

may be difficult to attain agreement among all parties.¹⁴⁵² Redefining riverine flood hazard zones to match projected expansion of flooding frequency and extent protects riverine systems and zones, but may impact flood insurance or require changing zoning ordinances, which can be difficult.¹⁴⁵³

Create a regional sediment management (RSM) plan

There is not a simple relationship between sea level rise and horizontal movement of the shoreline, and sediment budget approaches are most useful to assess beach response to climate change.¹⁴⁵⁴ A RSM considers the entire watershed, including upstream reaches, but requires more coordination across regions, including private lands.¹⁴⁵⁵ Any regional sediment management effort should include an emphasis on the beneficial use of dredged material.¹⁴⁵⁶ A sediment management program that recognizes sediment as a valuable resource and links needs with appropriate opportunities will be the most effective at reducing economic and environmental losses associated with climate change.¹⁴⁵⁷ Beneficial use of dredged material involves using sediment dredged from waterways for a productive purpose, such as beach nourishment, habitat restoration and development, public access facilities, and shore protection structures (e.g., levees and dikes), among other things.¹⁴⁵⁸

Integrate coastal management into land use planning

Integrating coastal management into land use planning allows conservation and management goals to be incorporated into land use planning, although it can be difficult to have local and state agencies agree or to address private property rights.¹⁴⁵⁹ Ecosystem-Based Management (EBM), Integrated Coastal Zone Management (ICZM), and Coastal and Marine Spatial Planning (C(MSP)) are common coastal management systems:

- ***Ecosystem-Based Management*** (EBM) is an integrated approach to management that considers the entire ecosystem, including humans.¹⁴⁶⁰ The goal of ecosystem-based management is to maintain an ecosystem in a healthy, productive and resilient condition so that it can provide the services humans want and need.¹⁴⁶¹ Ecosystem-based management differs from current approaches that usually focus on a single species, sector, activity or concern; it considers the cumulative impacts of different sectors.¹⁴⁶² Specifically, ecosystem-based management:
 - Emphasizes the protection of ecosystem structure, functioning, and key processes;
 - Is place-based in focusing on a specific ecosystem and the range of activities affecting it;

¹⁴⁵² Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

¹⁴⁵³ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

¹⁴⁵⁴ Verbatim or nearly verbatim from Nicholls et al. (2007, p. 324). The authors cite Cowell et al. (2006) for this information.

¹⁴⁵⁵ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 15)

¹⁴⁵⁶ Verbatim or nearly verbatim from NOAA. (2010, p. 84)

¹⁴⁵⁷ Verbatim or nearly verbatim from NOAA. (2010, p. 84)

¹⁴⁵⁸ Verbatim or nearly verbatim from NOAA. (2010, p. 84)

¹⁴⁵⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 10)

¹⁴⁶⁰ Verbatim or nearly verbatim from West Coast Ecosystem-Based Management Network. *Community-based management of coastal ecosystems: Highlights and lessons of success from the West Coast Ecosystem-Based Management Network* (pdf; website). (2010, p. 2)

¹⁴⁶¹ Verbatim or nearly verbatim from West Coast Ecosystem-Based Management Network. (2010, p. 2)

¹⁴⁶² Verbatim or nearly verbatim from West Coast Ecosystem-Based Management Network. (2010, p. 2)

- Explicitly accounts for the interconnectedness within systems, recognizing the importance of interactions between many target species or key services and other non-target species;
- Acknowledges interconnectedness among systems, such as between air, land and sea; and
- Integrates ecological, social, economic, and institutional perspectives, recognizing their strong interdependences.¹⁴⁶³
- ***Integrated Coastal Zone Management***, (ICZM) is a mechanism for bringing together the multiplicity of users, stakeholders, and decision-makers in the coastal zone in order to secure more effective ecosystem management whilst achieving economic development and intra- and inter-generational equity through the application of sustainability principles.¹⁴⁶⁴ It considers all stakeholders in planning and balancing objectives, and can address all aspects of climate change.¹⁴⁶⁵ However, stakeholders willing to compromise and more effort in planning are needed.¹⁴⁶⁶ The ICZM approach is generally facilitated through existing terrestrial and marine territorial planning legislation and mechanisms, where these exist.¹⁴⁶⁷
- ***(Coastal and) Marine Spatial Planning***, (C(MSP)) is a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process.¹⁴⁶⁸ Partners and stakeholders in The Pacific North Coast Integrated Management Area (PNCIMA), located along the Central and North Coast of British Columbia, are incorporating CMSP into their integrated management approach.¹⁴⁶⁹ Characteristics of effective marine spatial planning include:
 - Ecosystem-based, balancing ecological, economic, and social goals and objectives toward sustainable development;
 - Integrated, across sectors and agencies, and among levels of government;
 - Place-based or area-based;
 - Adaptive, capable of learning from experience;
 - Strategic and anticipatory, focused on the long-term;
 - Participatory, stakeholders actively involved in the process.¹⁴⁷⁰

Community planning

Local-level planning and involvement are key to achieving on-the-ground implementation of adaptation strategies.¹⁴⁷¹ Although international and national action are needed to address broad policies and reform, Gregg et al. (2011) note community planning and management have greater effects on local resources

¹⁴⁶³ Verbatim or nearly verbatim from West Coast Ecosystem-Based Management Network. (2010, p. 2). The authors cite McLeod et al. (2005) for this information.

¹⁴⁶⁴ Verbatim or nearly verbatim from Ramsar Convention Secretariat. *Coastal management: Wetland issues in Integrated Coastal Zone Management (pdf; website)*. (2007, p. 23)

¹⁴⁶⁵ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 11)

¹⁴⁶⁶ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 11)

¹⁴⁶⁷ Verbatim or nearly verbatim from Ramsar Convention Secretariat. (2007, p. 23)

¹⁴⁶⁸ Verbatim or nearly verbatim from Ehler and Douvère. (2009, p. 18)

¹⁴⁶⁹ Personal interviews, April and May 2011.

¹⁴⁷⁰ Verbatim or nearly verbatim from Ehler and Douvère. (2009, Box 4, p. 18)

¹⁴⁷¹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 62)

through land use planning and zoning.¹⁴⁷² Building local capacity is especially important for dealing with disaster risk management and gaining stakeholder support for action.¹⁴⁷³

Ensure that wildlife and biodiversity needs are considered as part of the broader societal adaptation process

Modern wildlife professionals and natural resource managers are aware that management activities take place within a broader societal context, and that the broader society must be supportive in order for management to succeed.¹⁴⁷⁴ Managers can take proactive steps to engage local and regional government entities in adaptation planning, thereby ensuring that the needs of wildlife and natural resources are included at the start of these discussions.¹⁴⁷⁵

Case Study 2. Planning for Sea level Rise in Olympia, WA.

Climate stressors addressed: Sea level rise

Lower downtown Olympia sits on reclaimed land created with hydraulic fill that abuts Budd Inlet, a tidally-influenced southern arm of Puget Sound. On average, downtown Olympia is 18 to 20 ft above sea level but, Budd Inlet can have tides that reach a maximum height of 18 ft. To assess the impacts sea level rise could have on downtown Olympia, the city invested in high resolution Light Detection and Ranging (LiDAR) elevation data and used the LiDAR maps to run flooding simulations during high tides and storms at 0.5 ft incremental increases in sea level relative to its current level. The City also invested in geological monitoring equipment to monitor land subsidence or uplifting and plans to install local tide gauges. The City is considering both short- and long-term adaptation strategies to enhance their resilience to sea level rise. Short-term strategies include: consolidate the number of stormwater outfalls by half to ease future management; finer scale SLR simulations; enact a new SEPA requirement to raise floor elevations that house critical resources in all new buildings; and, continue monitoring changes in land elevation. Long-term strategies include: update City comprehensive plans to address climate change impacts, including SLR; support state and federal officials in developing guidelines/regulations to assist the adaptation of local communities; and, create an institutional framework to work on climate change problems.

Source: Climate Action Knowledge Exchange, <http://www.cakex.org/case-studies/683> (accessed 12.14.2010)

¹⁴⁷² Verbatim or nearly verbatim from Gregg et al. (2011, p. 62)

¹⁴⁷³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 62)

¹⁴⁷⁴ Verbatim or nearly verbatim from Heinz Center (2008, p. 32)

¹⁴⁷⁵ Verbatim or nearly verbatim from Heinz Center (2008, p. 32)

5. CLIMATE ADAPTATION ACTIONS – INFRASTRUCTURE AND DEVELOPMENT

This section addresses threats to the coastal built environment and other infrastructure from sea level rise, storms, changes in precipitation, and increased flooding.¹⁴⁷⁶

Make infrastructure resistant or resilient to climate change

This strategy involves the consideration of climate change in both the planning of new or retrofitting of existing infrastructure, including stormwater systems, transportation, water supply, or buildings.¹⁴⁷⁷

Examples include:

- **Design new coastal drainage system:** While many systems need to be restructured, planning and construction can be very costly and time-consuming.¹⁴⁷⁸
- **Incorporate climate change impacts, including sea level rise into planning for new infrastructure:** Engineering could be modified to account for changes in precipitation or seasonal timing of flows and siting decisions could take into account sea level rise.¹⁴⁷⁹ The long-term functional integrity of structures (e.g. sewage systems) is preserved and contamination of the water supply is prevented.¹⁴⁸⁰ However, measures can be costly¹⁴⁸¹ and land owners will likely resist relocating away from prime coastal locations.¹⁴⁸²
- **Protect water supply systems from saltwater contamination:** Sea level rise and flooding will cause saltwater intrusion, increasing the salinity of surface and ground water.¹⁴⁸³ Increased salinity can also harm intolerant plant and animal species.¹⁴⁸⁴ Water management responses are needed to deal with saltwater intrusion and salinization of water supplies; these responses may include regulation of water quality and supply, monitoring to track saltwater intrusion, and water treatments such as desalination.¹⁴⁸⁵
- **Incorporate wetland protection into infrastructure planning:** The incorporation of wetland protection in transportation planning, sewer utilities, and other infrastructure planning helps protect infrastructure.¹⁴⁸⁶ It may also help maintain water quality and preserve habitat for vulnerable species.¹⁴⁸⁷
- **Develop adaptive stormwater management practices:** Adaptive stormwater practices such as removing impervious surface and replacing undersized culverts minimize pollutant and nutrient

¹⁴⁷⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 61)

¹⁴⁷⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 61)

¹⁴⁷⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 19)

¹⁴⁷⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 11)

¹⁴⁸⁰ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 20)

¹⁴⁸¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 20)

¹⁴⁸² Verbatim or nearly verbatim from U.S. EPA. (2009, p. 11)

¹⁴⁸³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 63)

¹⁴⁸⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 63)

¹⁴⁸⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 63)

¹⁴⁸⁶ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁴⁸⁷ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

overloading of existing wetlands.¹⁴⁸⁸ Further, promoting natural buffers and adequately sizing culverts preserves natural sediment flow and protects water quality of downstream reaches.¹⁴⁸⁹ However, they may require costly improvements.¹⁴⁹⁰

- **Manage realignment and deliberately realign engineering structures:** Realignment of engineering structures affecting rivers, estuaries, and coastlines could reduce engineering costs, protect ecosystems and estuaries, and allow for natural migration of rivers.¹⁴⁹¹ However, it can be costly.¹⁴⁹²

Create or modify shoreline management measures

Planners and developers often use shoreline hardening to address erosion and sea level rise issues.¹⁴⁹³ Shoreline armoring structures, such as rip-rap, concrete, and bulkheads, can require the removal of native vegetation and soils, and can also impede natural processes and the movement of wildlife that utilize the shoreline as migration corridors.¹⁴⁹⁴ Alternatives outlined by Gregg et al. (2011) include land or structure elevation (e.g., rebuilding or modifying infrastructure in high-risk coastal areas) and constructing “living shorelines” (e.g., planting vegetation to stabilize banks and reduce erosion).¹⁴⁹⁵ This strategy involves removing shoreline hardening structures, restoring coastal vegetation to minimize erosion, and encouraging low impact development along shorelines.¹⁴⁹⁶ Living shorelines are described next, while the remaining strategies are discussed in Section 7 of this Chapter: “*Climate adaptation actions – species and habitat conservation, restoration, protection and natural resource management.*”

Living shorelines

In low- to medium-energy coastal and estuarine environments and tidally influenced creeks, streams, and rivers, living shorelines can be effective alternatives to shore protection structures in efforts to restore, protect, and enhance the natural shoreline and its environment.¹⁴⁹⁷ Living shorelines use stabilization techniques that rely on vegetative plantings, other organic materials (e.g., biologs, matting), and sand fill or a hybrid approach combining vegetative planting with low rock sills or footers, living breakwaters (e.g., oysters), or other shore protection structures designed to keep sediment in place or reduce wave energy.¹⁴⁹⁸ NOAA (2010) describes a number of benefits to living shorelines in their climate change planning guide for state coastal managers.¹⁴⁹⁹ Specifically, they:

- Maintain natural shoreline dynamics and sand movement;
- Trap sand to rebuild eroded shorelines or maintain the current shoreline;

¹⁴⁸⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 20)

¹⁴⁸⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 15)

¹⁴⁹⁰ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 20)

¹⁴⁹¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 11)

¹⁴⁹² Verbatim or nearly verbatim from U.S. EPA. (2009, p. 11)

¹⁴⁹³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 64)

¹⁴⁹⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 64). The authors cite NRC (2002) for this information.

¹⁴⁹⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 64)

¹⁴⁹⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 65)

¹⁴⁹⁷ Verbatim or nearly verbatim from NOAA. (2010, p. 80)

¹⁴⁹⁸ Verbatim or nearly verbatim from NOAA. (2010, p. 80-81)

¹⁴⁹⁹ Verbatim or nearly verbatim from NOAA. (2010, p. 81)

- Provide important shoreline habitat;
- Reduce wave energy and coastal erosion;
- Absorb storm surge and flood waters;
- Filter nutrients and pollutants from the water;
- Maintain beach and intertidal areas that offer public access;
- Are aesthetically pleasing;
- Allow for landward migration as sea levels rise;
- Absorb atmospheric carbon dioxide;
- Are less costly than shore protection structures¹⁵⁰⁰

The techniques and materials used will depend on site-specific needs and characteristics.¹⁵⁰¹ Much of the site-specific information needed is similar to that for establishing coastal development setbacks, carrying out beach nourishment, and implementing other shoreline stabilization measures.¹⁵⁰² The U.S. Agency for International Development (2009) provides some design considerations and information needs including:

- Define the problem (episodic or chronic erosion) and scale of the shoreline region of concern.¹⁵⁰³ Analyze historical erosion rates, evaluate the condition of adjacent shorelines, and identify potential future problems related to sea level rise, storm frequency, and intensity.¹⁵⁰⁴
- Determine the (current and future) exposure of the shoreline from wind generated waves (referred to as fetch) as well as boat wakes, tidal ranges, and currents.¹⁵⁰⁵ This will help to verify that it is a low to medium energy environment.¹⁵⁰⁶
- Assess whether vegetation (upland, intertidal, subtidal) alone can address the problem, or if structural components (sand, stone) must be added in order to dampen wave energy and exposure to the shore.¹⁵⁰⁷
- Where feasible, employ an ecosystem approach—one that links subtidal, intertidal and upland protection and restoration initiatives.¹⁵⁰⁸ Consider the potential for landward transgression of vegetation with sea level rise.¹⁵⁰⁹
- Some erosion-controlling vegetation have very slow growth rates.¹⁵¹⁰ It may be necessary to take interim measures that involve the use of sand and stone or organic materials.¹⁵¹¹

¹⁵⁰⁰ Verbatim or nearly verbatim from NOAA. (2010, p. 81)

¹⁵⁰¹ Verbatim or nearly verbatim from NOAA. (2010, p. 81)

¹⁵⁰² Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵⁰³ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵⁰⁴ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵⁰⁵ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵⁰⁶ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵⁰⁷ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵⁰⁸ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵⁰⁹ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵¹⁰ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

¹⁵¹¹ Verbatim or nearly verbatim from U.S. AID. (2009, p. 103)

6. CLIMATE ADAPTATION ACTIONS – GOVERNANCE, POLICY, AND LAW

Local, regional, and national governments play important roles in many climate change policies and provide support to resource managers, conservation practitioners, and communities.¹⁵¹² Many projected climate impacts will have transboundary effects and require multilateral adaptation efforts.¹⁵¹³ The sections below describe components of governance, policy, and law.

*Note: Governance is not distinguished clearly from policy and law, as evidenced by the incorporation of policy and/or law into wide-ranging definitions of governance.*¹⁵¹⁴

Managed retreat of built infrastructure, relocation of people/communities

Some communities in low-lying coastal areas will be disproportionately affected by sea level rise and erosion.¹⁵¹⁵ These effects may require managed retreat of built infrastructure and/or relocation of people and communities.¹⁵¹⁶ Gregg et al. (2011) state this approach requires identification of high risk areas and cost-benefit analyses to determine if retreat and relocation are less costly options than installing, improving, and maintaining shoreline armoring structures.¹⁵¹⁷

Develop a disaster preparedness plan

Coastal hazards, such as erosion, landslides, and extreme weather events, can harm people and property; climate change is projected to exacerbate these effects in both frequency and magnitude.¹⁵¹⁸ Disaster preparedness plans can help coastal communities identify risks and vulnerabilities and develop options for response and recovery.¹⁵¹⁹

Maintain adequate financial resources for adaptation

Economic barriers are frequently cited by groups as reasons for not taking adaptation action.¹⁵²⁰ Gregg et al. (2011) suggest that if adaptation activities focus on building climate change into existing efforts or frameworks (e.g., incorporating climate projections into bridge designs or harvest limits), ensuring adequate financing for adaptation means simply ensuring that project budgets reflect any needed additional funding (e.g. more materials needed for a higher bridge, or downscaled climate models).¹⁵²¹ Climate adaptation actions undertaken as a new and distinct set of activities (e.g., scenario planning exercises) will require new and distinct funding.¹⁵²² Increased and sustainable funding sources can help

¹⁵¹² Verbatim or nearly verbatim from Gregg et al. (2011, p. 67)

¹⁵¹³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 67)

¹⁵¹⁴ United Nations Economic and Social Council. Committee of Experts on Public Administration (Fifth Session). *Definition of basic concepts and terminologies in governance and public administration (pdf, website)*. (2006).

¹⁵¹⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 67)

¹⁵¹⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 67)

¹⁵¹⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 67)

¹⁵¹⁸ Verbatim or nearly verbatim from Gregg et al. (2011, p. 68)

¹⁵¹⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 68)

¹⁵²⁰ Verbatim or nearly verbatim from Gregg et al. (2011, p. 69)

¹⁵²¹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 69)

¹⁵²² Verbatim or nearly verbatim from Gregg et al. (2011, p. 69)

organizations and governments overcome financial constraints and adapt to changing environmental conditions.¹⁵²³ Gregg et al. (2011) identify specific funding sources:

- **Grants and loans:** Some adaptation actions require up-front financial investment but more than pay for themselves in reduced long-term expenditures, meaning that grants or loans may be appropriate sources of financing.¹⁵²⁴ Grants can also provide short-term funds for strategy development and testing, but over the longer term it is important to diversify, for instance by building support for governmental adaptation funding, forging new partnerships, or reworking organizational budgets.¹⁵²⁵
- **Endowments:** Establishing endowments (e.g., the \$90 million provincial endowment that established the Pacific Institute for Climate Solutions in British Columbia) can provide more stable funding than year-by-year funding.¹⁵²⁶

Develop/implement adaptive management plans

Because of the uncertainty about climate change, its effects, and appropriate management responses, Gregg et al. (2011) suggest adaptive management policies and plans can play an important role in climate change adaptation (although adaptive management is not inherently linked to climate adaptation).¹⁵²⁷ Adaptive management involves testing hypotheses about system function and management efficacy and adjusting behavior and actions based on experience and actual changes (Box 19).¹⁵²⁸ These decisions can be either active or passive; active adaptive management involves experimenting with multiple options in order to determine the best strategy, while passive adaptive management requires selecting and implementing one option and monitoring to determine if changes are needed.¹⁵²⁹

Review existing laws, regulations, and policies

This strategy would initiate a review of all applicable laws, regulations, and other public policies related to wildlife management, natural resource management, and biodiversity conservation.¹⁵³⁰ Many of these laws and regulations are decades old, and most were developed before climate change became a significant concern.¹⁵³¹ The Heinz Center (2008) notes actually addressing the deficiencies that are identified through these reviews may be difficult without significant political will to overcome institutional inertia.¹⁵³² There will likely be significant concern expressed from all sides about any sweeping revisions to existing laws and regulations.¹⁵³³

¹⁵²³ Verbatim or nearly verbatim from Gregg et al. (2011, p. 69)

¹⁵²⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 69)

¹⁵²⁵ Verbatim or nearly verbatim from Gregg et al. (2011, p. 69)

¹⁵²⁶ Verbatim or nearly verbatim from Gregg et al. (2011, p. 69)

¹⁵²⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 71)

¹⁵²⁸ Verbatim or nearly verbatim from Gregg et al. (2011, p. 71)

¹⁵²⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 71)

¹⁵³⁰ Verbatim or nearly verbatim from Heinz Center. (2008, p. 33)

¹⁵³¹ Verbatim or nearly verbatim from Heinz Center. (2008, p. 33)

¹⁵³² Verbatim or nearly verbatim from Heinz Center. (2008, p. 33)

¹⁵³³ Verbatim or nearly verbatim from Heinz Center. (2008, p. 33)

Create new or enhance existing policy

Legislation, regulations, agreements, and enforcement policies at local, regional, national, and international levels can be created or enhanced to support climate adaptation action.¹⁵³⁴ New legislative tools or regulations may be necessary to address specific climate change impacts.¹⁵³⁵ For example, given that existing wildlife and biodiversity legislation is often decades old, new legislative or regulatory approaches may very well be needed to address specific effects or challenges associated with climate change.¹⁵³⁶ There are also opportunities to use existing regulatory frameworks to support conservation and management efforts to decrease the vulnerability of natural and human systems,¹⁵³⁷ provided that the program managers are given the flexibility needed to directly address climate threats.¹⁵³⁸

Create permitting rules that constrain locations for landfills, hazardous waste dumps, mine tailings, and toxic chemical facilities

Zoning regulations may allow zoning to protect estuaries and coastal zones, but can be difficult to enact.¹⁵³⁹

Setbacks

A coastal development setback may be defined as a prescribed distance to a coastal feature, such as the line of permanent vegetation, within which all or certain types of development are prohibited.¹⁵⁴⁰ The U.S. Agency for International Development (2009) state setbacks create a buffer between shoreline development and the sea that provides some protection against the destructive effects of erosion or land loss resulting from accelerated sea level rise or increased storm activity.¹⁵⁴¹ Setbacks are designed to minimize damage from erosion and increase public access to beaches.¹⁵⁴² Often setbacks contain a buffer zone.¹⁵⁴³ They also help maintain natural shore dynamics and shorefront access—both of which are critical in changing shoreline conditions.¹⁵⁴⁴ One potential issue with the use of setbacks is that once the water level reaches the setback, there is, in essence, an implicit contract that landowners will be able to build seawalls to protect their homes.¹⁵⁴⁵

¹⁵³⁴ Verbatim or nearly verbatim from Gregg et al. (2011, p. 72)

¹⁵³⁵ Verbatim or nearly verbatim from Heinz Center. (2008, p. 34)

¹⁵³⁶ Verbatim or nearly verbatim from Heinz Center. (2008, p. 34)

¹⁵³⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 72)

¹⁵³⁸ Verbatim or nearly verbatim from Heinz Center. (2008, p. 34)

¹⁵³⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 10)

¹⁵⁴⁰ Verbatim or nearly verbatim from U.S. AID. (2009, p. 98). The authors cite UNESCO (1997) for this information.

¹⁵⁴¹ Verbatim or nearly verbatim from U.S. AID. (2009, p. 98)

¹⁵⁴² Verbatim or nearly verbatim from U.S. AID. (2009, p. 98)

¹⁵⁴³ Verbatim or nearly verbatim from U.S. AID. (2009, p. 98)

¹⁵⁴⁴ Verbatim or nearly verbatim from U.S. AID. (2009, p. 98)

¹⁵⁴⁵ Verbatim or nearly verbatim from Kling and Sanchirico. *An Adaptation Portfolio for the United States Coastal and Marine Environment*. (2009, p. 46). The authors cite Caldwell and Segall (2007) for this information.

Setbacks require information that is similar in kind to living shorelines and non-structural shoreline protection:¹⁵⁴⁶

- Conduct an analysis of beach dynamics, shoreline ecology and historical erosion rates before establishing setbacks.¹⁵⁴⁷
- Set up basic beach profile monitoring transects to determine erosion rates—long term data sets will be more accurate to characterize shoreline dynamics.¹⁵⁴⁸
- When evaluating historical rates (from maps, beach profiles, traditional knowledge), determine if the rates of erosion have changed from one decade to the next.¹⁵⁴⁹ Also determine if changing trends are the result of climate change factors (changes in storm activity or sea level elevations) or man-made causes (e.g. removal of wetlands, construction of shoreline erosion control structures or local land subsidence).¹⁵⁵⁰
- Observe characteristics of the beach profile from seasonal changes and current climate variability (e.g. El Niño).¹⁵⁵¹ Consider the stability of landforms (barrier beaches, dunes, bluffs) and the potential changes that may result from accelerated sea level rise, increased storm activity and subsequent erosion.¹⁵⁵²

Rolling easements

Rolling easements are a more flexible approach than setbacks and are intended to induce property owners to yield to advancing shorelines or wetlands.¹⁵⁵³ They are a type of easement that prevent property owners from holding back the sea and moves or “rolls” with the rising seas.¹⁵⁵⁴ The advantages of a rolling easement are: (1) the lack of disturbance of sedimentation transport; (2) the potential for wetlands and other tidal habitat to migrate unimpeded; and (3) continued public access to the shore.¹⁵⁵⁵ A rolling easement can be implemented by statute, the permitting process, and eminent domain actions.¹⁵⁵⁶

¹⁵⁴⁶ Verbatim or nearly verbatim from U.S. AID. (2009, p. 99)

¹⁵⁴⁷ Verbatim or nearly verbatim from U.S. AID. (2009, p. 99)

¹⁵⁴⁸ Verbatim or nearly verbatim from U.S. AID. (2009, p. 99)

¹⁵⁴⁹ Verbatim or nearly verbatim from U.S. AID. (2009, p. 99)

¹⁵⁵⁰ Verbatim or nearly verbatim from U.S. AID. (2009, p. 99)

¹⁵⁵¹ Verbatim or nearly verbatim from U.S. AID. (2009, p. 99)

¹⁵⁵² Verbatim or nearly verbatim from U.S. AID. (2009, p. 99)

¹⁵⁵³ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 46)

¹⁵⁵⁴ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 46)

¹⁵⁵⁵ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 46). The authors cite Titus et al. (1991) for this information.

¹⁵⁵⁶ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 46). The authors cite Titus (1998) and Caldwell and Segall (2007) for this information.

7. CLIMATE ADAPTATION ACTIONS – SPECIES AND HABITAT CONSERVATION, RESTORATION, PROTECTION AND NATURAL RESOURCE MANAGEMENT

Addressing adaptation in management and conservation is necessary to deal with the actual and potential effects of climate change on ecosystems and the functions and services they provide.¹⁵⁵⁷ Climate change may have negative *and* positive effects on wildlife and habitat.¹⁵⁵⁸ Climate change may also interfere with the ability of ecosystems to withstand change.¹⁵⁵⁹ Managers and conservation practitioners can decrease ecosystem vulnerability by directly addressing expected climate change effects in policies and plans or by reducing the stressors that can exacerbate climate impacts.¹⁵⁶⁰ The sections below describe components of species and habitat conservation, restoration, protection, and natural resource management.

Maintain shorelines

NOAA (2010, 2011) and the U.S. EPA (2007, 2009) describe several options available to help maintain shorelines in a changing climate:

- ***Create dunes along backshore of beach:*** In addition to serving as buffers against erosion and flooding, which they do by trapping windblown sand, storing excess beach sand, and protecting inland areas against wave runup and overwash, dunes also provide habitat for wildlife.¹⁵⁶¹ Dune restoration is relatively inexpensive and entails the use of dune grass and other types of native vegetation and sand fences to capture shifting and blowing sands and stabilize dunes.¹⁵⁶² Dunes may be restored or created in conjunction with a beach nourishment project or may be managed as part of a separate effort.¹⁵⁶³ Since dunes and beaches are interdependent, dune management should be incorporated into a strategy that considers the broader coastal system.¹⁵⁶⁴ The use of vegetation and sand fences to build and stabilize dunes is not a quick fix, will only be effective under certain conditions, and may not be effective as a way of encouraging the growth of new dunes where dunes did not exist in the past.¹⁵⁶⁵
- ***Install natural or artificial breakwaters:*** Along energetic estuarine shorelines, oyster beds and other natural breakwaters, rock sills, artificial reefs, and other artificial breakwaters protect shorelines and marshes and inhibit erosion inshore of the reef.¹⁵⁶⁶ They also induce sediment deposition.¹⁵⁶⁷ Artificial reefs, for example, are constructed of a wide variety of man-made materials and placed underwater to restore, create, or enhance ecosystems, typically as a fisheries management tool.¹⁵⁶⁸ The use of artificial reefs is a complex issue that requires planning, long-

¹⁵⁵⁷ Verbatim or nearly verbatim from Gregg et al. (2011, p. 35)

¹⁵⁵⁸ Verbatim or nearly verbatim from Gregg et al. (2011, p. 35)

¹⁵⁵⁹ Verbatim or nearly verbatim from Gregg et al. (2011, p. 35)

¹⁵⁶⁰ Verbatim or nearly verbatim from Gregg et al. (2011, p. 35)

¹⁵⁶¹ Verbatim or nearly verbatim from NOAA. (2010, p. 82)

¹⁵⁶² Verbatim or nearly verbatim from NOAA. (2010, p. 82-83)

¹⁵⁶³ Verbatim or nearly verbatim from NOAA. (2010, p. 82)

¹⁵⁶⁴ Verbatim or nearly verbatim from NOAA. (2010, p. 82)

¹⁵⁶⁵ Verbatim or nearly verbatim from NOAA. (2010, p. 83)

¹⁵⁶⁶ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁵⁶⁷ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁵⁶⁸ Verbatim or nearly verbatim from NOAA. (2010, p. 91)

term monitoring, and evaluation to ensure the anticipated benefits are derived.¹⁵⁶⁹ There is still considerable debate on how artificial reefs impact the natural aquatic community into which they are introduced.¹⁵⁷⁰ Further, artificial breakwaters may not be sustainable in the long-term, because breakwaters are not likely to provide reliable protection against erosion in major storms.¹⁵⁷¹ They may require encroachment bayward or riverward, usually beyond the property limit, complicating the process for obtaining permits for construction.¹⁵⁷²

- **Remove shoreline hardening structures:** Shoreline modifications, such as bulkheads or seawalls, tend to harm habitat through the conversion of tidelands to uplands.¹⁵⁷³ Modification also indirectly affects habitat by altering nearshore processes.¹⁵⁷⁴ Removing hard structures such as bulkheads, dikes, and other engineered structures allows for shoreline migration, but may be costly for, and destructive to, shoreline property.¹⁵⁷⁵
- **Plant submerged aquatic vegetation:** Submerged aquatic vegetation such as seagrass beds dampen wave energy, stabilize sediments, improve water quality, and provide food and shelter for marine organisms.¹⁵⁷⁶ When used in conjunction with other living shoreline components such as marsh grasses, a natural shoreline buffer is created that reduces coastal erosion and stabilizes sediments via root growth.¹⁵⁷⁷ However, seagrasses may diminish in winter months, when wave activity is often more severe because of storms.¹⁵⁷⁸ Light availability is essential.¹⁵⁷⁹
- **Create marsh:** Planting the appropriate species – typically grasses, sedges, or rushes – in the existing substrate provides a protective barrier, and maintains and often increases habitat.¹⁵⁸⁰ For example, marsh grasses dissipate wave energy, filter upland runoff, and improve habitat for fish and wildlife.¹⁵⁸¹ Native grasses are planted in the water and at the mean high tide mark in the intertidal zone.¹⁵⁸² Marsh grasses may be more successful if they are planted in the spring in areas where there is evidence of existing marsh, where there is less than three miles of open water, and where the prevailing winds will not cause destruction of the newly planted grasses.¹⁵⁸³ Conditions must be right for the marsh to survive (e.g. sunlight for grasses, calm water) and the marsh may be affected by seasonal changes.¹⁵⁸⁴

¹⁵⁶⁹ Verbatim or nearly verbatim from NOAA. (2010, p. 91)

¹⁵⁷⁰ Verbatim or nearly verbatim from NOAA. (2010, p. 91)

¹⁵⁷¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁵⁷² Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁵⁷³ Verbatim or nearly verbatim from U.S. EPA. *National Estuary Program Coastal Condition Report. Chapter 6: West Coast National Estuary Program Coastal Condition (Puget Sound Action Team)*. (2007, p. 332)

¹⁵⁷⁴ Verbatim or nearly verbatim from U.S. EPA. (2007, p. 332)

¹⁵⁷⁵ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 12)

¹⁵⁷⁶ Verbatim or nearly verbatim from NOAA. *Living Shoreline Planning and Implementation (website)*. (2011)

¹⁵⁷⁷ Verbatim or nearly verbatim from NOAA. *Living Shoreline Planning and Implementation (website)*. (2011)

¹⁵⁷⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 12)

¹⁵⁷⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 12)

¹⁵⁸⁰ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁵⁸¹ Verbatim or nearly verbatim from NOAA. *Living Shoreline Planning and Implementation (website)*. (2011)

¹⁵⁸² Verbatim or nearly verbatim from NOAA. *Living Shoreline Planning and Implementation (website)*. (2011)

¹⁵⁸³ Verbatim or nearly verbatim from NOAA. *Living Shoreline Planning and Implementation (website)*. (2011)

¹⁵⁸⁴ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

- **Land exchange and acquisition:** Land exchange and acquisition programs allow for coastal land to be freed up for preservation uses.¹⁵⁸⁵ For example, a land acquisition program could purchase coastal land that is damaged or prone to damage and use it for conservation.¹⁵⁸⁶ Benefits of land acquisition include providing a buffer to inland areas and preventing development on the land.¹⁵⁸⁷ Constraints include costs and the availability of land to purchase.¹⁵⁸⁸ A land exchange program, such as a conservation easement, typically transfers some development and management options – such as the right to subdivide or to cut trees – from the landowner to a nonprofit or governmental organization that holds those rights.¹⁵⁸⁹ The landowner reserves certain rights, such as the right to build additional homes or add roads and also continues to own the property and manage it within the bounds set by the easement.¹⁵⁹⁰ The easement holder is responsible for monitoring and enforcing easement specifications.¹⁵⁹¹ Benefits of land exchange programs include the preservation of open space and making more land available to protect estuaries.¹⁵⁹² One constraint is that if an easement requirement cannot be readily monitored, it likely cannot be enforced.¹⁵⁹³

Maintain sediment transport

Sediment management is an important aspect of shoreline management and supports some of the other measures discussed in this category and the previous.¹⁵⁹⁴ It requires an understanding of sedimentation processes in the management area, recognizes the importance of sand and other sediments in protecting, maintaining, and restoring the shoreline and its associated waters and ecosystems, and incorporates activities affecting the erosion, transport, deposition, and removal of sediment.¹⁵⁹⁵ These activities include dredging and placing sediment, building shore protection structures and other structures that trap or divert sediment, and mining.¹⁵⁹⁶

- **Trap or add sand through beach nourishment:** Beach nourishment is the addition of sand to a shoreline to enhance or create a beach area, which creates protective beach for inland areas and replenishes sand lost to erosion.¹⁵⁹⁷ To maintain beaches, nourishment activities must be done repeatedly, as they treat only the symptoms and not the causes of the erosion.¹⁵⁹⁸ There are also high costs associated with importing beach material.¹⁵⁹⁹ However, even though beach nourishment efforts are typically costly and of uncertain value as a long-run solution to rising

¹⁵⁸⁵ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 16)

¹⁵⁸⁶ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 17)

¹⁵⁸⁷ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 17)

¹⁵⁸⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 17)

¹⁵⁸⁹ Verbatim or nearly verbatim from Merenlender et al. *Land trusts and conservation easements: Who is conserving what for whom?* (2004, p. 67)

¹⁵⁹⁰ Verbatim or nearly verbatim from Merenlender et al. (2004, p. 67)

¹⁵⁹¹ Verbatim or nearly verbatim from Merenlender et al. (2004, p. 67)

¹⁵⁹² Verbatim or nearly verbatim from U.S. EPA. (2009, p. 16)

¹⁵⁹³ Verbatim or nearly verbatim from Merenlender et al. (2004, p. 67)

¹⁵⁹⁴ Verbatim or nearly verbatim from NOAA. (2010, p. 83)

¹⁵⁹⁵ Verbatim or nearly verbatim from NOAA. (2010, p. 83)

¹⁵⁹⁶ Verbatim or nearly verbatim from NOAA. (2010, p. 83)

¹⁵⁹⁷ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

¹⁵⁹⁸ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 43)

¹⁵⁹⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

seas, they are among the only tools available to protect certain coastal wetlands and pre-existing communities.¹⁶⁰⁰

- ***Trap sand through construction of groins:*** Groins are a barrier-type structure that traps sand by interrupting longshore transport.¹⁶⁰¹ This creates a more natural shore face than bulkheads or revetments and is a quick fix.¹⁶⁰² However, it can trigger or accelerate erosion on the downdrift side and loss of beach habitat.¹⁶⁰³
- ***Reduce the diversion of water into channels and other stream diversions:*** This permits adequate sedimentation flows to build up coastal wetlands.¹⁶⁰⁴ Policies to increase sedimentation flows are weighed against the possibility that they may contradict policies meant to reduce the increased variability of precipitation on agricultural and drinking water supplies.¹⁶⁰⁵
- ***Promote wetland accretion by introducing sediment:*** Promoting wetland accretion by introducing sediment helps maintain sediment transport to wetlands, which helps protect coastal land from storms.¹⁶⁰⁶ However, it requires continual management and can be very costly.¹⁶⁰⁷

Maintain water quality

Two options identified by the U.S. EPA (2009) to help maintain water quality in a changing climate are:

- ***Plug drainage canals:*** Plugging drainage canals prevents subsidence-inducing saltwater intrusion and protects land subject to flooding.¹⁶⁰⁸ However, it may eliminate transportation routes.¹⁶⁰⁹
- ***Prevent or limit groundwater extraction from shallow aquifers:*** Preventing or limiting groundwater extraction reduces relative sea level rise by preventing subsidence and reducing saltwater intrusion into freshwater aquifers.¹⁶¹⁰ However, an alternative water source may need to be found.¹⁶¹¹

¹⁶⁰⁰ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 43)

¹⁶⁰¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

¹⁶⁰² Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

¹⁶⁰³ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 14)

¹⁶⁰⁴ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 43)

¹⁶⁰⁵ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 43)

¹⁶⁰⁶ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 12)

¹⁶⁰⁷ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 12)

¹⁶⁰⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 19)

¹⁶⁰⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 19)

¹⁶¹⁰ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 19)

¹⁶¹¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 19)

Preserve habitat for vulnerable species

Several options are available to help preserve habitat for vulnerable species in a changing climate.

Establish, expand, and/or connect protected areas and refugia

A number of studies provide evidence of elevated biodiversity within protected areas, with the greatest benefit accruing to nonmigratory species.¹⁶¹² For example, effectively managed Marine Protected Areas (MPAs) can be used to strategically target habitats and geographic areas that are critical to maintaining ecosystem goods (such as fisheries) and services (such as coastal protection, tourism and recreational use).¹⁶¹³ MPAs are defined by the World Conservation Union (IUCN) as any area of intertidal or subtidal terrain, together with its overlaying waters, and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part, or all, of the enclosed environment.¹⁶¹⁴ MPAs can be embedded within larger management and zoning efforts - such as coastal zone management, seascapes or networks of MPAs - or used as a stand-alone measure.¹⁶¹⁵ Ideally, MPAs should be part of a larger management effort, but the lack of resources and capacity often necessitate a more limited and targeted approach.¹⁶¹⁶ Regardless of their size or configuration, most MPAs use zoning schemes to designate certain areas for particular human uses or for ecological reserves.¹⁶¹⁷ Most MPAs include at least one core area within which all extractive and direct impact activities such as fishing and boat anchoring are prohibited.¹⁶¹⁸ To design MPAs, Hoffman (2003), Kling and Sanchirico (2009), and U.S. AID (2009) suggest the following information may be gathered or incorporated:

- Compile or develop resource maps that depict key habitat, species location, and population and migration patterns.¹⁶¹⁹ For example:
 - Map habitat types including location, area covered, structural elements (sand, kelp forests, seagrass beds, boulders, etc.), and functional elements (e.g. spawning grounds for particular species, nursery grounds, etc.).¹⁶²⁰
 - Identify key biotic and abiotic variables controlling species distribution in the region, and how they will be affected by climate change.¹⁶²¹
 - Identify the areas that may be more resilient to sea surface temperature change, or can help mitigate against sea level rise or increased frequency of storms.¹⁶²²
 - Account for the likelihood that species ranges—at least the ranges of mid-latitude species—will move toward the poles as the oceans warm.¹⁶²³

¹⁶¹² Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 40). The authors cite Halpern (2003) for this information.

¹⁶¹³ Verbatim or nearly verbatim from U.S. AID. (2009, p. 83)

¹⁶¹⁴ Verbatim or nearly verbatim from U.S. AID. (2009, p. 83)

¹⁶¹⁵ Verbatim or nearly verbatim from U.S. AID. (2009, p. 83)

¹⁶¹⁶ Verbatim or nearly verbatim from U.S. AID. (2009, p. 83)

¹⁶¹⁷ Verbatim or nearly verbatim from U.S. AID. (2009, p. 83)

¹⁶¹⁸ Verbatim or nearly verbatim from U.S. AID. (2009, p. 83)

¹⁶¹⁹ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶²⁰ Verbatim or nearly verbatim from Hoffman. *Designing reserves to sustain temperate marine ecosystems in the face of global climate change.* (2003, p. 146)

¹⁶²¹ Verbatim or nearly verbatim from Hoffman. (2003, p. 146)

¹⁶²² Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶²³ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 40)

- Identify nearshore currents and source and sink areas for seeds/larvae to replenish species in the MPA.¹⁶²⁴
- Determine if there are areas with reduced water circulation, upwelling and high sea surface temperatures, which might be increasingly vulnerable to climate change.¹⁶²⁵
- Design reserves to provide temperature refugia.¹⁶²⁶ While shifting habitats to greater depth and higher latitudes is one way of finding cooler temperatures, most regions have identifiable “hot spots” and “cold spots” due to factors such as upwelling, shade, subhabitats, timing of tides, and freshwater input.¹⁶²⁷ Designing reserves to include “cold spots” may reduce thermal stress from climate change.¹⁶²⁸
- Establish reserves in transitional zones between biogeographic regions as well as in core areas and add an “insurance factor” to reserve size calculations.¹⁶²⁹ As climate changes, the “best” area for a species may shift away from what had been the core of its range.¹⁶³⁰ An insurance factor is extra area added to the reserve, and assures that a reserve’s function goals are met despite catastrophes.¹⁶³¹ Such an approach could also be effective in buffering against possible effects of climate change, and would work well in conjunction with other hedging approaches.¹⁶³² This approach may be ineffective in protecting many spatially restricted habitats and ecosystems.¹⁶³³
- Design reserves based on features of the environment unlikely to change (e.g. physiographic features such as topography) and that show resistance and resilience to climate change.¹⁶³⁴
- Determine the types and intensities of resource uses and identify stakeholder dependency on fishing, tourism, and mining in the area.¹⁶³⁵ Identify existing community resident perceptions of resource access and use rights.¹⁶³⁶
- Identify the larger watersheds and river systems affecting the MPA, nearby human settlements and up-current sources of pollutants.¹⁶³⁷
- Determine which species and habitats are most vulnerable currently and in the future.¹⁶³⁸ Determine representative and replicate sites as insurance against future impacts.¹⁶³⁹

Design estuaries with dynamic boundaries and buffers

Buffers are land use regulations designed to reduce the impacts of land uses (e.g., development) on natural resources by providing a transition zone between a resource and human activities.¹⁶⁴⁰ Ecological

¹⁶²⁴ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶²⁵ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶²⁶ Verbatim or nearly verbatim from Hoffman. (2003, p. 140)

¹⁶²⁷ Verbatim or nearly verbatim from Hoffman. (2003, p. 140). The author cites Helmuth et al. (2002) for information on hot and cold spots.

¹⁶²⁸ Verbatim or nearly verbatim from Hoffman. (2003, p. 140)

¹⁶²⁹ Verbatim or nearly verbatim from Hoffman. (2003, p. 140-141)

¹⁶³⁰ Verbatim or nearly verbatim from Hoffman. (2003, p. 140)

¹⁶³¹ Verbatim or nearly verbatim from Hoffman. (2003, p. 141)

¹⁶³² Verbatim or nearly verbatim from Hoffman. (2003, p. 141)

¹⁶³³ Verbatim or nearly verbatim from Hoffman. (2003, p. 141)

¹⁶³⁴ Verbatim or nearly verbatim from Hoffman. (2003, p. 142)

¹⁶³⁵ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶³⁶ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶³⁷ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶³⁸ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

¹⁶³⁹ Verbatim or nearly verbatim from U.S. AID. (2009, p. 84)

buffer zones (buffers) are similar to setbacks (and may be included within setbacks), but are typically designed to protect the natural, rather than the built, environment.¹⁶⁴¹ By protecting natural resources, buffers protect the natural and beneficial functions those resources provide.¹⁶⁴² Protective services include providing habitat and connectivity; minimizing erosion and flooding by stabilizing soil, providing flood storage, and reducing flood velocities; and improving water quality through filtration of harmful sediment, pollutants, and nutrients.¹⁶⁴³ Buffers also protect breeding and foraging habits of highly migratory species.¹⁶⁴⁴

Typically, buffers are maintained in their natural vegetative state and activities such as vegetation removal, soil disturbance, and construction are restricted or prohibited.¹⁶⁴⁵ As climate changes, buffers will also be able to support inland wetland migration as well as carbon sequestration.¹⁶⁴⁶ NOAA (2010) notes the effectiveness of any buffer will depend on several factors, including size, elevation, vegetation, slope, soil, permitted activities, adjacent land uses, stormwater flow, and erosion rate.¹⁶⁴⁷ In addition, effectiveness will also be dependent on property owner compliance and the monitoring and enforcement of buffer regulations.¹⁶⁴⁸ In highly developed areas, boundaries may already be unmovable.¹⁶⁴⁹

Connect landscapes with corridors to enable migrations

The highly fragmented nature of today's landscapes has led many conservation biologists to promote increasing connectivity among protected areas to enhance movement in a changing climate (e.g., connecting protected lands along a coastline).¹⁶⁵⁰ Corridors allow for species migration with climate change and sustain wildlife biodiversity across the landscape.¹⁶⁵¹ The ability to move through a corridor depends on species-specific behavior and habitat affinities.¹⁶⁵² Given that many species, with diverse habitat requirements and dispersal abilities, will need to move in response to climate change, species-based corridor approaches may not be adequate or feasible.¹⁶⁵³ Further, significant effort and resources may be required.¹⁶⁵⁴ Two additional approaches to increasing connectivity have been proposed. First, small stepping-stone reserves can be placed between larger preserves to facilitate movement.¹⁶⁵⁵ The second approach is to manage the lands or waters between protected areas in ways that allow the most species to move through these spaces.¹⁶⁵⁶ Such approaches have been referred to as softening or managing

¹⁶⁴⁰ Verbatim or nearly verbatim from NOAA. (2010, p. 85)

¹⁶⁴¹ Verbatim or nearly verbatim from NOAA. (2010, p. 85)

¹⁶⁴² Verbatim or nearly verbatim from NOAA. (2010, p. 85)

¹⁶⁴³ Verbatim or nearly verbatim from NOAA. (2010, p. 85)

¹⁶⁴⁴ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 18)

¹⁶⁴⁵ Verbatim or nearly verbatim from NOAA. (2010, p. 85-86)

¹⁶⁴⁶ Verbatim or nearly verbatim from NOAA. (2010, p. 86)

¹⁶⁴⁷ Verbatim or nearly verbatim from NOAA. (2010, p. 86)

¹⁶⁴⁸ Verbatim or nearly verbatim from NOAA. (2010, p. 86)

¹⁶⁴⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 18)

¹⁶⁵⁰ Verbatim or nearly verbatim from Lawler. (2009, p. 83). The author cites Shafer (1999), Noss (2001), Hulme (2005), and Welch (2005) for this information.

¹⁶⁵¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 24)

¹⁶⁵² Verbatim or nearly verbatim from Lawler. (2009, p. 83)

¹⁶⁵³ Verbatim or nearly verbatim from Lawler. (2009, p. 84). The author cites Hulme (2005) for this information.

¹⁶⁵⁴ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 24)

¹⁶⁵⁵ Verbatim or nearly verbatim from Lawler. (2009, p. 84)

¹⁶⁵⁶ Verbatim or nearly verbatim from Lawler. (2009, p. 84)

the matrix.¹⁶⁵⁷ Some combination of matrix management, stepping-stone reserves, and corridors will likely allow the most movement in response to climate change.¹⁶⁵⁸ For further information on reserves, please see “Establish, expand, and/or connect protected areas and refugia” in this section.

Case Study 3. Federal, Tribal, and non-profit partners restore and study the Nisqually Delta (WA) to promote the recovery and resiliency of a treasured ecosystem in light of climate change and other stressors.

Climate stressors addressed: Increased frequency and severity of storms; SLR

Tidal wetlands restored by the Nisqually Indian Tribe and the Nisqually National Wildlife Refuge represent the largest estuarine restoration project in the Pacific Northwest, furthering the recovery of Puget Sound salmon and wildlife populations. Over the past decade, the Refuge and Tribe have restored 900 acres of estuarine habitat in the Nisqually Delta. With close partners, including Ducks Unlimited, more than 21 miles of historic tidal sloughs and historical floodplains have been reconnected to Puget Sound, increasing potential salt marsh habitat in the southern reach of Puget Sound by approximately 55%. The U.S. Geological Survey (USGS), in partnership with the Tribe and Refuge, is evaluating habitat development and changes in ecosystem functions associated with large-scale restoration, by conducting elevation, hydrology, geomorphology, vegetation, birds, fish, and invertebrate prey surveys. A sediment budget is being developed for the Delta to assess whether sufficient sedimentation will occur and enable the marsh and delta to accrete given present and projected rates of sea level rise and historic subsidence. Elevation and sedimentation data using surface elevation tables (SETs), feldspar marker horizons, and short cores will be compared to measured sediment fluxes through restored channels to quantify sediment transport and delivery. Vegetation development and habitat availability for birds will be evaluated using inundation (calculated from elevation and hydrology datasets) and salinity parameters. As the restoration progresses, the Tribe, USGS, and partners are also assessing the capacity and functioning of the restoring habitat to support salmonids, such as juvenile Chinook (*Oncorhynchus tshawytscha*). The monitoring and applied research forms the basis of models assessing near- and long-term restoration trajectories associated with climate and land-use change. These model scenarios can ultimately provide information to help land owners and land managers make decisions about future restorations and management in light of climate change and other stressors. Furthermore, estuary restoration is coupled with expansion of the Refuge boundary by 3,479 acres, providing future opportunities for protection, land acquisition, and upland migration of diverse habitats in response to climate change. In conclusion, the Nisqually Delta restorations helps promote system resiliency to loss of habitats and biodiversity, climate change effects such as increased winter storms, rainfall, and flooding, and rise in sea levels resulting in loss of shoreline areas.

Produced in collaboration with John Y. Takekawa, Isa Woo & Kelley Turner (USGS Western Ecological Research Center); Eric Grossman (USGS Pacific Coastal & Marine Science Center and Western Fisheries Research Center); Jean E. Takekawa & Jesse Barham (U.S. Fish and Wildlife Service Nisqually National Wildlife Refuge); and, Christopher Ellings (Nisqually Indian Tribe Salmon Recovery Program).

Sources: www.nisquallydeltarestoration.org; [Tide Returns to Nisqually Estuary](#) (press release); [Nisqually NWR CCP](#); unstructured interviews (December 2010 & April, July, & August 2011). All websites accessed 8.23.2011.

¹⁶⁵⁷ Verbatim or nearly verbatim from Lawler. (2009, p. 84). The author cites Franklin et al. (1992) and Noss (2001) for this information.

¹⁶⁵⁸ Verbatim or nearly verbatim from Lawler. (2009, p. 84)

Prohibit or remove hard protection or other barriers to tidal and riverine flow

The U.S. EPA (2009) states the prohibition or removal of barriers to tidal and riverine flow such as dikes may allow species and wetlands to migrate inland.¹⁶⁵⁹ Removal of barriers may be costly and destructive to shoreline property.¹⁶⁶⁰

Preserve and restore the structural complexity and biodiversity of vegetation in tidal marshes, seagrass meadows, and mangroves

Vegetation protects against erosion, protects mainland shorelines from tidal energy, storm surge, and wave forces, filters pollutants, and absorbs atmospheric CO₂.¹⁶⁶¹ This helps maintain water quality as well as shorelines, and may aid invasive species management.¹⁶⁶²

Identify and protect ecologically significant (“critical”) areas

Protecting critical areas such as nursery grounds, spawning grounds, and areas of high species diversity will promote biodiversity and ecosystem services.¹⁶⁶³ For example, critical areas produce and add nutrients to coastal systems, and serve as refugia and nurseries for species.¹⁶⁶⁴ However, the U.S. EPA (2009) notes federal or state protection may be required.¹⁶⁶⁵

Additional actions

The following adaptation actions for preserving habitat for vulnerable species were listed by the U.S. EPA (2009), but were not described in detail or are described elsewhere in this report:

- ***Retreat from, and abandonment of, coastal barriers:*** This may help protect estuaries, allowing them to return to their natural habitat, but may be politically unfavorable due to the high value of coastal property and infrastructure.¹⁶⁶⁶
- ***Purchase upland development rights or property rights:*** Please see the section “Maintain shorelines” for an explanation of land acquisition.
- ***Replicate coastal habitat types in multiple areas*** to spread risks associated with climate change: Biodiversity and critical areas are protected, but land may not be available to replicate habitats.¹⁶⁶⁷
- ***Expand land use planning horizons to incorporate longer climate predictions:*** Longer planning horizons could inhibit risky development and provide protection for estuarine

¹⁶⁵⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 12)

¹⁶⁶⁰ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 12)

¹⁶⁶¹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁶⁶² Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁶⁶³ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁶⁶⁴ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁶⁶⁵ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 13)

¹⁶⁶⁶ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 17)

¹⁶⁶⁷ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 18)

habitats.¹⁶⁶⁸ However, land use plans rarely incorporate hard prohibitions against development close to sensitive habitats and have limited durability over time.¹⁶⁶⁹

- ***Adapt protections of important biogeochemical zones and critical habitats:*** As the locations of critical habitats and biogeochemical zones change with climate, adapting protections allows for migration of critical areas, but will require consistent monitoring efforts.¹⁶⁷⁰

Case Study 4. Responding to Changes in Seawater Chemistry: The Oyster Emergency Project, WA.

Climate stressors addressed: Ocean acidification, upwelling

In 2005, shellfish growers began to encounter difficulties in rearing hatchery-produced oyster larvae and in successfully setting wild populations of oysters. Preliminary research indicated that increasingly acidic, nutrient replete, deep, upwelled waters could be the cause of the increase in oyster mortalities. In response to persistently low shellfish harvests from 2005-2008, the Pacific Coast Shellfish Growers Association (PCSGA) proposed the “Oyster Emergency Project,” a collaboration between regional shellfish growers, NOAA, Oregon State University and The Nature Conservancy. To help shellfish growers adapt, PCSGA initiated a targeted research project to identify environmental stressors of oyster populations and to isolate genetic stocks of oysters that offer enhanced resilience; four projects were proposed. As of December 2009, three of the four projects had been funded: monitoring sea water, the genetic study, and developing an assay to detect a harmful bacterium. PCSGA is continuing to look for funding for the final project, retrofitting hatcheries. Through the “Oyster Emergency Project” targeted research plan, PCSGA hopes to identify short-term solutions that can be implemented within months to help shellfish hatcheries adapt to changes in seawater chemistry. The long-term monitoring program will allow researchers to specify environmental parameters that retard oyster larval development.

Source: Climate Action Knowledge Exchange, <http://www.cakex.org/case-studies/50> (accessed 12.14.2010)

Manage invasive species in a changing climate

In a 2008 report, the EPA’s National Center for Environmental Assessment recommended the following initial steps to incorporate climate change into aquatic invasive species management plans:

- Incorporate climate change considerations into leadership and coordination activities;
- Identify new aquatic invasive species threats as a result of climate change;
- Identify ecosystem vulnerabilities and improve methods to increase ecosystem resilience;
- Evaluate the effectiveness of control mechanisms under changing conditions; and,
- Manage information systems to include considerations of changing conditions.¹⁶⁷¹

An aquatic invasive species program that considers climate change would also include a comprehensive monitoring system that can detect new aquatic invasive species and changes in existing ones and how they affect the management area.¹⁶⁷²

¹⁶⁶⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 17)

¹⁶⁶⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 17)

¹⁶⁷⁰ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 18)

¹⁶⁷¹ Verbatim or nearly verbatim from NOAA. (2010, p. 92)

¹⁶⁷² Verbatim or nearly verbatim from NOAA. (2010, p. 93)

Two additional options are available for managing invasive species in a changing climate:

- ***Strengthen rules that prevent the introductions of invasive species:*** Given the extreme difficulty and high cost of eradication of self-sustaining marine non-native invasive species populations, the most fruitful avenues for adapting to increased recruitment probability are regulations and incentive schemes targeting key introduction pathways, including ballast water, aquaculture, the exotic pet and aquarium trade, and the seafood trade.¹⁶⁷³ Practices that have proven effective in combating non-native invasive species introduction through ballast water range from low-tech options, such as ballast water exchange outside of less-saline estuaries, to biocide and the use of treatment facilities, such as those currently in place at California ports.¹⁶⁷⁴ No-discharge zones for ballast water are another option.¹⁶⁷⁵ Ballast water exchange is considered by some to be an inadequate response because it is ineffective against species capable of surviving more saline water or within drained ballasts.¹⁶⁷⁶ Current alternatives that would allow for the treatment of ballast water are costly; the cost of retrofitting a single commercial vessel to enable it to interface with existing port-based treatment facilities has been estimated at close to \$400,000.¹⁶⁷⁷
- ***Remove invasive species and restore native species:*** Local removals of invasives are viable to improve marsh characteristics that promote fish and wildlife.¹⁶⁷⁸ It may be difficult to implement on a larger scale.¹⁶⁷⁹

¹⁶⁷³ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 41). The authors cite Ruiz et al. (2000b) and Williams and Grosholz (2008) for this information.

¹⁶⁷⁴ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 41). The authors cite Buck (2006) for this information.

¹⁶⁷⁵ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 16)

¹⁶⁷⁶ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 41)

¹⁶⁷⁷ Verbatim or nearly verbatim from Kling and Sanchirico. (2009, p. 41). The authors cite Buck (2006) for this information.

¹⁶⁷⁸ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 16)

¹⁶⁷⁹ Verbatim or nearly verbatim from U.S. EPA. (2009, p. 16)

8. STATUS OF ADAPTATION STRATEGIES AND PLANS IN THE STATES, PROVINCES, AND SELECTED TRIBAL NATIONS OF THE NPLCC

Alaska

To address the impacts of climate change on Alaska, Governor Sarah Palin signed Administrative Order 238 on September 14, 2007, which established and charged the Alaska Climate Change Sub-Cabinet to advise the Office of the Governor on the preparation and implementation of a comprehensive Alaska Climate Change Strategy (AO 238).¹⁶⁸⁰ The Adaptation Advisory Group (AAG) was charged with evaluating and developing options to adapt to climate change.¹⁶⁸¹ The Final Report Submitted by the Adaptation Advisory Group to the Alaska Climate Change Sub-Cabinet was released in January 2010. The types of recommendations made by the AAG vary.¹⁶⁸² The options cover four broad sectors (public infrastructure, health and culture, natural systems, and economic activities) and range from new systems approaches and institutional structures to adoption of new or revised policies, initiatives, and other actions.¹⁶⁸³ The Sub-Cabinet will consider these, as well as recommendations from the Immediate Action Work Group, the Mitigation Advisory Group, and the Research Needs Work Group in the context of other complementary efforts.¹⁶⁸⁴ A comprehensive Climate Change Strategy for Alaska will then be drafted for consideration by the Governor.¹⁶⁸⁵

Yukon Territory

Within the Yukon Territory (186,272 mi², 482,443 km²),¹⁶⁸⁶ the only land within the NPLCC region is that covered by the Kluane National Park and Preserve (8,487 miles², 21, 980 km²; ~4.6% of total area in Yukon Territory),¹⁶⁸⁷ located in the southwest corner of the Territory. Parks Canada lists impacts in its Pacific Coast parks largely consistent with those described in this report for the region: higher temperatures, a moderate increase in winter precipitation and drier summers, increased ocean surface temperatures, greater storm intensity, and altered ocean currents (please see relevant sections of this report for further information).¹⁶⁸⁸ Information on climate change adaptation planning for the Kluane National Park and Preserve was limited; however, information on adaptation planning by the Government of Yukon is described below.

The Government of Yukon Climate Change Strategy, released in 2006, sets out the government's role and key goals for its response to climate change.¹⁶⁸⁹ After its release, Environment Yukon began researching and collecting information needed to develop the Yukon Government Climate Change Action Plan, which

¹⁶⁸⁰ Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, Ch 1, p. v-vi)

¹⁶⁸¹ Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, Ch 1, p. vi)

¹⁶⁸² Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, Ch 1, p. vi)

¹⁶⁸³ Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, Ch 1, p. vi)

¹⁶⁸⁴ Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, Ch 1, p. vi)

¹⁶⁸⁵ Verbatim or nearly verbatim from AK Department of Environmental Conservation. (2010, Ch 1, p. vi)

¹⁶⁸⁶ Government of Yukon. *Executive Council Office: General Facts: Land (website)*. (2011)

¹⁶⁸⁷ Parks Canada. *Kluane National Park and Preserve of Canada Management Plan*. (2010, p. 3)

¹⁶⁸⁸ Verbatim or nearly verbatim from Parks Canada. *The Climate is Changing Our National Parks: Impacts on Pacific Parks (website)*. (2009)

¹⁶⁸⁹ Verbatim or nearly verbatim from Yukon Government. *Government of Yukon Climate Change Strategy*. (July 2006, p. 1)

was released February 2009.¹⁶⁹⁰ The Climate Change Strategy includes broad goals targeted at enhancing the awareness and understanding of climate change impacts, taking measures to reduce the levels of greenhouse gas emissions in Yukon, building environmental, social and economic systems that are able to adapt to climate change impacts and positioning Yukon as a northern leader for applied climate change research and innovation.¹⁶⁹¹ The Action Plan, providing clear direction and action, advances the goals of the Climate Change Strategy.¹⁶⁹² The four goals outlined in the Action Plan are: (1) enhance knowledge and understanding of climate change; (2) adapt to climate change; (3) reduce greenhouse gas emissions; and, (4) lead Yukon action in response to climate change.¹⁶⁹³

Preparation of the Action Plan included discussions with a wide variety of government and non-government representatives, an interdepartmental workshop, working-group meetings and several external workshops.¹⁶⁹⁴ A draft of the Action Plan was circulated for public comment from May 12 to July 31, 2008 before its release in February 2009.¹⁶⁹⁵

The Yukon government will pursue the implementation of its Climate Change Strategy in partnership and collaboration with First Nation governments, municipalities, industry, the public, the other northern territories and the provinces, the federal government and other governments around the world.¹⁶⁹⁶

Implementation of the Action Plan will involve all departments and agencies of the Yukon government.¹⁶⁹⁷ The Yukon government will also work with partners to meet the challenges and opportunities of climate change in Yukon – other governments, non-governmental organizations, industry, and the academic community.¹⁶⁹⁸

British Columbia

Building on a framework established in 2007, British Columbia released a Climate Action Plan in 2008.¹⁶⁹⁹ The section on adaptation outlines a range of coordinated actions to help B.C. adapt to climate change, including options for investing in new ideas and solutions, protecting forests, protecting water, and building carbon smart communities.¹⁷⁰⁰ The Climate Change Adaptation Strategy addresses three main themes that provide a solid framework to address climate change impacts and adaptation: (1) build a strong foundation of knowledge and tools to help public and private decision-makers across B.C. prepare for a changing climate, (2) make adaptation a part of B.C. Government's business, ensuring that climate change impacts are considered in planning and decision-making across government, and (3) assessing risks and implementing priority adaptation actions in key climate sensitive sectors.¹⁷⁰¹

¹⁶⁹⁰ Verbatim or nearly verbatim from Yukon Government. *Yukon Government Climate Change Action Plan*. (February 2009, p. 9)

¹⁶⁹¹ Verbatim or nearly verbatim from Yukon Government. (July 2006, p. 1)

¹⁶⁹² Verbatim or nearly verbatim from Yukon Government. (February 2009, p. 5)

¹⁶⁹³ Verbatim or nearly verbatim from Yukon Government. (February 2009, p. 7)

¹⁶⁹⁴ Verbatim or nearly verbatim from Yukon Government. (February 2009, p. 9)

¹⁶⁹⁵ Verbatim or nearly verbatim from Yukon Government. (February 2009, p. 9)

¹⁶⁹⁶ Verbatim or nearly verbatim from Yukon Government. (July 2006, p. 1)

¹⁶⁹⁷ Verbatim or nearly verbatim from Yukon Government. (February 2009, p. 5)

¹⁶⁹⁸ Verbatim or nearly verbatim from Yukon Government. (February 2009, p. 5)

¹⁶⁹⁹ Verbatim or nearly verbatim from Government of British Columbia. *Climate Action Plan*. (2008, p. 1)

¹⁷⁰⁰ Government of British Columbia. *Climate Action Plan*. (2008, p. 66-69)

¹⁷⁰¹ Verbatim or nearly verbatim from B.C. Ministry of Environment. *Climate Change Adaptation Strategy (website)*. (2011)

Washington

In the spring of 2009, Governor Gregoire signed legislation (E2SSB 5560) that included provisions for the formation of an “integrated climate change response strategy” that would “better enable state and local agencies, public and private businesses, nongovernmental organizations, and individuals to prepare for, address, and adapt to the impacts of climate change.”¹⁷⁰² The legislation directs Ecology, in partnership with the departments of Agriculture, Commerce, Fish and Wildlife, Natural Resources, and Transportation to develop an initial state strategy by December of 2011.¹⁷⁰³

Four Topic Advisory Groups (TAGs) were formed to assist in developing a state strategy for how Washington can prepare for and adapt to the impacts of climate change.¹⁷⁰⁴ The TAGs are structured around four areas (built environment, infrastructure, and communities; human health and security; ecosystems, species, and habitats; natural resources) and will address a wide range of key issues that citizens, governments, and businesses will face in a changing climate.¹⁷⁰⁵ The Departments of Agriculture, Ecology, Fish and Wildlife, Health, Natural Resources, Transportation, and the University of Washington lead TAGs that examine climate change impacts and identify preparation and adaptation strategies as well as additional research needs.¹⁷⁰⁶ TAG members met regularly since their inception in early 2010 through January 2011, including three cross-cutting TAG meetings.¹⁷⁰⁷ The draft strategy will be completed in Spring 2011, followed by a period of public comment and outreach through Summer 2011.¹⁷⁰⁸ The final strategy will be submitted to the Legislature in December 2011.¹⁷⁰⁹

Jamestown S’Klallam Tribe

In late 2009, Tribal Council approved a proposal by the Tribe’s Natural Resources Department to write a formal Jamestown S’Klallam Plan for Climate Change.¹⁷¹⁰ The purpose of the plan is to prepare for a warming climate, and to help reduce the Tribe’s carbon footprint, to slow down the warming planet.¹⁷¹¹

Swinomish Indian Tribal Community

In the fall of 2008 the Swinomish Indian Tribal Community started work on a landmark two-year Climate Change Initiative to study the impacts of climate change on the resources, assets, and community of the Swinomish Indian Reservation and to develop recommendations on actions to adapt to projected

¹⁷⁰² Verbatim or nearly verbatim from WA Department of Ecology. *Preparing for impacts: adapting to climate change (website)*. (2011)

¹⁷⁰³ Verbatim or nearly verbatim from WA Department of Ecology. *Preparing for impacts: adapting to climate change (website)*. (2011)

¹⁷⁰⁴ Verbatim or nearly verbatim from WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)

¹⁷⁰⁵ Verbatim or nearly verbatim from WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)

¹⁷⁰⁶ Verbatim or nearly verbatim from WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)

¹⁷⁰⁷ Verbatim or nearly verbatim from WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)

¹⁷⁰⁸ WA Department of Ecology Topic Advisory Groups. *Integrated Climate Change Response Plan: Draft Topic Advisory Group Work Plan (unpublished internal document)*. (2009)

¹⁷⁰⁹ WA Department of Ecology Topic Advisory Groups. (2009)

¹⁷¹⁰ Verbatim or nearly verbatim from Jamestown S’Klallam Tribe. *Newsletter (Vol 32, Issue 2) (pdf; website)*. (2011, p. 9)

¹⁷¹¹ Verbatim or nearly verbatim from Jamestown S’Klallam Tribe. (2011, p. 9)

impacts.¹⁷¹² This followed issuance of a Proclamation by the Tribal Senate in 2007 directing action to study and assess climate change impacts on the Reservation.¹⁷¹³ Under the guidance and coordination of the Swinomish Office of Planning & Community Development, the first year of the project was devoted to assessment of projected impacts, as presented in an Impact Assessment Technical Report issued in the fall of 2009.¹⁷¹⁴ The second year of the project was focused on evaluation of strategies and options for recommended actions to counter identified impacts, which resulted in preparation and release of the *Climate Adaptation Action Plan*.¹⁷¹⁵ The ultimate goal of the project was to help ensure an enduring and climate-resilient community that can meet the challenges of anticipated impacts in the years to come.¹⁷¹⁶

The Action Plan discusses climate change within the context of Swinomish cultural traditions, community health, and cultural resilience, and reviews the relationship between tribal traditions and effective adaptation planning. This information, along with the climate change impacts assessed in the Technical Report and strategic evaluation of many adaptation options, was used to derive the adaptation goals, action recommendations and priorities described in the Action Plan. These are organized into four focal areas (coastal resources, upland resources, physical health, and community infrastructure and services). Strategic evaluation included assessment of six key objectives (comprehensive, sustainable, dynamic response, fiscally feasible, non-regulatory, and meets community goals).¹⁷¹⁷ Strategies were then screened against a number of key considerations (evaluation objectives met, existing authority and capacity versus required authority and capacity, potential internal and external partners, and timeframe anticipated for potential implementation), as well as the vulnerability and estimated risk to the system in question.¹⁷¹⁸ At time of writing, the Swinomish are moving forward on a number of their priority actions. For example, they are seeking grants for their work, evaluating existing management plans and regulations, and assessing needed changes to building and zoning codes. A description of the Swinomish Tribe's Climate Adaptation Action Plan can be found at http://www.swinomish-nsn.gov/climate_change/Docs/SITC_CC_AdaptationActionPlan_complete.pdf (accessed 4.7. 2011).

Tulalip Tribe

The Tulalip Adaptation and Mitigation Policy Frameworks for Climate Change lists six criteria for incorporating policies and law in planning and management that allow the Tulalip Tribes to sustainably maintain healthy, resilient human communities in the face of change.¹⁷¹⁹ These policies and law need, among other things, to be *integrated* (involve multiple independent sectors in the creation of holistic solutions that address a full range of natural and social factors), *cross-scale* (address problems at multiple scales, and devise scale-appropriate actions, working to ensure policies and actions do not defeat measures taken at any one scale), *adaptive* (monitor and respond to the effectiveness of efforts and advances in scientific and local knowledge, adapt objectives when necessary), *restorative* (use historical

¹⁷¹² Verbatim or nearly verbatim from Swinomish Indian Tribal Community. *Swinomish Climate Change Initiative: Climate Adaptation Action Plan*. (2010, p. 1)

¹⁷¹³ Verbatim or nearly verbatim from Swinomish Indian Tribal Community. (2010, p. 1)

¹⁷¹⁴ Verbatim or nearly verbatim from Swinomish Indian Tribal Community. (2010, p. 1)

¹⁷¹⁵ Verbatim or nearly verbatim from Swinomish Indian Tribal Community. (2010, p. 1)

¹⁷¹⁶ Verbatim or nearly verbatim from Swinomish Indian Tribal Community. (2010, p. 1)

¹⁷¹⁷ Swinomish Indian Tribal Community. (2010, p. 38)

¹⁷¹⁸ Swinomish Indian Tribal Community. (2010, p. 40)

¹⁷¹⁹ Verbatim or nearly verbatim from Tulalip Tribes. *Climate Change Impacts on Tribal Resources* (pdf; website). (2006, p. 2)

baselines for mitigation goals for processes that maintain healthy watersheds and communities), *participatory* (recognize stakeholder equity by including federal, state, tribal and local governments, businesses and citizens in the transparent development of baselines, objectives, and mitigation and adaptation measures), and *sustainable* (design objectives and actions on a basis of ecological and cultural sustainability, and include mechanisms to ensure the sustained financial and administrative support for their implementation).¹⁷²⁰

Oregon

In October 2009, Governor Kulongoski of Oregon asked the directors of several state agencies, universities, research institutions and extension services to develop a climate change adaptation plan.¹⁷²¹ Among other things, the plan provides a framework for state agencies to identify authorities, actions, research, and resources needed to increase Oregon's capacity to address the likely effects of a changing climate.¹⁷²² *The Oregon Climate Change Adaptation Framework* was released in December 2010. The Framework lays out eleven expected climate-related risks, the basic adaptive capacity to deal with those risks, short-term priority actions for each risk, and several steps that will evolve into a long-term process to improve Oregon's capacity to adapt to variable and changing climate conditions.¹⁷²³

Coquille Tribe

Building on the traditions and values of the Tribal community, the Coquille Indian Tribe is focused on developing a plan to adapt to the challenges presented by climate change and related threats to the tribe's well-being.¹⁷²⁴ Currently, the tribe is focused on building capacity within the Tribal government to understand the impacts of climate change, engaging the tribal community in climate change discourse, and strengthening collaboration and partnerships with non-tribal organizations within the region.¹⁷²⁵ The Tribe has committees in place to identify and investigate the issues, including the Climate Change Committee and the Emergency Preparedness and Disaster Mitigation Committee.¹⁷²⁶ The Climate Change Committee, for example, was established in 2008 and has been tasked by Tribal Council to: become familiar with the causes of climate change and consequences of climate change to the Tribe, tribal members, tribal enterprises and the outlying community; evaluate practices, policies operations and enterprises and make recommendations regarding opportunities, adaptations and mitigations regarding the climate change process as it affects the Tribe and its members; and, provide information to the Tribal membership regarding the causes, effects and prudent responses to climate change.¹⁷²⁷

In addition to continuing current efforts, the Tribe is preparing a *Climate Action Plan*, a more detailed and informed plan that incorporates insight and knowledge from Tribal members, the Tribe's natural

¹⁷²⁰ Verbatim or nearly verbatim from Tulalip Tribes. (2006, p. 2)

¹⁷²¹ Verbatim or nearly verbatim from State of Oregon. *The Oregon Climate Change Adaptation Framework*. (2010, p. i)

¹⁷²² Verbatim or nearly verbatim from State of Oregon. (2010, p. i)

¹⁷²³ State of Oregon. (2010, p. i)

¹⁷²⁴ Verbatim or nearly verbatim from Institute for Tribal Environmental Professionals. *Climate Change and the Coquille Indian Tribe: Planning for the effects of climate change and reducing greenhouse gas emissions (pdf)*. (2011, p. 1)

¹⁷²⁵ Verbatim or nearly verbatim from Institute for Tribal Environmental Professionals. (2011, p. 2)

¹⁷²⁶ Verbatim or nearly verbatim from Institute for Tribal Environmental Professionals. (2011, p. 2)

¹⁷²⁷ Verbatim or nearly verbatim from Institute for Tribal Environmental Professionals. (2011, p. 3)

resources and planning staff, information and data from climate scientists, research and other organizations dedicated to climate issues, and the assistance and resources available from local, state and federal government.¹⁷²⁸ The plan will help to further identify local risks to Coquille Tribal land and natural resources, infrastructure and transportation systems, and in turn, the Tribe's culture, economy, health, and safety.¹⁷²⁹ Additionally, impacts to other regions of the northwest and the world that may also bring adverse local impacts will be investigated.¹⁷³⁰ Further information on the Coquille Tribe's efforts around climate change can be found at http://tribalclimate.uoregon.edu/files/2010/11/tribes_Coquille_web2.pdf (accessed 4.7. 2011).

California

California strengthened its commitment to managing the impacts from sea level rise, increased temperatures, shifting precipitation and extreme weather events when Governor Arnold Schwarzenegger signed Executive Order (EO) S-13-08 on November 14, 2008.¹⁷³¹ The order called on state agencies to develop California's first strategy to identify and prepare for these expected climate impacts.¹⁷³² The California Natural Resources Agency (CNRA) has taken the lead in developing this adaptation strategy, working through the Climate Action Team (CAT).¹⁷³³ Seven sector-specific working groups led by twelve state agencies, boards and commissions, and numerous stakeholders were convened for this effort.¹⁷³⁴ The strategy proposes a comprehensive set of recommendations designed to inform and guide California decision-makers as they begin to develop policies that will protect the state, its residents and its resources from a range of climate change impacts.¹⁷³⁵ Four comprehensive state adaptation planning strategies were identified by all climate adaptation sectors.¹⁷³⁶ These strategies were intended to be in place or completed by the end of 2010.¹⁷³⁷

Following a 45-day public comment period since its release as a Discussion Draft in August 2009, the CNRA and sector working groups have revised the strategy incorporating public stakeholder input.¹⁷³⁸ This document will be updated approximately every two years to incorporate progress in strategies and changing climate science.¹⁷³⁹ The current draft reviews projections for temperature, precipitation, sea level rise, and extreme events, then evaluates climate impacts by sector.¹⁷⁴⁰

Yurok Tribe

In 2010, the Yurok Tribe received a grant from the U.S. Environmental Protection Agency for a Climate

¹⁷²⁸ Verbatim or nearly verbatim from Institute for Tribal Environmental Professionals. (2011, p. 1)

¹⁷²⁹ Verbatim or nearly verbatim from Institute for Tribal Environmental Professionals. (2011, p. 1)

¹⁷³⁰ Verbatim or nearly verbatim from Institute for Tribal Environmental Professionals. (2011, p. 1)

¹⁷³¹ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 4)

¹⁷³² Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 4)

¹⁷³³ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 4)

¹⁷³⁴ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 4)

¹⁷³⁵ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 4)

¹⁷³⁶ CA Natural Resources Agency. (2009, p. 23)

¹⁷³⁷ CA Natural Resources Agency. (2009, p. 23)

¹⁷³⁸ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 4)

¹⁷³⁹ Verbatim or nearly verbatim from CA Natural Resources Agency. (2009, p. 4)

¹⁷⁴⁰ CA Natural Resources Agency. (2009, p. 4)

Change Impacts Assessment and Prioritization Project.¹⁷⁴¹ The final goal of the project is the preparation and completion of the Yurok Tribe Climate Change Prioritization Plan and an initial assessment of potential climate change impacts that will serve as a guide for future tribal climate change research and planning efforts.¹⁷⁴² The project also aims to build tribal government and community capacity via technical training of the program staff and participation in national meetings.¹⁷⁴³ The project will engage the reservation community in potential localized changes through the production of educational materials, including a brochure outlining various opportunities to participate in local and regional climate change planning efforts.¹⁷⁴⁴

West Coast Governor's Agreement

On September 18, 2006 the Governors of California, Oregon and Washington announced the [West Coast Governors' Agreement on Ocean Health](#).¹⁷⁴⁵ The Agreement launched a new, proactive regional collaboration to protect and manage the ocean and coastal resources along the entire West Coast, as called for in the recommendations of the U.S. Commission on Ocean Policy and the Pew Oceans Commission.¹⁷⁴⁶ The [Executive Committee](#) established multiple workgroups, known as Action Coordination Teams (ACTs).¹⁷⁴⁷ At the present time, there are ten functioning ACTs: Climate Change, Integrated Ecosystem Assessment, Marine Debris, Ocean Awareness and Literacy, Polluted Runoff, Renewable Ocean Energy, Seafloor Mapping, Sediment Management, *Spartina* eradication, and Sustainable Ocean Communities.¹⁷⁴⁸ The primary objective of the Climate Change ACT is to create a framework and access to information that helps local governments wisely plan for the shoreline impacts resulting from climate change over the next several decades.¹⁷⁴⁹ The products from this ACT should assist state agencies in their various roles managing coastal lands, with an emphasis on those activities involving local land use and infrastructure planners as well as resource managers.¹⁷⁵⁰ In addition, this group will provide recommendations to facilitate continuing coordination among the states and federal agencies by identifying the common regional issues and solutions.¹⁷⁵¹ Specifically, the Climate Change ACT seeks to provide access to tools and information that will allow the states to develop strategies necessary to address shoreline change, and for local governments to develop detailed vulnerability assessments.¹⁷⁵²

¹⁷⁴¹ U.S. EPA. *Environmental Justice Grant Recipients in the Pacific Southwest: Yurok Tribe Project* (website). (2011)

¹⁷⁴² Verbatim or nearly verbatim from U.S. EPA. (2011)

¹⁷⁴³ Verbatim or nearly verbatim from U.S. EPA. (2011)

¹⁷⁴⁴ Verbatim or nearly verbatim from U.S. EPA. (2011)

¹⁷⁴⁵ Verbatim or nearly verbatim from West Coast Governor's Agreement on Ocean Health. *Homepage* (website). (2011b)

¹⁷⁴⁶ Verbatim or nearly verbatim from West Coast Governor's Agreement on Ocean Health. (2011b)

¹⁷⁴⁷ West Coast Governor's Agreement on Ocean Health. *Action Teams* (website). (2011a)

¹⁷⁴⁸ West Coast Governor's Agreement on Ocean Health. (2011a)

¹⁷⁴⁹ Verbatim or nearly verbatim from West Coast Governor's Agreement on Ocean Health. *Climate Change Action Coordination Team Work Plan* (pdf) (2010, p. 4)

¹⁷⁵⁰ Verbatim or nearly verbatim from West Coast Governor's Agreement on Ocean Health. (2010, p. 4)

¹⁷⁵¹ Verbatim or nearly verbatim from West Coast Governor's Agreement on Ocean Health. (2010, p. 4)

¹⁷⁵² Verbatim or nearly verbatim from West Coast Governor's Agreement on Ocean Health. (2010, p. 4)

IX. NEXT STEPS

In partnership with the University of Washington Climate Impacts Group (CIG), National Wildlife Federation (NWF) will convene expert focus groups to confirm, augment, and disseminate the findings of this report. Leveraging NWF's existing efforts in outreach and stakeholder engagement and CIG's expertise conducting similar focus groups, NWF will utilize a participatory, integrative approach to engage experts in focus group discussions of climate change effects and adaptation strategies in marine and coastal ecosystems in the NPLCC geography. Results of the assessment will be compiled in a report for the NPLCC describing climate change-related challenges, needs, and opportunities for landscape-scale conservation, sustainable resource management, and climate change adaptation in the NPLCC region.

NWF is also seeking funding to produce a report on climate change effects and adaptation approaches for the NPLCC region's terrestrial ecosystems. The methodology and production process employed would be similar to that used to produce this report, emphasizing early, frequent and inclusive stakeholder engagement, compilation of credible and regionally relevant peer-reviewed studies, government reports and publications from non-governmental organizations, and a thorough review process. At its completion, the terrestrial report, in conjunction with this report and the companion report focusing on freshwater ecosystems, would be the first-ever compilation of information on climate change effects and adaptation approaches particular to the NPLCC region's ecosystems.

X. APPENDICES

Appendix 1. Key Terms and Definitions

A

Absolute sea level: a measurement of sea level incorporating steric and eustatic effects

Adaptive capacity: the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Aerosol: highly dispersed solid or liquid particles suspended in a gas

Anoxia: a water column devoid of oxygen

Aragonite: a calcium carbonate (limestone) mineral, used by shell- or skeleton-forming, calcifying organisms such as corals (warm- and coldwater corals), some macroalgae, pteropods (marine snails) and non-pteropod molluscs such as bivalves (e.g., clams, oysters), cephalopods (e.g., squids, octopuses). Aragonite is more sensitive to ocean acidification than calcite, also used by many marine organisms.¹⁷⁵³

Avulse: when a river changes its course from one channel to another as a result of a flood.¹⁷⁵⁴

¹⁷⁵³ Parry et al. (Eds.) *Climate Change 2007: Impacts, Adaptation, Vulnerability: Appendix I: Glossary*. (2007, p. 871)

¹⁷⁵⁴ Nicholls et al. (2007, p. 326)

B

Benthic community: the community of organisms living on or near the bottom of a water body such as a river, a lake, or an ocean.¹⁷⁵⁵

C

Calcite: a calcium carbonate (limestone) mineral, used by shell- or skeleton-forming, calcifying organisms such as foraminifera, some macroalgae, lobsters, crabs, sea urchins and starfish. Calcite is less sensitive to ocean acidification than aragonite, also used by many marine organisms.¹⁷⁵⁶

California Current System: a ~621-mile-wide (1000 km), sluggish current spanning the North American Pacific Coast from ~20°N (near Guadalajara Mexico) to 50°N (northern Vancouver Island);¹⁷⁵⁷ the dominant current in the NPLCC region south of 50°N; the large marine ecosystem in the NPLCC region south of 50°N

Climate: Climate in a narrow sense is usually defined as the ‘average weather’, or more

¹⁷⁵⁵ Parry et al. (Eds.) (2007, p. 870)

¹⁷⁵⁶ Parry et al. (Eds.) (2007, p. 871)

¹⁷⁵⁷ Hickey and Banas. (2008, p. 93)

rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. Climate in a wider sense is the state, including a statistical description, of the climate system. The classical period of time is 30 years, as defined by the World Meteorological Organization (WMO).¹⁷⁵⁸

Climate change: Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines ‘climate change’ as: ‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods’.¹⁷⁵⁹

Climate change adaptation: a dynamic management strategy that involves identifying, preparing for, and responding to expected climate change in order to promote ecological resilience, maintain ecological function, and provide the necessary elements to support biodiversity and sustainable ecosystem services.¹⁷⁶⁰

Climate shift: a rapid change in relatively stable physical ocean properties that affects biota and ecosystems

Climate threshold: The point at which external forcing of the climate system, such as the increasing atmospheric concentration of greenhouse gases, triggers a significant climatic or environmental event which is considered unalterable, or recoverable only on very long time-scales, such as widespread bleaching of corals or a collapse of oceanic circulation systems.¹⁷⁶¹ *See also Threshold.*

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).¹⁷⁶²

Coastal squeeze: the squeeze of coastal ecosystems (e.g., salt marshes, mangroves and mud and sand flats) between rising sea levels and naturally or artificially fixed shorelines, including hard engineering defenses¹⁷⁶³

¹⁷⁵⁸ Parry et al. (Eds.) (2007, p. 871)

¹⁷⁵⁹ Parry et al. (Eds.) (2007, p. 871)

¹⁷⁶⁰ Glick et al. (2009, p. 8).

¹⁷⁶¹ Parry et al. (Eds.) (2007, p. 872)

¹⁷⁶² Parry et al. (Eds.) (2007, p. 872)

¹⁷⁶³ Parry et al. (Eds.) (2007, p. 872)

D

Delta: landforms naturally shaped by a combination of river, wave and tide processes;¹⁷⁶⁴ River-dominated deltas receiving river sediment input show prominent levees and channels that meander or avulse, leaving abandoned channels on the coastal plains. Wave-dominated deltas are characterized by shore-parallel sand ridges, often coalescing into beach-ridge plains. Tide domination is indicated by exponentially tapering channels, with funnel-shaped mouths. Delta plains contain a diverse range of landforms but, at any time, only part of a delta is active, and this is usually river-dominated, whereas the abandoned delta plain receives little river flow and is progressively dominated by marine processes.¹⁷⁶⁵

E

Ecosystem: The interactive system formed from all living organisms and their abiotic (physical and chemical) environment within a given area. Ecosystems cover a hierarchy of spatial scales and can comprise the entire globe, biomes at the continental scale or small, well-circumscribed systems such as a small pond.¹⁷⁶⁶

¹⁷⁶⁴ Nicholls et al. (2007, p. 326).

¹⁷⁶⁵ Nicholls et al. (2007, p. 326).

¹⁷⁶⁶ Parry et al. (Eds.) (2007, p. 874)

El Niño: the warm phase of ENSO; characterized by stronger than average sea surface temperatures in the central and eastern equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and an eastward shift in the region of intense tropical rainfall

El Niño-Southern Oscillation: the major source of inter-annual climate variability in the Pacific Northwest (PNW), abbreviated ENSO. ENSO variations are more commonly known as **El Niño** (the warm phase of ENSO) or **La Niña** (the cool phase of ENSO)

Estuary: partially enclosed body of water formed where freshwater from rivers and streams flows into the ocean, mixing with the salty sea water; Primary estuarine problems include habitat alterations, degradation, and loss; diverted freshwater flows; marine sediment contamination; and exotic species introductions.¹⁷⁶⁷ West Coast estuaries (defined as the coasts of BC, WA, OR, and CA) are geologically young and composed of a variety of geomorphological types.¹⁷⁶⁸

Eustatic sea level rise: changes in global ocean volume due to melting of ice caps, continental ice sheets and mountain glaciers, and thermal expansion due to rising water temperatures

¹⁷⁶⁷ PSNP (2003); PSNERP (2010); LCREP (2010); Snover et al. (2005, p. 28)

¹⁷⁶⁸ Emmett et al. (2000, p. 765)

Expendable bathythermograph (XBT): a probe which is dropped from a ship and measures the temperature as it falls through the water. Two very small wires transmit the temperature data to the ship where it is recorded for later analysis. The probe is designed to fall at a known rate, so that the depth of the probe can be inferred from the time since it was launched. By plotting temperature as a function of depth, scientists can get a picture of the temperature profile of the water up to 4921 feet (1500 m) depth.¹⁷⁶⁹

Exposure (to climate change): the nature and degree to which a system is exposed to significant climatic variations

Extinction (of species): the state of a species that no longer exists anywhere on Earth (includes wild and captive species)

Extirpation (of species): native species that no longer exist in the wild in any part of their original distribution area, although they may exist elsewhere

F

Flux: the amount of a substance flowing through an area over a certain period of time

G

¹⁷⁶⁹ NOAA. *Upper Ocean Thermal Center: The Expendable Bathythermograph (XBT) (website)*. (2011)

Gyre: a spiral oceanic surface current moving in a clockwise direction

H

Habitat: the locality or natural home in which a particular plant, animal, or group of closely associated organisms lives.¹⁷⁷⁰

Hydrologic cycle: the existence and movement of water on, in, and above the Earth; composed of sixteen components: water storage in oceans, evaporation, sublimation, evapotranspiration, water in the atmosphere, condensation, precipitation, water storage in ice and snow, snowmelt runoff to streams, surface runoff, streamflow, freshwater storage, infiltration, groundwater storage, groundwater discharge, springs; the processes and pathways involved in the circulation of water from land and water bodies to the atmosphere and back again (Brooks, et al. 2003, 21)

Hydrology: the science encompassing the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground

Hypoxia: a water column largely deficient of dissolved oxygen; generally, a water column with less than 2.0 milligrams of oxygen per liter of water dissolved within it

¹⁷⁷⁰ Parry et al. (Eds.) (2007, p. 876)

I

(climate change) Impacts: the effects of climate change on natural and human systems.¹⁷⁷¹

J

Joule: a measure of energy, work, or quantity of heat

K

L

La Niña: the cool phase of ENSO; characterized by the opposite – cooler than average sea surface temperatures, stronger than normal easterly trade winds, and a westward shift in the region of intense tropical rainfall.

M

N

Nearshore: the estuarine/delta, marine shoreline and areas of shallow water from the top of the coastal bank or bluffs to the water at a depth of about 10 meters relative to Mean Lower Low

¹⁷⁷¹ Parry et al. (Eds.) (2007, p. 876)

Water. This is the average depth limit of light penetration. This zone incorporates geological and ecological processes, such as sediment movement, freshwater inputs, and subtidal light penetration, which are key to determining the distribution and condition of aquatic habitats.

The nearshore extends landward into the tidally influenced freshwater heads of estuaries and coastal streams and includes deltas, beaches, mudflats, kelp and eelgrass beds, salt marshes, and gravel spits.¹⁷⁷²

O

Ocean acidification: process in which carbon dioxide is absorbed by seawater, and chemical reactions occur that reduce seawater pH, carbonate ion concentration, and saturation states of the biologically important calcium carbonate minerals (calcite and aragonite); the term used to describe the process responsible for the observed decline in average ocean pH since the Industrial Revolution (ca. 1800).

Oxygen minimum zone (OMZ): the depth of seawater at which oxygen saturation is at its lowest

P

Pacific Decadal Oscillation (PDO): long-lived El Niño-like pattern of Pacific climate variability

¹⁷⁷² PSNP (2003); PSNERP (2010)

Pacific Northwest: a region in the northwestern continental United States, largely comprised of the states of Oregon, Washington, Idaho, western Montana, and southern British Columbia

pH: activity of hydrogen ions (which is closely related to concentration), expressed as \log_{10} (moles H^+ liter⁻¹)¹⁷⁷³; a measure of the acidity or alkalinity (i.e. basicity) of a substance, ranging on a scale of 0 to 14, where 7 is “neutral” (neither acidic nor basic). The scale is logarithmic (i.e. a substance with pH 5 is ten times more acidic than a substance with pH 6).

Phenology: the study of natural phenomena that recur periodically (e.g. development stages, migration) and their relation to climate and seasonal changes.¹⁷⁷⁴

Phytoplankton: the plant forms of plankton; the dominant plants in the sea, and the basis of the entire marine food web. These single-celled organisms are the principal agents of photosynthetic carbon fixation in the ocean.¹⁷⁷⁵

Plankton: microscopic aquatic organisms that drift or swim weakly.¹⁷⁷⁶ The plant form is phytoplankton and the animal form is zooplankton.

Precipitation: the general term for rainfall, snowfall and other forms of frozen or liquid water falling from clouds

Puget Sound: a large estuary complex in the Pacific Northwest

Q

R

Radiative forcing: measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system; an index of the importance of the factor as a potential climate change mechanism

Realignment adaptation: a type of adaptation typically used in already significantly disturbed systems in which the system (e.g., an organism, population, community, or ecosystem) is changed to be healthy under expected future conditions rather than returned to historical conditions

Recruitment: the number of fish entering each size or age class¹⁷⁷⁷

Relative sea level: a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land-level uplift,

¹⁷⁷³ Dodds & Whiles. (2010)

¹⁷⁷⁴ Parry et al. (Eds.) (2007, p. 879)

¹⁷⁷⁵ Parry et al. (Eds.) (2007, p. 879)

¹⁷⁷⁶ Parry et al. (Eds.) (2007, p. 879)

¹⁷⁷⁷ Dodds & Whiles. (2010)

relative sea level can fall;¹⁷⁷⁸ a measurement of sea level that includes local and regional ocean (e.g. altered wave heights due to upwelling or storms), land (e.g. uplift and subsidence), hydrologic (e.g. coastal runoff) and atmospheric (e.g. winds) dynamics in addition to eustatic and steric effects

Relocation: a type of adaptation in which a system (e.g., an organism, population, community, or ecosystem) is moved to a new location, either by natural processes or through human assistance (latter also known as assisted migration)

Resilience: the amount of change or disturbance that can be absorbed by a system (e.g., an organism, population, community, or ecosystem) before the system is redefined by a different set of processes and structures; the ability of a system to recover from change or disturbance without a major phase shift

Resistance: the ability of a system (e.g. an organism, population, community, or ecosystem) to withstand a change or disturbance without significant loss of structure or function

Response adaptation: a type of adaptation that facilitates the transition of ecosystems from current, natural states to new conditions brought about by a changing climate

¹⁷⁷⁸ Parry et al. (Eds.) (2007, p. 881)

S

Saltmarsh: highly productive habitats found near river mouths where fresh and saltwater mix. Salt marshes support a mix of plant and animal species, including sedges, rushes, shrimp, crabs, salmon, terns and herons. The plants filter suspended sediments and nutrients, regulate dissolved oxygen in the water column, stabilize bottom sediments, and reduce flooding by retaining stormwater during high-flow periods. Salt marsh growth and distribution are affected by sea level, salinity, temperature, freshwater inputs, tidal flooding, and the physical characteristics of the landscape.¹⁷⁷⁹

Saltwater intrusion / encroachment: displacement of fresh surface water or groundwater by the advance of salt water due to its greater density; usually occurs in coastal and estuarine areas due to reducing land-based influence (e.g. from reduced runoff & associated groundwater recharge; from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative SLR).¹⁷⁸⁰

Saturation horizon: a natural depth boundary in seawater above which calcium carbonate forms, and below which it does not

¹⁷⁷⁹ PSNP (2003); PSNERP (2010); LCREP (2010); Emmett et al. (2000, p. 765); Snover et al. (2005, p. 28)

¹⁷⁸⁰ Parry et al. (Eds.) (2007, p. 880)

Saturation state of seawater: a measure of the thermodynamic potential for a mineral to form or dissolve

Sea level rise: an increase in the mean level of the ocean. *See also eustatic sea level rise, steric sea level rise, absolute sea level, and relative sea level*

Sensitivity (to climate change): the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.

Species diversity: generally measured as the number of species in an area and their evenness (relative abundance)¹⁷⁸¹

Species richness: the number of species in an area¹⁷⁸²

Steric sea level rise: global and regional changes in ocean volume due to thermal expansion and salinity effects on water density (warmer, fresher water occupies more volume than colder, saltier water)

Stratification: density differences in water that can maintain stable layers¹⁷⁸³

T

Thermal expansion: in connection with sea level rise, this refers to the increase in volume

¹⁷⁸¹ Dodds & Whiles. (2010)

¹⁷⁸² Dodds & Whiles. (2010)

¹⁷⁸³ Dodds & Whiles. (2010)

(and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level.¹⁷⁸⁴

U

Upwelling: process occurring when alongshore winds blow toward the equator along the western margin of continents, pushing surface waters offshore and replacing them with deeper, (100-200 m), colder, saltier, nutrient and carbon dioxide-rich but oxygen-poor ocean waters moving up the continental shelf toward shore

V

Threshold: The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.¹⁷⁸⁵ *See also climate threshold.*

Vulnerability (to climate change): the extent to which a species, habitat, or ecosystem is susceptible to harm from climate change impacts. It is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

¹⁷⁸⁴ Parry et al. (Eds.) (2007, p. 882)

¹⁷⁸⁵ Parry et al. (Eds.) (2007, p. 882)

Vulnerability Assessment: structured approaches to identify species and ecological systems likely to be most sensitive to climatic changes and assist managers in setting priorities for natural resource adaptation efforts and funding.

WXYZ

Water column: a conceptual column of water from surface to bottom sediments

Water cycle *See hydrologic cycle*

Watt: a measure of power (the rate at which work is performed or energy is converted) or radiant flux (the rate of flow of electromagnetic waves); one Watt (W) is equivalent to one Joule per second (J/s)

Wetland: lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.¹⁷⁸⁶; areas inundated or saturated by surface or groundwater at a frequency and duration sufficient to support a prevalence of vegetation adapted for life in saturated soil conditions¹⁷⁸⁷

¹⁷⁸⁶ U.S. FWS. 660 FW 2, *Wetlands Classification System (website)*. (1993)

¹⁷⁸⁷ Dodds & Whiles. (2010)

Appendix 2. SRES Scenarios and Climate Modeling

The explanation of SRES scenarios is excerpted from the IPCC's AR4 Synthesis Report (p. 44). Figure 28 was accessed online at <http://sedac.ciesin.columbia.edu/ddc/sres/>, December 2, 2010.

SRES scenarios

SRES refers to the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES, 2000). The SRES scenarios are grouped into four scenario families (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The SRES scenarios do not include additional climate policies above current ones. The emissions projections are widely used in the assessments of future climate change, and their underlying assumptions with respect to socio-economic, demographic and technological change serve as inputs to many recent climate change vulnerability and impact assessments. {WGI 10.1; WGII 2.4; WGIII TS.1, SPM}

The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. No likelihood has been attached to any of the SRES scenarios. {WGIII TS.1, SPM}

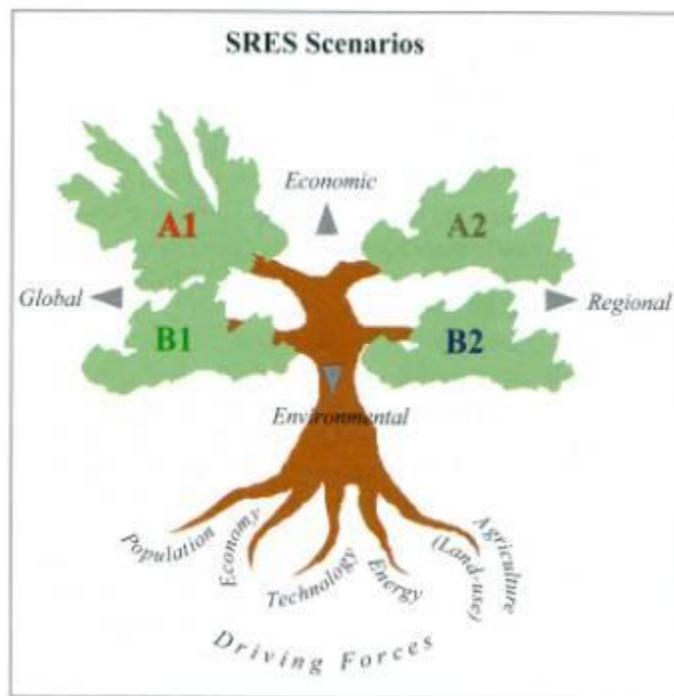


Figure 28. SRES Scenarios.

Climate modeling

Global Models

Envisioning global climate in a future with much higher greenhouse gases requires the use of physically based numerical models of the ocean, atmosphere, land, and ice, often called global climate models

(GCMs) or climate system models.¹⁷⁸⁸ A common set of simulations using 21 GCMs was coordinated through the Intergovernmental Panel on Climate Change (IPCC).¹⁷⁸⁹ These models typically resolve the atmosphere with between 6,000 and 15,000 grid squares horizontally, and with between 12 and 56 atmospheric layers.¹⁷⁹⁰

Simulations of 21st century climate require projections of future greenhouse gases and sulfate aerosols (which reflect sunlight and also promote cloud formation, thereby offsetting greenhouse gases locally), of which more than 40 were produced and six “marker” scenarios selected (B1, B2, A1, A1B, A1F1, A2) under the auspices of the IPCC.¹⁷⁹¹ Three of these scenarios were commonly chosen for forcing the GCMs: B1, A1B, and A2.¹⁷⁹² A2 produces the highest climate forcing by the end of the century, but before mid-century, none of the scenarios is consistently the highest.¹⁷⁹³ Though B1 is the lowest of the IPCC illustrative scenarios, it still produces changes in climate that many scientists call “dangerous” — a threshold that a growing number of political leaders have stated their intention to avoid.¹⁷⁹⁴ At the high end, scenario A1F1 results in even higher climate forcing by 2100 than A2 or A1B.¹⁷⁹⁵ Mid-2000s global emissions of CO₂ exceeded even the A1F1 scenario.¹⁷⁹⁶

Downscaled Climate Models

Note: While the information described here pertains to Washington State, it is often applicable for sub-global (e.g., regional, local) modeling elsewhere.

Global climate models do not account for the atmospheric processes that determine the unique spatially heterogeneous climatic features of Washington.¹⁷⁹⁷ Statistical downscaling is based on fine-scale data derived using assumptions about how temperature and precipitation vary over complex terrain in order to interpolate the sparse station network (about 50-km spacing) to a 0.0625° grid.¹⁷⁹⁸ Information simulated by the coarse-resolution global models (with output on a 100-to-300 km grid) is then used to project the future climate.¹⁷⁹⁹ This approach represents the mean climate and local regimes quite well but does not take into account how the terrain influences individual weather systems.¹⁸⁰⁰

Salathé, Jr. et al.’s (2010) results show that, with increased spatial resolution relative to global models, regional climate models can represent the local forcing from the complex terrain to produce more realistic spatial and temporal variability of temperature, precipitation, and snowpack in the State of

¹⁷⁸⁸ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 29)

¹⁷⁸⁹ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 29-30)

¹⁷⁹⁰ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 30)

¹⁷⁹¹ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 30)

¹⁷⁹² Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 30)

¹⁷⁹³ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 30)

¹⁷⁹⁴ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 31). The authors cite Schellnhuber et al. (2006) for information on changes in climate that many scientists call dangerous.

¹⁷⁹⁵ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 31).

¹⁷⁹⁶ Verbatim or nearly verbatim from Mote and Salathé, Jr. (2010, p. 31). The authors cite Raupach et al. (2007) for information on mid-2000s emissions and state “... we must emphasize that the scenarios used here may not span the range of possibilities” (p. 31).

¹⁷⁹⁷ Verbatim or nearly verbatim from Salathé, Jr. et al. *Regional climate model projections for the State of Washington*. (2010, p. 52)

¹⁷⁹⁸ Verbatim or nearly verbatim from Salathé, Jr. et al. (2010, p. 52)

¹⁷⁹⁹ Verbatim or nearly verbatim from Salathé, Jr. et al. (2010, p. 52)

¹⁸⁰⁰ Verbatim or nearly verbatim from Salathé, Jr. et al. (2010, p. 52)

Washington.¹⁸⁰¹ With the ability to resolve topographic effects, more robust changes in mountain snowpack and extreme precipitation emerge.¹⁸⁰² These changes are consistent between the two regional simulations despite differences in seasonal precipitation and temperature changes in the global and regional model results.¹⁸⁰³ It is clear that changes in the seasonal climate and the frequency of extreme events may be locally much more intense than can be inferred from statistical methods.¹⁸⁰⁴ The implication is that, while a valuable tool for regional climate impacts assessment, multi-model ensembles of global climate projections and statistical methods may under represent the local severity of climate change.¹⁸⁰⁵

¹⁸⁰¹ Verbatim or nearly verbatim from Salathé, Jr. et al. “Regional climate model projections for the State of Washington.” In: *Washington Climate Change Impact Assessment*. (2009, p. 65)

¹⁸⁰² Verbatim or nearly verbatim from Salathé, Jr. et al. (2009, p. 65)

¹⁸⁰³ Verbatim or nearly verbatim from Salathé, Jr. et al. (2009, p. 65)

¹⁸⁰⁴ Verbatim or nearly verbatim from Salathé, Jr. et al. (2009, p. 65)

¹⁸⁰⁵ Verbatim or nearly verbatim from Salathé, Jr. et al. (2009, p. 65)

Appendix 3. Major Climate Patterns in the NPLCC: ENSO and PDO

This explanation is excerpted from a webpage written by Nathan J. Mantua (Ph.D.) of the University of Washington's Joint Institute for the Study of the Atmosphere and Oceans and Climate Impacts Group. The webpage is not copied in its entirety; sections that explain climate variability and its impacts on climate in the NPLCC region are emphasized. The full-text can be accessed at http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm (accessed December 9, 2010).

Introduction

In addition to El Niño, there are other heavily researched climate patterns that exert important influences on regional climates around the world. For instance, many studies highlight the relative importance of the Pacific Decadal Oscillation and Arctic Oscillation/North Atlantic Oscillation in North American climate. Each of these major patterns--El Niño/Southern Oscillation, Pacific Decadal Oscillation, and Arctic Oscillation/North Atlantic Oscillation--has characteristic signatures in seasonally changing patterns of wind, air temperature, and precipitation; each pattern also has a typical life time for any given "event".

A PDO definition

The Pacific Decadal Oscillation, or PDO, is often described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al. 1997). As seen with the better-known El Niño/Southern Oscillation (ENSO), extremes in the PDO pattern are marked by widespread variations in Pacific Basin and North American climate. In parallel with the ENSO phenomenon, the extreme phases of the PDO have been classified as being either *warm* or *cool*, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean.

Two main characteristics distinguish the PDO from ENSO. First, typical PDO "events" have shown remarkable persistence relative to that attributed to ENSO events - in this century, major PDO eras have persisted for 20 to 30 years (Mantua et al. 1997, Minobe 1997). Second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. Several independent studies find evidence for just two full PDO cycles in the past century (e.g. Mantua et al. 1997, Minobe 1997): cool PDO regimes prevailed from 1890-1924 and again from 1947-1976, while warm PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990's. Recent changes in Pacific climate suggest a possible reversal to cool PDO conditions in 1998, an issue that is discussed in more detail at the end of this article.

The North American climate anomalies associated with PDO warm and cool extremes are broadly similar to those connected with El Niño and La Niña (Latif and Barnett 1995, Latif and Barnett 1996, Zhang et al. 1997, Mantua et al. 1997). Warm phases of the PDO are correlated with North American temperature and precipitation anomalies similar to those correlated with El Niño (Figure 4): above average winter and spring time temperatures in northwestern North America, below average temperatures in the southeastern US, above average winter and spring rainfall in the southern US and northern Mexico, and below average precipitation in the interior Pacific Northwest and Great Lakes regions. Cool phases of the PDO are simply correlated with the reverse climate anomaly patterns over North America (not shown), broadly similar to typical La Niña climate patterns. The PDO-related temperature and precipitation patterns are also strongly expressed in regional snow pack and stream flow anomalies, especially in western North America (see Cayan 1995, Mantua et al. 1997, Bitz and Battisti 1999, Nigam et al. 1999). A summary of major PDO climate anomalies are listed in Table 1.

Table 1: Summary of North American climate anomalies associated with extreme phases of the PDO.

<u>Climate Anomalies</u>	<u>Warm Phase PDO</u>	<u>Cool Phase PDO</u>
Ocean surface temperatures in the northeastern and tropical Pacific	Above average	Below average
October-March northwestern North American air temperatures	Above average	Below average
October-March Southeastern US air temperatures	Below average	Above average
October-March southern US/Northern Mexico precipitation	Above average	Below average
October-March Northwestern North America and Great Lakes precipitation	Below average	Above average
Northwestern North American spring time snow pack	Below average	Above average
Winter and spring time flood risk in the Pacific Northwest	Below average	Above average

An ENSO definition

This definition is excerpted from the Climate Impacts Group website [El Niño/Southern Oscillation](http://cses.washington.edu/cig/pnwc/aboutenso.shtml), available at <http://cses.washington.edu/cig/pnwc/aboutenso.shtml> (accessed 1.18.2011)

The El Niño/Southern Oscillation (ENSO) is the major source of inter-annual climate variability in the Pacific Northwest (PNW). ENSO variations are more commonly known as **El Niño** (the warm phase of ENSO) or **La Niña** (the cool phase of ENSO).

An El Niño is characterized by stronger than average sea surface temperatures in the central and eastern equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and an eastward shift in the region of intense tropical rainfall. A La Niña is characterized by the opposite – cooler than average sea surface temperatures, stronger than normal easterly trade winds, and a westward shift in the region of intense tropical rainfall. Average years, i.e., years where there is no statistically significant deviation from average conditions at the equator, are called ENSO-neutral. Each ENSO phase typically lasts 6 to 18 months.

Although ENSO is centered in the tropics, the changes associated with El Niño and La Niña events affect climate around the world. ENSO events tend to form between April and June and typically reach full strength in December (hence the name El Niño, which is Spanish for “Little Boy” or “Christ Child”; La

Niña means “Little Girl”). The ENSO influence on PNW climate is strongest from October to March; by summer, Northern Hemisphere wind patterns are such that they effectively trap ENSO-related disturbances in the tropics.

The CIG has demonstrated numerous linkages between changes in ENSO and variations in PNW climate and natural resources. El Niño winters, for example, tend to be warmer and drier than average with below normal snowpack and streamflow. La Niña winters tend to be cooler and wetter than average with above normal snowpack and streamflow. These linkages and the availability of ENSO forecasts a few months to one year in advance of the event’s maturation provide resource managers opportunity to consider how a particular ENSO forecast may affect resource management choices.

Interactions between ENSO and PDO

This definition is excerpted from the Climate Impacts Group website [Impacts of Natural Climate Variability on Pacific Northwest Climate](http://cse.washington.edu/cig/pnwc/clvariability.shtml), available at <http://cse.washington.edu/cig/pnwc/clvariability.shtml> (accessed 1.18.2011).

The potential for temperature and precipitation extremes increases when ENSO and PDO are in the same phases and thereby reinforce each other. This additive effect is also seen in the region’s streamflow and snowpack. There is no evidence at this time to suggest that either PDO or ENSO dominates with respect to temperature and precipitation when the two climate patterns are in opposite phases (i.e., an El Niño during a cool phase PDO or a La Niña during a warm phase PDO). The opposite effects on temperature and precipitation can cancel each other out, but not in all cases and not always in the same direction. Similar effects are seen on regional streamflow.

Implications for climate predictions

This explanation is excerpted from a webpage written by Nathan J. Mantua (Ph.D.) of the University of Washington’s Joint Institute for the Study of the Atmosphere and Oceans and CIG. The full-text can be accessed at http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm (accessed 1.18.2011).

Recent studies suggest that ENSO teleconnections with North American climate are strongly dependent on the phase of the PDO, such that the "canonical" El Niño and La Niña patterns are only valid during years in which ENSO and PDO extremes are "in phase" (i.e. with warm PDO+El Niño, and cool PDO+La Niña, but not with other combinations) (Gershunov and Barnett 1999, Gershunov et al. 1999, McCabe and Dettinger 1999). Other studies have identified PDO connections with summer rainfall and drought in the US (Nigam et al. 1999), and the relative risks for winter and spring flood events in the Pacific Northwest (Hamlet and Lettenmeier, in press).

Appendix 4. Sea level Affecting Marshes Model (SLAMM): Limitations, Improvements, & Alternatives

Reviewers commented the report would benefit from a discussion of the SLAMM model, including limitations and alternatives. SLAMM simulates dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise (SLR). Within later versions of SLAMM (5.0, 6.0, 6.0.1 Beta), five primary processes can affect wetland fate under different scenarios of SLR: inundation, erosion, overwash, saturation, and salinity.

Development of the Model: SLAMM was first developed in the mid-1980s and is now managed by Warren Pinnacle Consulting, Inc. The most recent version was released January 2010 (version 6.0.1 Beta).

Model Limitations: Like all models, SLAMM makes certain simplifying assumptions and excludes certain processes and factors. Jonathan Clough of Warren Pinnacle Consulting, Inc. lists six primary limitations:

- No mass balance of solids (i.e., accretion rates are not affected by freshwater flow rates or nutrients; no consolidation of inundated tidal flats, beaches).
- It is not a detailed bathymetrical model (i.e., the tidal effects of estuary geometry are not predicted and must be entered as a model input; geometry effects on salinity are quite simple).
- There is no model of sea grasses or marine flora.
- The overwash model is subject to additional uncertainty (frequency of storms and magnitude of effects is uncertain; may be turned off or parameters refined).
- No concept of “marsh health” (e.g., transitional marsh produced when dry lands regularly inundated)
- Accretion rates are based on empirical relationships (not a mechanistic model; does not account for peat collapse)

Regarding SLAMM5 limitations, Kirwan and Guntenspergen (2009) cite a lack of feedback among variables that may be altered by changes in sea level and the use of declining accretion rates in the model. The latter may exacerbate projections of coastal vegetated habitat loss (e.g., convert to open water), particularly where habitat conversion may be more likely. Mcleod et al. (2004) note changes in wave regime from erosion or sub-surface vegetative properties are not modeled. Further, SLAMM lacks a socioeconomic component for estimating the costs of SLR, which may limit its usefulness in informing adaptation policies.

Recent Model Improvements: Based on feedback from scientists working in the field and the experience of modelers, SLAMM 6 was upgraded from previous versions. Key updates include:

- An accretion feedback component, wherein feedbacks based on wetland elevation, distance to channel, and salinity may be specified.
- A salinity model with the ability to specify multiple time-variable freshwater flows and habitat switching as a function of salinity. Estimates of salinity at Mean Lower-Low Water, Mean Higher-High Water, and Mean Tide Level are mapped.

- Using an integrated elevation analysis, SLAMM will summarize site-specific categorized elevation ranges for wetlands. Ranges will be derived from Light-imaging Detection and Ranging (LiDAR) data or other high-resolution data sets.
- Flexible elevation ranges for land categories, useful for situations in which site-specific data indicate that wetlands range beyond SLAMM defaults.
- An improved user interface and improved memory management, including backwards compatibility with SLAMM5 and new maps of elevations, salinity, and variable accretion rates.

Alternatives to SLAMM: The USGS’s *Coastal Vulnerability Index* is a relative ranking of the likelihood that physical change will occur along the shoreline as sea level changes. *The Kirwan marsh model* couples sediment transport processes with vegetation biomass productivity. The more straight-forward “bathtub” models assess which coastal areas are likely to be inundated under various SLR scenarios based on coastal elevation. *Ecological landscape spatial simulation models* (e.g., BTELSS) incorporate environmental and biotic feedbacks to calculate the rate of marsh elevation change as a function of depth and sediment supply. They are often used to examine marsh platform evolution over hundreds of years. Finally, several multidisciplinary support tools have been developed that can provide information on potential physical, ecological, and socioeconomic impacts, e.g. *the Dynamic Interactive Vulnerability Assessment Tool*, which also assesses the costs and benefits of adaptation, and *SimCLIM*, which allows users to examine sectoral impacts, conduct sensitivity analyses, test adaptation measures under present and future conditions, and in some custom applications, to estimate monetary costs and benefits of adaptation.

Sources: Clough, Park, & Fuller. *SLAMM 6 beta Technical Documentation (draft; pdf)*. (2010, p. 5); Glick, Clough and Nunley (2010); Glick, Clough and Nunley (2007); Kirwan and Guntenpergen. *Accelerated sea level rise - A response to Craft et al.* (2009); Mcleod et al. *Sea level rise impact models and environmental conservation: A review of models and their applications*. (2010); Warren Pinnacle Consulting, Inc. *SLAMM Overview (presentation)*. (2010a); Warren Pinnacle Consulting, Inc. *SLAMM: Sea level Affecting Marshes Model: SLAMM Version and Development History (website)*. (2010b).

Appendix 5. Resources for Adaptation Principles and Responses to Climate Change

1. **Recommendations for a National Wetlands and Climate Change Initiative.** Association of Wetland Managers, Inc. January 20, 2009. Available online at http://www.aswm.org/calendar/wetlands2008/recommendations_2008_112008.pdf (accessed January 14, 2011).

Summary: The report discusses the role U.S. agencies, Congress, states and local governments could play in implementing a national wetlands and climate change initiative (pp. 4-6). It also includes chapters on specific measures needed to better protect and adapt coastal and estuarine lands (pp. 7-10) and freshwater wetlands (pp.10-12). It concludes with a chapter on priority management-oriented and basic research needs (pp. 13-15)

2. **A New Era for Conservation: Review of Climate Change Adaptation Literature.** Glick, Patty; Staudt, Amanda; Stein, Bruce. March 12, 2009. Report produced by the National Wildlife Federation. Available online at <http://www.nwf.org/News-and-Magazines/Media-Center/Faces-of-NWF/~media/PDFs/Global%20Warming/Reports/NWFClimateChangeAdaptationLiteratureReview.ashx> (accessed January 25, 2011).

Summary: The report reviews the common barriers to climate change adaptation (including solutions; pp. 9-13), describes five overarching principles of climate change adaptation (pp. 12-17) and provides a six-stage framework to use as a guideline for developing adaptation strategies (pp. 18-23). It also includes sector-specific adaptation strategies for forests (pp. 23-29), grasslands and shrublands (pp. 30-35), rivers, streams, and floodplains (pp. 36-43), and coasts and estuaries (pp. 44-52).

3. **Biodiversity management in the face of climate change: A review of 22 years of recommendations.** Heller, Nicole E. and Zavaleta, Erika S. 2009. *Biological Conservation*. 142: 14-32. Available online at <http://people.umass.edu/gce/Heller%20and%20Zavaleta,%202009.pdf> (accessed January 13, 2011).

Summary: See Table 1 (pp. 18-22) for a list of recommendations for climate change adaptation strategies for biodiversity management.

4. **Climate change adaptation strategies for resource management and conservation planning.** Lawler, Joshua J. 2009. *Annals of the New York Academy of Sciences (The Year in Ecology and Conservation Biology)*. 1162: 79-98. Available online at http://training.fws.gov/branchsites/lkm/climate_change/june_09/cc-adaptreview.pdf (accessed January 13, 2011).

Summary: Lawler provides an overview of general strategies for addressing climate change including removing other threats and reducing additional stressors, expanding reserve networks, increasing connectivity, restoring habitat and system dynamics, adaptive management, and translocation. Specific recommendations for addressing climate change in freshwater, marine, and terrestrial systems are also provided.

5. **A review of climate-change adaptation strategies for wildlife management and biodiversity conservation.** Mawdsley, Jonathan R.; O'Malley, Robin; and Ojima, Dennis S. 2009. Available online at <http://www.uwpsc.washington.edu/documents/PCC/mawdsley-et-al-2009.pdf> (accessed January 13, 2011). *Conservation Biology*. 23(5): 1080-1089.

Summary: Mawdsley and colleagues describe sixteen adaptation strategies, organized by strategies related to land and water protection and management (seven strategies), direct species management (four strategies), monitoring and planning (four strategies), and reviewing and modifying existing laws, regulations, and policies regarding wildlife and natural resource management (one strategy).

6. **Preparing for climate change: a guidebook for local, regional, and state governments.** Snover, Amy K.; Whitely Binder, Lara; Lopez, Jim; and Colleagues. 2007. In association with and published by ICLEI – Local Governments for Sustainability, Oakland, CA. Available online at <http://cses.washington.edu/cig/fpt/guidebook.shtml> (accessed January 13, 2011).

Summary: The guidebook provides a suggested checklist for governments on how to prepare for climate change. It includes five milestones: initiate your climate resiliency effort, conduct a climate resiliency study, set preparedness goals and develop your preparedness plan, implement your preparedness plan, and measure your progress and update your plan.

7. **Climate Savvy: Adapting conservation and resource management to a changing world.** Hansen, Lara J. and Hoffman, Jennifer R. 2011. Island Press: Washington, DC. Available online for preview and purchase at <http://islandpress.org/bookstore/detailsee40.html> (accessed July 13, 2011).

Summary: Hansen and Hoffman assess the vulnerabilities of existing conservation and resource management tools to climate change, then describe how these tools can be adapted to address climate change impacts. The book begins with a general overview of climate change and its effects, and key facets of building a plan to address climate change impacts. The tools include protected areas, species-based protection, connectivity, regulating harvests, reduction of pollutants, control of invasive species, pests, and disease, restoration, and a broader rethinking of governance, policy, and regulation.

8. **U.S. natural resources and climate change: concepts and approaches for management adaptation.** West, Jordan M.; Julius, Susan H.; Kareiva, Peter; and Colleagues. 2009. *Environmental Management*. 44: 1001-1021. Available online at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2791483/pdf/267_2009_Article_9345.pdf (accessed January 13, 2011).

Summary: West and colleagues provide several concepts and approaches for assessing impacts to support adaptation, management strategies for resilience to climate change, responding to barriers and opportunities for implementation, and advancing the nation's capability to adapt. Twelve tables provide examples of specific approaches that are in use or have been proposed (e.g. Table 5, pp. 1009, provides examples of adaptation actions that focus on restoration as a means of supporting resilience).

Appendix 6. List of Reviewers and Interviewees

Reviewers

Alaska

Laura Baker, The Nature Conservancy
Mandy Lindeberg, National Oceanic and Atmospheric Administration
Scott W. Johnson, National Oceanic and Atmospheric Administration

British Columbia

Dave Secord, Tides Canada Foundation
Tory Stevens, BC Ministry of Environment
Trevor Murdock, Pacific Climate Impacts Consortium

Washington

Carey Smith, US Fish and Wildlife Service
Curtis Tanner, Washington Department of Fish and Wildlife
Hugh Shipman, Washington State Department of Ecology
Jean Takekawa, US Fish and Wildlife Service
Lara Whitely Binder, Climate Impacts Group
Mark Scheuerell, National Marine Fisheries Service
Nathan Mantua, Climate Impacts Group
Paul McElhany, National Marine Fisheries Service
Richard Feely, National Oceanic and Atmospheric Administration
Shallin Busch, National Marine Fisheries Service
Spencer Reeder, Cascadia Consulting Group

Oregon

Bruce Taylor, Pacific Coast Joint Venture
Kathie Dello, Oregon Climate Change Research Institute
Kathy Lynn, University of Oregon
Laura Brophy, Estuary Technical Group, Institute for Applied Ecology
Rowan Baker, US Fish and Wildlife Service
Sara O'Brien, Defenders of Wildlife
Tim Mayer, US Fish and Wildlife Service
William Percy, Oregon State University

California

Laura Rogers-Bennett, California Department of Fish and Game
Paula Golightly, US Fish and Wildlife Service
Susan Schlosser, California Sea Grant Extension Program

Native Alaskans, First Nations, Tribal

Other

Doug Inkley, National Wildlife Federation
Patty Glick, National Wildlife Federation

Interviewees (*continued on following two pages*)

Alaska

Andrew Schroth, US Geological Survey
Bill Hanson, US Fish and Wildlife Service
Doug DeMaster, Alaska Fisheries Science Center
Doug Vincent-Lang, Alaska Department of Fish and Game
Eran Hood, University of Alaska - Southeast
Evie Witten, The Nature Conservancy
Gordie Reeves, US Forest Service
John Crusius, US Geological Survey
Laura Baker, The Nature Conservancy
Lilian Petershoare, US Forest Service
Mandy Lindeberg, National Oceanic and Atmospheric Administration
Mark Shasby, Alaska Climate Science Center
Michael F. Sigler, Alaska Fisheries Science Center
Mike Goldstein, Alaska Coastal Rainforest Center
Ray Paddock, Central Council Tlingit and Haida Indian Tribes of Alaska
Reid Johnson, Central Council Tlingit and Haida Indian Tribes of Alaska
Richard T. Edwards, US Forest Service
Rick Fritsch, National Oceanic and Atmospheric Administration
Roman Motyka, University of Alaska – Southeast
Sarah Fleisher Trainor, University of Alaska – Fairbanks
Scott W. Johnson, National Oceanic and Atmospheric Administration
Shannon Atkinson, University of Alaska – Fairbanks
Tom Ainsworth, National Oceanic and Atmospheric Administration

British Columbia

Darcy Dobell, World Wildlife Fund
Dave Secord, Tides Canada Foundation
Hans Schreier, University of British Columbia
James Casey, World Wildlife Fund
Jenny Fraser, BC Ministry of Environment
Robyn Hooper, Pacific Institute for Climate Solutions
Stewart Cohen, Environment Canada
Tory Stevens, BC Ministry of Environment
Trevor Murdock, Pacific Climate Impacts Consortium

Oregon

Ben Clemens, Oregon State University
Carl Schreck, Oregon State University
Chris Hathaway, Lower Columbia River Estuary Partnership
Kathie Dello, Oregon Climate Change Research Institute
Kathy Lynn, University of Oregon
Keith Hatch, Bureau of Indian Affairs
Laurele Fulkerson, Wild Salmon Center
Mark Trenholm, North American Salmon Stronghold Partnership
Rowan Baker, US Fish and Wildlife Service
Roy Lowe, US Fish and Wildlife Service
Sara O'Brien, Defenders of Wildlife
Steve Caico, US Fish and Wildlife Service
Tim Mayer, US Fish and Wildlife Service
William Percy, Oregon State University

California

Aldaron Laird, Trinity Associates
Armand Gonzales, California Department of Fish and Game
Jeff Black, Humboldt State University
Eric T. Nelson, US Fish and Wildlife Service
Frank Shaughnessy, Humboldt State University
Iris Stewart-Frey, Santa Clara University
Laura Rogers-Bennett, California Department of Fish and Game
Lisa Ballance, University of California San Diego
Paula Golightly, US Fish and Wildlife Service
Peter Moyle, University of California - Davis
Susan Schlosser, California Sea Grant Extension Program

Native Alaskans, First Nations, Tribal

Abby Hook, Tulalip Tribe
Charles P. O'Hara, Swinomish Indian Tribal Community
Christopher Ellings, Nisqually Indian Tribe
Claire Wood, Confederated Tribes of Siletz Indians
Ed Knight, Swinomish Indian Tribal Community
Mike Kennedy, Confederated Tribes of Siletz Indians
Preston Hardison, Tulalip Tribe
Scott Andrews, Swinomish Indian Tribal Community
Stephen Kullmann, Wiyot Tribe
Tim Nelson, Wiyot Tribe

Washington

Alan Parker, The Evergreen State College
Bruce Jones, Northwest Indian Fisheries
Commission
Carey Smith, US Fish and Wildlife Service
Charlie Stenvall, US Fish and Wildlife Service
Curtis Tanner, Washington Department of
Fish and Wildlife
Elizabeth Gray, The Nature Conservancy
Eric Grossman, US Geological Survey
Greg Hood, Skagit River System Cooperative
Hugh Shipman, Washington State Department
of Ecology
Jean Takekawa, US Fish and Wildlife Service
Jennie Hoffman, EcoAdapt
Jesse Barham, US Fish and Wildlife Service
Jim Weber, Northwest Indian Fisheries
Commission
Jon Hoekstra, The Nature Conservancy
Kate Skaggs, Washington State Department of
Ecology
Kelley Turner, US Geological Survey
Lara Whitely Binder, Climate Impacts Group
Lisa Crozier, National Oceanic and
Atmospheric Administration
Mark Scheuerell, National Marine Fisheries
Service
Mary Mahaffy, US Fish and Wildlife Service
Mike Grayum, Northwest Indian Fisheries
Commission
Nathan Mantua, Climate Impacts Group
Patty Glick, National Wildlife Federation
Paul McElhany, National Marine Fisheries
Service
Rachel M. Gregg, EcoAdapt
Richard Cook, Bureau of Indian Affairs
Richard Feely, National Oceanic and
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Spencer Reeder, Cascadia Consulting Group
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Tom Dwyer, Ducks Unlimited

Other

Garrit Voggeser, National Wildlife Federation
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XI. BIBLIOGRAPHY

- Abeysirigunawardena, D. S., and I. J. Walker. (2008). Sea level responses to climatic variability and change in northern British Columbia. *Atmosphere-Ocean*. 46(3): 277-296. Available at <http://www.tandfonline.com/doi/abs/10.3137/ao.460301> (accessed December 2011).
- Ackerly, D. D., S. R. Loarie, W. K. Cornwell, S. B. Weiss, H. Hamilton, R. Branciforte, and N. J. B. Kraft. (2010). The geography of climate change: implications for conservation biogeography (Supplemental Information). *Diversity and Distributions*. 16: Available at http://onlinelibrary.wiley.com/store/10.1111/j.1472-4642.2010.00654.x/asset/supinfo/DDI_654_sm_Data_S1andFig_S1-S8.pdf?v=1&s=93f8310b31bb81d495bae87579a8d7f4d710ca3e (accessed 6.8.2011).
- ACRC, Alaska Climate Research Center. (2009). *Temperature Change in Alaska*. Available at <http://climate.gi.alaska.edu/ClimTrends/Change/TempChange.html> (accessed January 7, 2011).
- Adams, P. N. and D. L. Inman. (2009). *Climate change hotspots and potential hotspots of coastal erosion along the southern California coast: Final Paper (CEC-500-2009-022-F)*. California Climate Change Center. 73 pp. Available at <http://www.energy.ca.gov/2009publications/CEC-500-2009-022/CEC-500-2009-022-F.PDF> (accessed December 2011).
- ADB, Asian Development Bank. (2005). *Climate Proofing: A risk-based approach to adaptation*. Asian Development Bank. 219 pp. Available at <http://www.adb.org/publications/climate-proofing-risk-based-approach-adaptation> (accessed December 2011).
- AK CCAP, Alaska Center for Climate Assessment and Policy. *Climate Change Impacts on Water Availability in Alaska (presentation)*. September 15, 2009. Available at http://ine.uaf.edu/accap//documents/2009_09_Water_Availability_OBrien.pdf (accessed January 6, 2011).
- AK-DEC, Alaska Department of Environmental Conservation. (2010). Final Report Submitted by the Adaptation Advisory Group to the Alaska Climate Change Sub-Cabinet. *Climate Change in Alaska: Adaptation Advisory Group of the Governor's Sub-Cabinet on Climate Change*. Available at <http://www.climatechange.alaska.gov/aag/aag.htm> (accessed January 13, 2011)
- Alaska State Legislature. (2008). Final Commission Report: Alaska Climate Impact Assessment Commission. March 17. 125 pp. Available at http://www.housemajority.org/coms/cli/cli_finalreport_20080301.pdf (accessed December 2011).
- Arora, V. K, J. F. Scinocca, G. J. Boer, J. R. Christian, K. L. Denman, G. M. Flato, V. V. Kharin, W. G. Lee, and W. J. Merryfield. (2011). Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases. *Geophysical Research Letters* 38(L05805): 6 pp. Available at <http://www.rcinet.ca/projects/en/PDF/Climate%20change%20report.PDF> (accessed December 2011).
- Bakun, A. (1990). Global climate change and intensification of coastal ocean upwelling. *Science*. 247: 198-201. Available at <http://swfsc.noaa.gov/publications/cr/1990/9003.pdf> (accessed December 2011).
- Bakun, A., and S. J. Weeks. (2004). Greenhouse gas buildup, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems. *Ecology Letters*. 7: 1015-1023. Available at <http://onlinelibrary.wiley.com/doi/10.1111/j.1461-0248.2004.00665.x/abstract> (accessed December 2011).
- Baron, J. S., L. Gunderson, C. D. Allen, E. Fleishman, D. H. McKenzie, L. A. Meyerson, J. Oropeza, and N. Stephenson. (2009). Options for national parks and reserves for adapting to climate change. *Environmental Management*. 44(6): 1033-1042. Available at http://www.fort.usgs.gov/Products/Publications/pub_abstract.asp?PubId=22281 (accessed December 2011).
- Bauman, Y., B. Doppelt, S. Mazze, and E. C. Wolf. (2006). Impacts of climate change on Washington's economy: a preliminary assessment of risks and opportunities. Edited by Edward C. Wolf. November 2006. Available at <http://www.ecy.wa.gov/pubs/0701010.pdf> (accessed January 18, 2011).
- B.C. MOE, British Columbia Ministry of Environment. (2006). *Alive and Inseparable: British Columbia's Coastal Environment: 2006*. (2006). BC Ministry of Environment. 335 pp. Available at <http://www.env.gov.bc.ca/soe/archive/#reports> (accessed December 2011).
- . *Climate Change Adaptation Strategy*. (2011). Available at <http://www.env.gov.bc.ca/cas/adaptation/strategy.html> (accessed January 13, 2011).
- . *Environmental Trends in British Columbia: 2007*. (2007). Victoria B.C.: State of Environment Reporting. Available at <http://www.env.gov.bc.ca/soe/archive/#reports> (accessed December 2011).

- In-depth report: Climate Change. In *Environmental Trends in British Columbia: 2007*. (2007). Available at http://www.env.gov.bc.ca/soe/et07/04_climate_change/technical_paper/climate_change.pdf (accessed November 23, 2010).
- In-depth report: Ecosystems. In *Environmental Trends in British Columbia: 2007*. (2007). Available at http://www.env.gov.bc.ca/soe/et07/06_ecosystems/technical_paper/ecosystems.pdf (accessed November 23, 2010).
- In-depth report: Species Conservation. In *Environmental Trends in British Columbia: 2007*. (2007). Available at http://www.env.gov.bc.ca/soe/et07/07_species_conserv/technical_paper/species_conservation.pdf (accessed November 23, 2010).
- BBC. (2009). *The key effects of climate change*. March 10, 2009. Available at <http://news.bbc.co.uk/2/hi/science/nature/7933589.stm> (accessed June 8, 2011).
- Berkes, F., J. Colding, and C. Folke. (2000). Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications*. 10(5): 1251-1262. Available at http://www.fws.gov/nativeamerican/graphics/TEK_Berkes_2000.pdf (accessed December 2011).
- Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C. K. Shum, L. D. Talley, and A. Unnikrishnan. (2007). *FAQ 5.1 - AR4 WG1 Chapter 5: Observations: Oceanic Climate Change and Sea Level*. Edited by S. Solomon, et al. Cambridge, United Kingdom and New York, NY, USA Cambridge University Press. Available at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html (accessed March 28, 2011).
- Biodiversity BC. (2009). *Taking Nature's Pulse: Table of Contents, Exec. Summary, and Introduction*. April 3, 2009. Available at <http://www.biodiversitybc.org/EN/main/downloads/tnp-introduction.html#sabout> (accessed January 14, 2011).
- Boe, J., A. Boone Vierra, W. Brown, T. Butler, J. Gerwein, M. Herborg, P. Olofson, M. Spellman, J. Steger, M. Sytsma, and M. Toohey. (2010). West Coast Governor's Agreement on Ocean Health Spartina Eradication Action Coordination Team Work Plan. May 2010. Available at http://www.westcoastcoceans.org/media/Spartina_Final_Work_Plan.pdf (accessed December 2011).
- Boeing, W. J., and J. T. Duffy-Anderson. (2008). Ichthyoplankton dynamics, and biodiversity in the Gulf of Alaska: responses to environmental change. *Ecological Indicators* 8: 292-302. Available at <http://www.pmel.noaa.gov/foci/publications/2008/boeiN617.pdf> (accessed December 2011).
- Bornhold, B. D. (2008). *Projected sea level changes for British Columbia in the 21st century*. Library and Archives Canada Cataloguing in Publication. Available at <http://www.env.gov.bc.ca/cas/pdfs/sea-level-changes-08.pdf> (accessed December 2011).
- Brandenberger, J. M., E. Crecelius, P. Louchouart, S. Cooper, K. McDougall, and E. Leopold, G. Liu. (2008). *Reconstructing trends in hypoxia using multiple paleoecological indicators recorded in sediment cores from Puget Sound, WA*. National Oceanic and Atmospheric Administration, Pacific Northwest National Laboratory, Report No. PNWD-4013. 158 pp. Available at http://faculty.washington.edu/pmacc/Classes/PS_2009/refs/Brandenberger_etal_2008_HCDO.pdf (accessed December 2011).
- British Columbia. (2008). Climate Action Plan. Available at http://www.livesmartbc.ca/attachments/climateaction_plan_web.pdf (accessed January 13, 2011).
- Brooks, K. N., P. F. Ffolliott, H. M. Gregerson, and L. F. DeBano. Hydrologic Processes and Land Use. In *Hydrology and the Management of Watersheds* (pp. 21-22). Ames, Iowa: Blackwell Publishing, 2003.
- Brown, A. C., and A. McLachlan. (2002). Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation*. 29(1): 62-77. Available at <http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=107775> (accessed December 2011).
- Burgette, R. J., R. J. Weldon II, and D. A. Schmidt. (2009). Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone. *Journal of Geophysical Research* 114: 1-24 (B01408). Available at <http://www.washington3d.org/docs/UniversityofOregon.pdf> (accessed December 2011).
- Burgiel, S. W., and A. A. Muir. (2010). *Invasive species, climate change and ecosystem-based adaptation: Addressing multiple drivers of global change*. Washington DC, US, and Nairobi, Kenya: Global Invasive Species Programme (GISP). 56 pp. Available at <http://data.iucn.org/dbtw-wpd/edocs/2010-054.pdf> (accessed December 2011).

- Butz, R. J., and H. Safford. (2010). A summary of current trends and probable future trends in climate and climate-driven processes for the Six Rivers National Forest and surrounding lands. December 15, 2010. Available at http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5251124.pdf (accessed March 7, 2011).
- Byrne, R. H., S.Mecking, R. A. Feely, and X. Liu. (2010). Direct observations of basin-wide acidification of the North Pacific Ocean. *Geophysical Research Letters* 37(L02601): 1-5. Available at <ftp://soest.hawaii.edu/coastal/Climate%20Articles/Acidification%20Pacific%20Byrne%202010.pdf> (accessed December 2011).
- CA NRA, California Natural Resources Agency. (2009). 2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008. 200 pp. Available at <http://www.energy.ca.gov/2009publications/CNRA-1000-2009-027/CNRA-1000-2009-027-F.PDF> (accessed December 2011).
- Capalbo, S., J. Julian, T. Maness, and E. Kelly. (2010). Toward assessing the economic impacts of climate change on Oregon. *The Oregon Climate Assessment Report*. Edited by K. D. Dello and P. W. Mote. Corvallis, OR: College of Oceanic and Atmospheric Sciences, Oregon State University. Available at <http://occri.net/ocar> (accessed December 2011).
- Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe. (2008). Climate change scenarios for the California region. *Climatic Change*. 87(Suppl 1): S21-S42. Available at http://tenaya.ucsd.edu/~dettinge/cccc08_scenarios.pdf (accessed December 2011).
- Cazenave, A., K. Dominh, S. Guinehut, E. Berthier, W. Llovel, G. Ramillien, M. Ablain, and G. Larnicol. (2009). Sea level budget over 2003-2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo. *Global and Planetary Change*. 65: 83-88. Available at <http://www.sciencedirect.com/science/article/pii/S0921818108001343> (accessed December 2011).
- Chan, F., J. A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W. T. Peterson, and B. A. Menge. (2008). Emergence of anoxia in the California Current large marine ecosystem. *Science*. 319: 920. Available at http://www.whoi.edu/cms/files/Chanetal_anoxia_science2008_51503.pdf (accessed December 2011).
- Chang, H., and J. Jones. (2010). Climate change and freshwater resources in Oregon. In *Oregon Climate Assessment Report (OCAR)*. Edited by K. D. Dello and P. W. Mote. Corvallis, OR: Oregon Climate Change Research Institute, College of Oceanic and Atmospheric Sciences, Oregon State University. pp. 69-150. Available at <http://occri.net/wp-content/uploads/2011/04/chapter3ocar.pdf> (13.2 MB; accessed December 2011).
- Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and M. Niquen C. (2003). From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science*. 299(10): 217-221. Available at http://cmhc.ucsd.edu/Students/Current_Students/MCB/Chavez%202003pdf.pdf (accessed December 2011).
- Chen, J. L., C. R. Wilson, and B. D. Tapley. (2006). Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet. *Science*. 313(5795): 1958-1960. Available at ftp://ftp.csr.utexas.edu/pub/ggfc/papers/Science_2006.pdf (accessed December 2011).
- Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*. 16: 24-35. Available at <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2009.01995.x/abstract> (accessed December 2011).
- CIG, Climate Impacts Group. (March 2008). *Climate Change*. Available at <http://cses.washington.edu/cig/pnwc/cc.shtml> (accessed January 14, 2011).
- . *Climate Change Scenarios: Future Northwest Climate*. (August 1, 2008). Available at <http://cses.washington.edu/cig/fpt/ccscenarios.shtml> (accessed January 14, 2011).
- . *Climate Change: Future Climate Change in the Pacific Northwest*. March 2008. Available at <http://cses.washington.edu/cig/pnwc/cc.shtml> (accessed January 14, 2011).
- . *Pacific Northwest Climate Maps*. (2011). Available at <http://cses.washington.edu/cig/maps/index.shtml> (accessed March 16, 2011).
- . *Preparing for climate change: A guidebook for local, regional, and state governments*. (2007). Joint Institute for the Study of the Atmosphere and Ocean, University of Washington; King County, Washington. 186 pp. Available at <http://www.cses.washington.edu/db/pdf/snoveretalgb574.pdf> (accessed December 2011).

- . *The Washington Climate Change Impacts Assessment (WACCIA)*. (2009). Seattle: University of Washington Climate Impacts Group. Available at <http://cses.washington.edu/cig/res/ia/waccia.shtml> (accessed January 14, 2011).
- Clough, J. S., R. A. Park, and R. Fuller. (May 2010). SLAMM 6 beta Technical Documentation (draft). May 2010. Available at http://warrenpinnacle.com/prof/SLAMM6/SLAMM6_Technical_Documentation.pdf (accessed August 16, 2011).
- Collins, M., S-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F-F. Jin, M. Jochum, M. Lengaigne, S. Power, A. Timmermann, G. Vecchi, and A. Wittenberg. (2010). The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience*. 3: 391-397. Available at http://geosci.sfsu.edu/courses/gmo405/articles/ClimChngENSO_NatGeosci_May2010_Collins.pdf (accessed December 2011).
- Connolly, T. P., B. M. Hickey, S. L. Geier, and W. P. Cochlan. (2010). Processes influencing seasonal hypoxia in the northern California Current System. *Journal of Geophysical Research*. 115(C03021): 36 pp. Available at <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2867361/> (accessed December 2011).
- Cooley, S. R., H. L. Kite-Powell, and S. C. Doney. (2009). Ocean acidification's potential to alter global marine ecosystem services. *Oceanography*. 22(4): 172-181. Available at http://tos.org/oceanography/archive/22-4_cooley.pdf (accessed December 2011).
- Crozier, L. G., A. P. Hendry, P. W. Lawson, T. P. Quinn, N. J. Mantua, J. Battin, R. G. Shaw, and R. B. Huey. (2008). Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon. *Evolutionary Applications*. 1(2): 252-270. Available at http://faculty.washington.edu/hueyrb/pdfs/Crozier_et_al_Evol_Appl_2008.pdf (accessed December 2011).
- Crusius, J., A. W. Schroth, S. Gasso, C. M. Moy, R. C. Levy, and M. Gatica. (2011). Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron. *Geophysical Research Letters*. 38(L06602): 1-5. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2010GL046573/abstract> (accessed December 2011).
- Davidson, T. M., V. E. F. Brenneis, C. de Rivera, R. Draheim, and G. E. Gillespie. (2008). Northern range expansion and coastal occurrences of the New Zealand mud snail *Potamopyrgus antipodarum* (Gray, 1843) in the northeast Pacific. *Aquatic Invasions*. 3(3): 349-353. Available at <http://www.fws.gov/answest/Projects/AI2008Davidsonetal.pdf> (accessed December 2011).
- Dawe, J. T., and L. Thompson. (2007). PDO-related heat and temperature changes in a model of the North Pacific. *Journal of Climate*. 20(May 15): 2092-2108. Available at <http://journals.ametsoc.org/doi/pdf/10.1175/JCLI4229.1> (accessed December 2011).
- Defeo, O., A. McLachlan, D. S. Schoeman, T. A. Schlacher, J. Dugan, A. Jones, M. Lastra, and F. Scapini. (2009). Threats to sandy beach ecosystems: a review. *Estuarine, Coastal and Shelf Science*. 81: 1-12. Available at http://mhk.pnnl.gov/wiki/images/b/b6/threats_to_sandy_beach_ecosystems.pdf (accessed December 2011).
- Diffenbaugh, N. S., M. A. Snyder, and L. C. Sloan. (2004). Could CO₂-induced land-cover feedbacks alter near-shore upwelling regimes? *Proceedings of the National Academy of Sciences*. 101(1): 27-32. Available at <http://www.pnas.org/content/101/1/27.full.pdf> (accessed December 2011).
- Domingues, C. M., J. A. Church, N. J. White, P. J. Gleckler, S. E. Wijffels, P. M. Barker, and J. R. Dunn. (2008). Improved estimates of upper-ocean warming and multi-decadal sea level rise. *Nature*. 453(19): 1090-1093. Available at <http://www.nature.com/nature/journal/v453/n7198/abs/nature07080.html> (accessed December 2011).
- DU, Ducks Unlimited, Inc. (2010a). *SLAMM Analysis of Grays Harbor, Washington*. Unpublished technical report, Vancouver, WA: Ducks Unlimited. 197 pp.
- . *SLAMM Analysis of the Lower Columbia River, Washington and Oregon*. (2010b). Unpublished technical report, Vancouver, WA: Ducks Unlimited. 63 pp.
- . *SLAMM Analysis of Willapa Bay, Washington*. (2010c). Unpublished technical report, Vancouver, WA: Ducks Unlimited. 207 pp.
- . *Update of Puget Sound SLAMM Analysis*. (2010d). Unpublished technical report, Vancouver, WA: Ducks Unlimited. 29 pp.
- DU-Canada, Ducks Unlimited Canada. (2009). British Columbia Spartina Eradication Program: 2009 Progress Report. Available at http://www.spartina.org/referencemtr/BC_Spartina_Progress_Report_09.pdf (accessed April 13, 2011).
- Ehler, C., and F. Douvère. (2009). Marine Spatial Planning: a step-by-step approach toward ecosystem-based management. Paris: UNESCO. 100 pp. Available at <http://unesdoc.unesco.org/images/0018/001865/186559e.pdf> (accessed December 2011).

- Ekau, W., H. Auel, H-O. Portner, and D. Gilbert. (2010). Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). *Biogeosciences*. 7: 1669-1699. Available at <http://www.biogeosciences.net/7/1669/2010/bg-7-1669-2010.pdf> (accessed December 2011).
- Elston, R. A., H. Hasegawa, K. L. Humphrey, I. K. Polyak, and C. C. Hase. (2008). Re-emergence of *Vibrio tubiashii* in bivalve shellfish aquaculture: severity, environmental drivers, geographic extent and management. *Diseases of Aquatic Organisms*. 82(2): 119-34. Available at <http://www.int-res.com/articles/dao2008/82/d082p119.pdf> (accessed December 2011).
- Emmett, R., R. Llanso, J. Newton, R. Thom, M. Hornberger, C. Morgan, C. Levings, A. Copping, and P. Fishman. (2000). Geographic signatures of North American West Coast Estuaries. *Estuaries*. 23(6): 765-792. Available at http://wwwrcamnl.wr.usgs.gov/tracel/references/pdf/Estuaries_v23n6p765.pdf (accessed December 2011).
- EPA, United States Environmental Protection Agency. (2008). Effects of Climate Change on Aquatic Invasive Species and Implications for Management and Research [EPA/600/R-08/014]. National Center for Environmental Assessment, Office of Research and Development, Washington, DC: U.S. Environmental Protection Agency. 337 pp. Available at <http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=188305> (accessed December 2011).
- . Inventory of U.S. Greenhouse Gas Emissions Emissions and Sinks: 1990-2006: Introduction. (2006). Available at http://www.epa.gov/climatechange/emissions/downloads/ghg_gwp.pdf (accessed December 28, 2010).
- . Lessons Learned from the Climate Ready Estuaries Program. (2011). U.S. Environmental Protection Agency, Climate Ready Estuaries Program. Available at http://water.epa.gov/type/oceb/cre/upload/CRE_Lesson_Learned_508.pdf (accessed December 2011).
- . Synthesis of Adaptation Options for Coastal Areas. (2009). Washington, D.C.: U.S. Environmental Protection Agency, Climate Ready Estuaries Program. 32 pp. Available at http://water.epa.gov/type/oceb/cre/upload/CRE_Synthesis_1-09.pdf (accessed December 2011).
- ESR, Earth and Space Research. (January 21, 2004). *Outreach and Education: Oceanographic Glossary*. Available at <http://www.esr.org/outreach/glossary.html#m> (accessed April 8, 2011).
- Fabry, V. J., J. B. McClintock, J. T. Mathis, and J. M. Grebmeier. (2009). Ocean acidification at high latitudes: the Bellwether. *Oceanography*. 22(4): 160-171. Available at http://www.tos.org/oceanography/archive/22-4_fabry.pdf (accessed December 2011).
- Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales. (2008). Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science*. 320(13): 1490-1492. Available at http://www.psp.wa.gov/downloads/SP2009/0509/12a_FeelyetalScience2008.pdf (accessed December 2011).
- Feely, R. A., S. R. Alin, J. Newton, C. L. Sabine, M. Warner, A. Devol, C. Krembs, and C. Maloy. (2010). The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine, Coastal and Shelf Science*. 88: 442-449. Available at <http://faculty.wvu.edu/~shulld/ESCI%20432/Feely2010.pdf> (accessed December 2011).
- Feely, R. A., S. C. Doney, S. R. Cooley. (2009). Ocean acidification: present conditions and future changes in a high CO₂ world. *Oceanography*. 22(4): 36-47. Available at https://darchive.mblwhoilibrary.org/bitstream/handle/1912/3180/22-4_feely.pdf?sequence=1 (accessed December 2011).
- Field, C. B., L. D. Mortsch, M. Brklacich, D. L. Forbes, P. Kovacs, J. A. Patz, S. W. Running, and M. J. Scott. (2007). "North America." In *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson. Cambridge: Cambridge University Press. pp. 617-652. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter14.pdf> (accessed December 2011).
- Field, J. C., K. Baltz, A. J. Phillips, and W. A. Walker. (2007). Range expansion and trophic interactions of the jumbo squid, *Dosidicus gigas*, in the California Current. *California Cooperative Oceanic Fisheries Investigations (CalCOFI)*. 48: 131-146. Available at http://calcofi.org/~calcofi/publications/calcofireports/v48/Vol_48_Field.pdf (accessed December 2011).
- Fierstein, D. (2007). Scientists and decision makers discuss the fate of the ocean. *Monterey Bay Aquarium Research Institute*. Available at http://www.mbari.org/news/news_releases/2008/oceansummit/oss-advisory.html (accessed December 6, 2010).

- Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schultz, and R. Van Dorland. (2007). *Changes in Atmospheric Constituents and in Radiative Forcing*. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change. pp. 129-234. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf> (accessed December 2011).
- FWS, U.S. Fish and Wildlife Service. (2009). *Marbled Murrelet (Brachyramphus marmoratus): 5-Year Review (Final)*. Lacey: U.S. Fish and Wildlife Service, Washington Fish and Wildlife Office. 108 pp. Available at http://www.fws.gov/wafwo/pdf/Mamu2009_5yr_review%20FINAL%2061209.pdf (accessed December 2011).
- Galatowitsch, S., L. Frelich, and L. Phillips-Mao. (2009). Regional climate change adaptation strategies for biodiversity conservation in a midcontinental region of North America. *Biological Conservation*. 142: 2012-2022. Available at <http://www.nwf-wcr.org/PDFs-ClimateChangeFWP/NRNRC-GW-FWP-Galatowitsch-Paper.pdf> (accessed December 2011).
- Galbraith, H., R. Jones, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page. (2005). Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. *Forest Service General Technical Report PSW-GTR-191*. United States Department of Agriculture. pp. 1119-1122. Available at http://research.fit.edu/sealevelriselibrary/documents/doc_mgr/470/Global_Potential_Losses_of_Shorebird_Habitats_-_Galbraith_et_al._2005.pdf (accessed December 2011).
- GCRP, United States Global Change Research Program. (2009). *Global Climate Change Impacts in the United States*. Edited by Thomas R. Karl, Jerry M. Melillo and Thomas C. Peterson. Cambridge University Press. Available at <http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf> (accessed January 6, 2011).
- Glick, P., A. Staudt, B. Stein. (2009). A New Era for Conservation: Review of Climate Change Adaptation Literature. National Wildlife Federation. 69 pp. Available at <http://www.nwf.org/News-and-Magazines/Media-Center/Faces-of-NWF/~media/PDFs/Global%20Warming/Reports/NWFClimateChangeAdaptationLiteratureReview.ashx> (accessed 12.14.2010).
- Glick, P., B. A. Stein, and N. A. Edelson (Eds.). (2011b). *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment*. Washington, D.C.: National Wildlife Federation. Available at <http://www.nwf.org/~media/PDFs/Global-Warming/Climate-Smart-Conservation/NWFScanningtheConservationHorizonFINAL92311.pdf?dmc=1&ts=20130329T1612385296> (accessed December 2011).
- Glick, P., J. Hoffman, M. Koslow, A. Kane, and D. Inkley. (2011a). *Restoring the Great Lakes' Coastal Future: Technical Guidance for the Design and Implementation of Climate-Smart Restoration Projects*. Ann Arbor, MI: National Wildlife Federation. Available at http://www.habitat.noaa.gov/pdf/final_restoring_the_great_lakes_coastal_future_2011.pdf (accessed December 2011).
- Glick, P., J. Clough, and B. Nunley. (2007) *Sea level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon*. National Wildlife Federation. 106 pp. Available at <http://www.nwf.org/~media/PDFs/Wildlife/PacificNWSeaLevelRise.pdf?dmc=1&ts=20130329T1615328566> (accessed December 2011).
- Glick, P., J. Clough, and B. Nunley. (2010). *Assessing the Vulnerability of Alaska's Coastal Habitats to Accelerating Sea level Rise Using the SLAMM Model: A Case Study for Cook Inlet*. National Wildlife Federation. 30 pp. Available at <http://www.fws.gov/slamm/Alaska%20SLAMM%20Summary%20Report-1.ashx.pdf> (accessed December 2011).
- Grafton, R. Q. (2010). Adaptation to climate change in marine capture fisheries. *Marine Policy*. 34: 606-615. Available at <http://www.sciencedirect.com/science/article/pii/S0308597X09001845> (accessed December 2011).
- Grantham, B. A., F. Chan, K. J. Nielsen, D. S. Fox, J. A. Barth, A. Huyer, J. Lubchenco, and B. A. Menge. (2004). Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature*. 429: 749-754. Available at <http://www.nature.com/nature/journal/v429/n6993/abs/nature02605.html> (accessed December 2011).
- Gregg, R. M., L. J. Hansen, K. M. Feifel, J. L. Hitt, J. M. Kershner, A. Score, and J. R. Hoffman. (2011). *The State of Marine and Coastal Adaptation in North America: A Synthesis of Emerging Ideas (Final Report)*. Bainbridge Island, WA: EcoAdapt. 145 pp. Available at <http://ecoadapt.org/documents/marine-adaptation-report.pdf> (accessed December 2011).

- Grinsted, A., J. C. Moore, and S. Jevrejeva. (2009). Reconstructing sea level from paleo and projected temperatures 200 to 2100AD. *Climate Dynamics*. 34(4): 461-472. Available at <ftp://ftp.soest.hawaii.edu/coastal/Climate%20Articles/Grinsted%20Jevrejeva%202009%20SLR.pdf> (accessed December 2011).
- Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. Lawrimore. (2004). Contemporary changes in the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology*. 5: 64-85. Available at [http://journals.ametsoc.org/doi/abs/10.1175/1525-7541\(2004\)005%3C0064:CCOTH%3E2.0.CO;2](http://journals.ametsoc.org/doi/abs/10.1175/1525-7541(2004)005%3C0064:CCOTH%3E2.0.CO;2) (accessed December 2011).
- Guinotte, J. M., and V. J. Fabry. (2008). Ocean acidification and its potential effects on marine ecosystems. *Annals of New York Academy of Sciences*. 320: 320-342. Available at <http://www.gg.mq.edu.au/rep/websites/docs/paper.pdf> (accessed December 2011).
- Guinotte, J. M., J. Orr, S. Cairns, A. Freiwald, L. Morgan, and R. George. (2006). Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? *Frontiers in Ecology and the Environment*. 4(3): 141-146. Available at http://cmbe.ucsd.edu/Students/Current_Students/SIO277/2006_Guinotte_etal.pdf (accessed December 2011).
- Hamlet, A. F., and D. P. Lettenmaier. (2007). Effects of 20th century warming and climate variability on flood risk in the western U.S. *Water Resources Research*. 43: 17. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2006WR005099/abstract> (accessed December 2011).
- Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. (2007). Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. *Journal of Climate*. 20(8): 1468-1486. Available at <http://journals.ametsoc.org/doi/abs/10.1175/JCLI4051.1> (accessed December 2011).
- Hansen, J., L. Nazarenko, R. Ruedy, M. Sato, J. Willis, A. Del Genio, D. Koch, A. Lacis, K. Lo, S. Menon, T. Novakov, J. Perlwitz, G. Russell, G. A. Schmidt, and N. Tausnev. (2005). Earth's energy imbalance: confirmation and implications. *Science*. 308(3): 1431-1435. Available at <http://www.micro.utexas.edu/courses/THOC/Hansen-et-al-2005-Science.pdf> (accessed December 2011).
- Hare, S. R., N. J. Mantua, and R. C. Francis. (1999). Inverse production regimes: Alaska and West Coast Pacific Salmon. *Fisheries*. 24(1): 6-14. Available at <http://www.tandfonline.com/doi/abs/10.1577/1548-8446%281999%29024%3C0006%3AIPR%3E2.0.CO%3B2> (accessed December 2011).
- Harris, P. M., A. D. Neff, S. W. Johnson, and J. F. Thedinga. (2008). *Eelgrass habitat and faunal assemblages in the City and Borough of Juneau, Alaska*. Technical Memorandum NMFS-AFSC-182, NOAA National Marine Fisheries Service Alaska Fisheries Science Center. 59 pp. Available at <http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-182.pdf> (accessed December 2011).
- Hasegawa, H., E. J. Lind, M. A. Boin, and C. C. Hase. (2008). The extracellular metalloprotease of *Vibrio tubiashii* is a major virulence factor for Pacific oyster (*Crassostrea gigas*) larvae. *Applied and Environmental Microbiology*. 74(13): 4101-4110. Available at <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2446533/> (accessed December 2011).
- Haufler, J. B., C. A. Mehl, and S. Yeats. (2010). *Climate change: anticipated effects on ecosystem services and potential actions by the Alaska Region, U.S. Forest Service*. Seeley Lake, Montana, USA: Ecosystem Management Research Institute. Available at http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev2_038171.pdf (accessed December 2011).
- Hauri, C., N. Gruber, G-K. Plattner, S. Alin, R. A. Feely, B. Hales, and P. A. Wheeler. (2009). Ocean acidification in the California Current System. *Oceanography*. 22(4): 60-71. Available at http://www.tos.org/oceanography/archive/22-4_hauri.pdf (accessed December 2011).
- Heinz Center, The H. John Heinz III Center for Science, Economics and the Environment. (2008). *Strategies for Managing the Effects of Climate Change on Wildlife and Ecosystems*. Available from <http://www.heinzctr.org/contact> (accessed April 7, 2011).
- Heller, N. E., and E. S. Zavaleta. (2009). Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*. 142: 14-32. Available at <http://www.lagunadesantarosa.org/knowledgebase/sites/default/files/Heller%20and%20Zavaleta%202009.pdf> (accessed December 2011).
- Helly, J. J., and L. A. Levin. (2004). Global distribution of naturally occurring marine hypoxia on continental margins. *Deep-Sea Research I*. 51: 1159-1168. Available at http://www.legos.obs-mip.fr/~dewitte/bxd_data/resources/chipemocs/doc/biblio/HellyandLevin2004dsr.pdf (accessed December 2011).

- Hermann, A. J., S. Hinckley, E. L. Dobbins, D. B. Haidvogel, N. A. Bond, C. Mordy, N. Kachel, and P. J. Stabeno. (2009). Quantifying cross-shelf and vertical nutrient flux in the Coastal Gulf of Alaska with a spatially nested, coupled biophysical model. *Deep-Sea Research II*. 56: 2474-2486. Available at <http://www.pmel.noaa.gov/foci/publications/2009/hermG712.pdf> (accessed December 2011).
- Hickey, B.M., and N. S. Banas. (2003). Oceanography of the U.S. Pacific Northwest Coastal Ocean and Estuaries with Application to Coastal Ecology. *Estuaries*. 26(4B): 1010-1031. Available at <http://coast.ocean.washington.edu/coastfiles/HickeyBanas-PNWcoast.pdf> (accessed December 2011).
- Hickey, B. M., and N. S. Banas. (2008). Why is the northern end of the California Current System so productive? *Oceanography*. 21(4): 90-107. Available at <http://www.math.ust.hk/~magan/AMCE6082010/paperpool2010/why%20is%20the%20northern%20end%20of%20the%20california%20current%20system%20so%20productive.pdf> (accessed December 2011).
- Hinch, S. G., and E. G. Martins. (2011). *A review of potential climate change effects on survival of Fraser River sockeye salmon and an analysis of interannual trends in en route loss and pre-spawn mortality*. Cohen Commission Tech. Rept. 9, Vancouver, B.C.: Cohen Commission. 134 pp. Available at <http://www.cohencommission.ca/en/pdf/TR/Project9-Report.pdf> (accessed December 2011).
- Hoegh-Guldberg, O., and J.F. Bruno. (2010). The impact of climate change on the world's marine ecosystems. *Science*. 328: 1523-1528. Available at http://johnfbruno.web.unc.edu/files/2011/11/Hoegh-Guldberg-and-Bruno_climate-change-impacts-on-oceans_Science-2010.pdf (accessed December 2011).
- Hoffman, J. (2003). Designing reserves to sustain temperate marine ecosystems in the face of global climate change. In *Buying Time: A user's manual for building resistance and resilience to climate change in natural systems*. Edited by L. J. Hansen, J. L. Biringer and J. R. Hoffman. World Wildlife Fund. pp. 121-154. Available at <http://wwf.panda.org/?8678/BUYING-TIME-A-Users-Manual-for-Building-Resistance-and-Resilience-to-Climate-Change-in-Natural-Systems> (accessed December 2011).
- Hood, E., and D. Scott. (2008). Riverine organic matter and nutrients in southeast Alaska affected by glacial coverage. *Nature Geoscience*. 1: 583-587. Available at http://jun-web01.uas.alaska.edu/arts_sciences/naturalsciences/envs/faculty_staff/pubs/hood_scott_glaciernutrients_ngs2008.pdf (accessed December 2011).
- Hood, E., J. Fellman, R. G. M. Spencer, P. J. Hernes, R. Edwards, D. D'Amore, and D. Scott. (2009). Glaciers as a source of ancient and labile organic matter to the marine environment. *Nature*. 462(24): 1044-1048. Available at http://jun-web01.uas.alaska.edu/arts_sciences/naturalsciences/envs/faculty_staff/pubs/hood_et_al_nature2009.pdf (accessed December 2011).
- Howat, I. M., S. Tulaczyk, P. Rhodes, K. Israel, and M. Snyder. (2007). A precipitation-dominated, mid-latitude glacier system: Mount Shasta, California. *Climate Dynamics*. 28: 85-98. Available at <http://link.springer.com/article/10.1007/s00382-006-0178-9> (accessed December 2011).
- Huppert, D. D., A. Moore, and K. Dyson. (2009). Impacts of climate change on the coasts of Washington State. In *Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. Edited by J. S. Littell, M McGuire Elsner, L. C. Whitely Binder and A. K. Snover. Seattle, WA: Climate Impacts Group, University of Washington. Chapter 8: pp. 285-309. Available at <http://cses.washington.edu/db/pdf/wacciach8coasts651.pdf> (accessed December 2011).
- ICCWG, Intertribal Climate Change Working Group. (2009). A Tribal White Paper on Climate Change Adaptation and Mitigation. 13 pp. Available at http://www.tribesandclimatechange.org/docs/tribes_3.pdf (accessed December 2011).
- IPCC, Intergovernmental Panel on Climate Change. (2007). *2.3 Chemically and Radiatively Important Gases - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and Radiative Forcing*. Available at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-3.html#2-3-1 (accessed 2010 йил 28-December).
- . *Climate Change 2007: Impacts, Adaptation, Vulnerability: Introduction*. (2007). Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-intro.pdf> (accessed June 6, 2011).
- . *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]*. (2007). Geneva: IPCC. Available at http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html (accessed December 2011).

- . *Climate Change 2007: Synthesis Report: Summary for Policymakers*. (2007). Available at http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf (accessed December 2011).
- . *FAQ 10.1 Are extreme events, like heat waves, droughts or floods, expected to change as the Earth's climate changes?* (2010). Available at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-10-1.html (accessed December 15, 2010).
- . *IPCC Fourth Assessment Report: Climate Change 2007: Foreword*. (2007). Available at http://www.ipcc.ch/publications_and_data/ar4/syr/en/frontmattersforeword.html (accessed January 14, 2011).
- . *IPCC Special Report on Emissions Scenarios: Chapter 5.1 Introduction*. (2010). Available at http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/index.htm (accessed March 16, 2011).
- . *SRES Final Data (version 1.1) Breakdown*. (July 2000). Available at http://sres.ciesin.org/final_data.html (accessed March 16, 2011).
- . Summary for Policymakers. (2001). In *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. 18 pp. Available at http://www.grida.no/climate/ipcc_tar/wg2/pdf/wg2TARspm.pdf (accessed December 2011).
- . Summary for Policymakers. (2007). In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by S. Solomon, et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf> (accessed December 2011).
- . Summary for Policymakers. (2007). In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson. Cambridge: Cambridge University Press. pp. 7-22. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf> (accessed December 2011).
- . *The SRES Emissions Scenarios*. (2010). Available at <http://sedac.ciesin.columbia.edu/ddc/sres/> (accessed January 5, 2011).
- . *Working Group I Home*. (2011). Available at <https://www.ipcc-wg1.unibe.ch/> (accessed January 14, 2011).
- Irvine, J. R., and M. Fukuwaka. (2011). Pacific salmon abundance trends and climate change. *ICES Journal of Marine Science*. 68(6): 1122-1130. Available at <http://icesjms.oxfordjournals.org/content/68/6/1122.full> (accessed December 2011).
- ISAB, Independent Scientific Advisory Board. (2007). Climate change impacts on Columbia River Basin Fish and Wildlife. Available at <http://www.nwcouncil.org/library/isab/ISAB%202007-2%20Climate%20Change.pdf> (accessed March 15, 2011).
- ITEP, Institute for Tribal Environmental Professionals. (2011). Climate Change and the Coquille Indian Tribe: Planning for the effects of climate change and reducing greenhouse gas emissions. *Tribes and Climate Change: Tribal Profiles: Pacific Northwest*. Available at http://tribalclimate.uoregon.edu/files/2010/11/tribes_Coquille_web2.pdf (accessed April 7, 2011).
- Jamestown S'Klallam Tribe. (February 2011). Newsletter (Vol 32, Issue 2). Available at http://www.jamestowntribe.org/announce/newsletter/tribal_newsletter_2011_02.pdf (accessed April 7, 2011).
- Janetos, A., L. Hansen, D. Inouye, B. P. Kelly, L. Meyerson, W. Peterson, and R. Shaw. (2008). Biodiversity. In *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States*. Washington DC: A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. pp. 151-181. Available at <http://www.sap43.ucar.edu/documents/Biodiversity.pdf> (accessed December 2011).
- Karl, T. R., J.M. Melillo, and T. C. Peterson. (2009). *Global Climate Change Impacts in the United States*. Cambridge University Press. Available at <http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf> (accessed January 6, 2011).
- Keefer, M. L., M. L. Moser, C. T. Boggs, W. R. Daigle, and C. A. Peery. (2009). Variability in migration timing of adult Pacific lamprey (*Lampetra tridentata*) in the Columbia River, U.S.A. *Environ Biol Fish*. 85: 253-264. Available at <http://www.webpages.uidaho.edu/uiferl/pdf%20reports/pages%20from%20keefe%20et%20al.%202009%20pacific%20lamprey%20timing.pdf> (accessed December 2011).
- Kelly, B. P., T. Ainsworth, Jr., D. A. Boyce, E. Hood, P. Murphy, and J. Powell. (2007). Climate Change: Predicted impacts on Juneau. Report to: Mayor Bruce Botelho and the City and Borough of Juneau Assembly. Available at http://www.juneau.org/clerk/boards/Climate_Change/CBJ%20Climate_Report_Final.pdf (accessed March 1, 2011).

- Killam, D., A. Bui, W. C. Patzert, J. K. Willis, S. LaDochy, and P. Ramirez. (2010). California rainfall is becoming greater, with heavier storms. *22nd Conference on Climate Variability and Change*. American Meteorological Society. 4 pp. Available at https://ams.confex.com/ams/90annual/techprogram/paper_163828.htm (accessed December 2011).
- Kirwan, M. L., and G. R. Guntenspergen. (2009). Accelerated sea level rise - A response to Craft et al. *Frontiers in Ecology and the Environment*. 7(3): 126-127. Available at <http://people.virginia.edu/~mlk4n/papers/Kirwan2009FEE.pdf> (accessed December 2011).
- Kling, D., and J. N. Sanchirico. (2009). *An Adaptation Portfolio for the United States Coastal and Marine Environment*. Resources for the Future. 73 pp. Available at <http://www.rff.org/rff/documents/RFF-Rpt-Adaptation-KlingSanchirico.pdf> (accessed December 2011).
- Kopp, R. E., F. J. Simons, J. X. Mitrovica, A. C. Maloof, and M. Oppenheimer. (2009). Probabilistic assessment of sea level during the last interglacial stage. *Nature*. 462(17 December): 863-867. Available at <http://www.princeton.edu/geosciences/people/maloof/pdf/Kopp2009b.pdf> (accessed December 2011).
- Kroeker, K. J., R. L. Kordas, R. N. Crim, and G. G. Singh. (2010). Meta-analysis reveals negative yet variable effects on ocean acidification on marine organisms. *Ecology Letters*. 13: 1419-1434. Available at http://shadow.eas.gatech.edu/~kcobb/ocean_acid/Kroeker%20et%20al%202010.pdf (accessed December 2011).
- Krueger, K. L., Jr., K. B. Pierce, T. Quinn, and D. E. Penttila. (2010). Anticipated effects of sea level rise in Puget Sound on two beach-spawning fishes. Edited by H. Shipman, M. N. Dethier, G. Gelfenbaum, K. L. Fresh and R. S. Dinicola. *Puget Sound Shorelines and the Impacts of Armoring - Proceedings of a State of the Science Workshop, May 2009*. U.S. Geological Survey Scientific Investigations Report 2010-5254. pp. 171-178. Available at <http://wdfw.wa.gov/publications/01210/wdfw01210.pdf> (accessed December 2011).
- Lawler, J. J. (2009). Climate change adaptation strategies for resource management and conservation planning. *Annals of the New York Academy of Sciences (The Year in Ecology and Conservation Biology)*. 1162: 79-98. Available at http://training.fws.gov/csp/resources/climate_change/lcc/june_09/cc-adaptreview.pdf (accessed December 2011).
- Levin, L. A., W. Ekau, A. J. Gooday, F. Jorissen, J. J. Middelburg, S. W. A. Naqvi, C. Neira, N. N. Rabalais, and J. Zhang. (2009). Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences Discussions*. 6: 3563-3654. Available at <http://www.biogeosciences.net/6/2063/2009/bg-6-2063-2009.pdf> (accessed December 2011).
- Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov. (2009). Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems. *Geophysical Research Letters*. 36(L07608): 5 pp. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2008GL037155/abstract> (accessed December 2011).
- Littell, J. S., M. McGuire Elsner, L. C. Whitely Binder, and A. K. Snover. (2009). The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate - Executive Summary. In *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. Seattle, Washington: Climate Impacts Group, University of Washington. Available at <http://cses.washington.edu/db/pdf/wacciaexecsummary638.pdf> (accessed December 2011).
- Litzow, M. A. (2006). Climate regime shifts and community reorganization in the Gulf of Alaska: how do recent shifts compare with 1976/1977. *ICES Journal of Marine Science*. 63: 1386-1396. Available at <http://icesjms.oxfordjournals.org/content/63/8/1386.short> (accessed December 2011).
- Loehle, C. (2009). Cooling of the global ocean since 2003. *Energy and Environment*. 20(1&2): 99-102. Available at <http://multi-science.metapress.com/content/cw17434027026726/> (accessed December 2011).
- Logerwell, E. A., N. Mantua, P. W. Lawson, R. C. Francis, and V. N. Agostini. (2003). Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (*Oncorhynchus kisutch*) marine survival. *Fisheries Oceanography*. 12(6): 554-568. Available at <http://cses.washington.edu/cig/outreach/workshopfiles/portland2004salmon/logerwelletal2003.pdf> (accessed December 2011).
- Lueker, T. J. (2004). Coastal upwelling fluxes of O₂, N₂O, and CO₂ assessed from continuous atmospheric observations at Trinidad, CA. *Biogeosciences*. 1: 101-111. Available at <http://www.biogeosciences.net/1/101/2004/bg-1-101-2004.pdf> (accessed December 2011).
- Lyman, J. M., et al. (2010). Robust warming of the global upper ocean. *Nature*. 465(20): 334-337. Available at <http://www.nature.com/nature/journal/v465/n7296/full/nature09043.html> (accessed December 2011).

- Mach, M. E., S. Wyllie-Echeverria, and J. Rhode Ward. (2010). Distribution and potential effects of a non-native seagrass in Washington State: *Zostera japonica* workshop. Available at http://www.dnr.wa.gov/Publications/aqr_zostera_study.pdf (accessed August 16, 2011).
- Madsen, T., and E. Figdor. (2007). When it rains, it pours: Global warming and the rising frequency of extreme participation in the United States. Environment America. Available at <http://www.environmentamerica.org/sites/environment/files/reports/When-It-Rains-It-Pours---US---WEB.pdf> (accessed December 2011).
- Mantua, N. J., and S. R. Hare. (2002). The Pacific Decadal Oscillation. *Journal of Oceanography*. 58(1): 35-44. Available at <http://www.terrapub.co.jp/journals/JO/pdf/5801/58010035.pdf> (accessed December 2011).
- Mantua, N., I. Tohver, and A. Hamlet. (2010). Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change*. 102: 187-223. Available at <http://link.springer.com/article/10.1007%2Fs10584-010-9845-2?LI=true> (accessed December 2011).
- Martin, J., and P. Glick. (2008). *A great wave rising: solutions for Columbia and Snake River salmon in the age of global warming*. Light in the River. 28 pp. Available at <http://www.nwf.org/~media/PDFs/Global-Warming/Reports/AGreatWaveRising.pdf?dmc=1&ts=20130329T2115354375> (accessed December 2011).
- Mawdsley, J. R., R. O. O'Malley, and D. S. Ojima. (2009). A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology*. 23(5): 1080-1089. Available at [http://nctc.fws.gov/courses/climatechange/climateacademy/documents/Mawdsley_et_al_2009%20\(2\).pdf](http://nctc.fws.gov/courses/climatechange/climateacademy/documents/Mawdsley_et_al_2009%20(2).pdf) (accessed December 2011).
- MBARI, Monterey Bay Aquarium Research Institute. *Upwelling*. (2010). Available at <http://www.mbari.org/chemosensor/n/upwelling.html> (accessed December 15, 2010).
- McLeod, E., B. Poulter, J. Hinkel, E. Reyes, R. Salm. (2010). Sea level rise impact models and environmental conservation: A review of models and their applications. *Ocean & Coastal Management*. 53: 507-517. Available at <http://www.sciencedirect.com/science/article/pii/S0964569110000852> (accessed December 2011).
- Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z-C. Zhao, et al.. (2007). Global Climate Projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by S. Solomon, et al. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter10.pdf> (accessed December 2011).
- Meehl, G. A., W. M. Washington, W. D. Collins, J. M. Arblaster, A. Hu, L. E. Buja, W. G. Strand, and H. Teng. (2005). How much more global warming and sea level rise? *Science*. 307(18 March): 1769-1772. Available at <http://www.geo.utexas.edu/courses/387h/PAPERS/meehl2005.pdf> (accessed December 2011).
- Menge, B. A., F. Chan, K. J. Nielsen, E. di Lorenzo, and J. Lubchenco. (2009). Climatic variation alters supply-side ecology: impact of climate patterns on phytoplankton and mussel recruitment. *Ecological Monographs*. 79(3): 379-395. Available at https://www.sonoma.edu/users/n/nielseka/pubications/Menge_et_al_2009_EcolMono_79.pdf (accessed December 2011).
- Merenlender, A. M., L. Huntsinger, G. Guthey, and S. K. Fairfax. (2004). Land trusts and conservation easements: Who is conserving what for whom? *Conservation Biology*. 18(1): 65-75. Available at <http://ucanr.org/sites/merenlender/files/143679.pdf> (accessed December 2011).
- Merryfield, W. J., B. Pal, and M. G. G. Foreman. (2009). Projected future changes in surface marine winds off the west coast of Canada. *Journal of Geophysical Research Letters*. 114: 10. Available at http://www.ccma.ec.gc.ca/papers/bmerryfield/PDF/Merryfield_et_al_JGR_2009.pdf (accessed December 2011).
- Morrison, J., M. C. Quick, and M. G.G. Foreman. (2002). Climate change in the Fraser River watershed: flow and temperature projections. *Journal of Hydrology*. 263: 230-244. Available at <http://www.cohencommission.ca/en/pdf/InterimReport/Responses/Report%20025/025%20-%20Morrison%20et.%20al%200202.pdf> (accessed December 2011).
- Moser, S., G. Franco, S. Pittiglio, W. Chou, and D. Cayan. (2009). The future is now: An update on climate change science impacts and response options for California. *2008 Climate Change Impacts Assessment: Second Biennial Science Report to the California Climate*

- Action Team. Available at <http://www.energy.ca.gov/2008publications/CEC-500-2008-071/CEC-500-2008-071.PDF> (accessed January 6, 2011).
- Mote, P. W. (2003). Trends in temperature and precipitation in the Pacific Northwest during the Twentieth Century. *Northwest Science*. 77(4): 271-282. Available at <http://research.wsulibs.wsu.edu/xmlui/bitstream/handle/2376/1032/v77%20p271%20Mote.PDF?sequence=1> (accessed December 2011).
- Mote, P. W., and E.P. Salathe Jr. (2010). Future climate in the Pacific Northwest. *Climatic Change*. 102(1-2): 29-50. Available at http://www.atmos.washington.edu/~salathe/papers/published/Mote_Salathe_2010.pdf (accessed December 2011).
- Mote, P. W., and N. J. Mantua. (2002). Coastal upwelling in a warmer future. *Geophysical Research Letters*. 29(23): 2138. Available at http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/18704/Mote_and_Mantua_Geophys_Res_Lett_2002.pdf?sequence=1 (accessed December 2011).
- Mote, P. W., D. Gavin, and A. Huyer. (2010). Climate change in Oregon's land and marine environments. In *Oregon Climate Assessment Report*. Edited by K. D. Dello and P. W. Mote. Corvallis, OR: College of Oceanic and Atmospheric Sciences, Oregon State University. Available at <http://occri.net/wp-content/uploads/2011/04/chapter1ocar.pdf> (accessed December 2011).
- Mote, P. W., E. A. Parson, A. F. Hamlet, W. S. Keeton, D. Lettenmaier, N. Mantua, E. L. Miles, D. W. Peterson, D. L. Peterson, R. Slaughter, and A. K. Snover. (2003). Preparing for climatic change: the water, salmon and forests of the Pacific Northwest. *Climatic Change*. 61(1-2): 45-88. Available at <http://link.springer.com/article/10.1023/A%3A1026302914358> (accessed December 2011).
- Mote, P., A. Petersen, S. Reeder, H. Shipman, and L. Whitely Binder. (2008). *Sea level rise in the coastal waters of Washington State*. Seattle & Olympia: University of Washington Climate Impacts Group & Washington State Department of Ecology. 11 pp. Available at <http://cses.washington.edu/db/pdf/moteetalslr579.pdf> (accessed December 2011).
- Mumford, T. F. (2007). *Kelp and eelgrass in Puget Sound*. Puget Sound Nearshore Partnership Report No. 2007-05. Technical Report 2007-5, Seattle, Washington: Seattle District, U.S. Army Corps of Engineers. 37 pp. Available at http://www.pugetsoundnearshore.org/technical_papers/kelp.pdf (accessed December 2011).
- NABCI, United States Committee North American Bird Conservation Initiative. (2010). *The State of the Birds 2010 Report on Climate Change, United States of America*. Washington, DC: U.S. Department of Interior. 32 pp. Available at <http://www.stateofthebirds.org/2010> (accessed December 2011).
- Najjar, R. G., H. A. Walker, P. J. Anderson, E. J. Barron, R. J. Bord, J. R. Gibson, V. S. Kennedy, C. G. Knight, J. P. Megonigal, R. E. O'Connor, C. D. Polsky, N. P. Psuty, B. A. Richards, L. G. Sorenson, E. M. Steele, and R. S. Swanson. (2000). The potential impacts of climate change on the mid-Atlantic coastal region. *Climate Research*. 14: 219-233. Available at <http://www.int-res.com/articles/cr/14/c014p219.pdf> (accessed December 2011).
- NAS, National Academy of Sciences. (2009). Ecological impacts of climate change. Available at http://dels-old.nas.edu/dels/rpt_briefs/ecological_impacts.pdf (accessed December 14, 2010).
- NASA, National Aeronautics and Space Administration. *GLOBAL Land-Ocean Temperature Index in 0.01 degrees Celsius (base period: 1951-1980)*. 2010. Available at <http://data.giss.nasa.gov/gistemp/tabledata/GLB.Ts+dSST.txt> (accessed December 10, 2010).
- . *Moody Pacific Unleashes Another Climate Mystery*. (April 15, 2004). Available at <http://www.nasa.gov/vision/earth/environment/PDO.html> (accessed January 17, 2011).
- Neal, E. G., E. Hood, and K. Smikrud. (2010). Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska. *Geophysical Research Letters*. 37(L06404): 1-5. Available at http://www.uas.alaska.edu/arts_sciences/naturalsciences/envs/faculty_staff/pubs/nealetal_glacier_runoff_grl_2010.pdf (accessed December 2011).
- Nicholls, R. J., P. P. Wong, V. Burkett, J. Codignotto, J. Hay, R. McLean, S. Ragoonaden, and C. D. Woodroffe. (2007). Coastal systems and low-lying areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson. Cambridge, UK: Cambridge University Press. pp. 315-356. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter6.pdf> (accessed December 2011).

- Nicholls, R. J., and A. Cazenave. (2010). Sea level rise and its impact on coastal zones. *Science*. 328: 517-1520. Available at <http://www.sciencemag.org/content/328/5985/1517.abstract> (accessed December 2011).
- NIST, National Institute of Standards and Technology. *International System of Units (SI): SI base units*. Available at <http://physics.nist.gov/cuu/Units/units.html> (accessed January 17, 2011).
- NOAA, National Oceanic and Atmospheric Administration. (2010). *Adapting to Climate Change: A Planning Guide for State Coastal Managers*. NOAA Office of Ocean and Coastal Resource Management. Available at <http://coastalmanagement.noaa.gov/climate/adaptation.html> (accessed December 2011).
- . *California Current: LME #3*. (2009). Available at http://www.lme.noaa.gov/index.php?option=com_content&view=article&id=49:lme3&catid=41:briefs&Itemid=72 (accessed August 9, 2011).
- . *Gulf of Alaska: LME #2*. (2009). Available at http://www.lme.noaa.gov/index.php?option=com_content&view=article&id=48:lme2&catid=41:briefs&Itemid=72 (accessed August 9, 2011).
- . *Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr*. 2007. Available at <http://tidesandcurrents.noaa.gov/sltrends/msltrendstable.htm> (accessed November 24, 2010).
- . *Living Shoreline Planning and Implementation*. (2011). Available at <http://www.habitat.noaa.gov/restoration/techniques/limplementation.html> (accessed April 14, 2011).
- . *Salmon Life Cycle (image)*. Available at http://www.swr.noaa.gov/recovery/life_cycle.gif (accessed December 14, 2010).
- . *Shoreline Boundaries Diagram*. FGDC Marine Boundary Working Group. Available at http://www.csc.noaa.gov/mbwg/_pdf/products/Shoreline31.pdf (accessed December 10, 2010).
- . *State of the Climate Global Analysis 2010*. (January 14, 2011). Available at <http://lwf.ncdc.noaa.gov/sotc/global/2010/13> (accessed March 16, 2011).
- . *Tides and Currents: Sea Level Trends*. (2010). Available at <http://tidesandcurrents.noaa.gov/sltrends/sltrends.html> (accessed November 24, 2010).
- . *Trends in Atmospheric Carbon Dioxide: Global*. (2011). Available at <http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html> (accessed March 16, 2011).
- . *Upper Ocean Thermal Center: The Expendable Bathythermograph (XBT)*. (2011). Available at <http://www.aoml.noaa.gov/goos/uot/xbt-what-is.php> (accessed August 10, 2011).
- OCCRI, Oregon Climate Change Research Institute. (2010). Oregon Climate Assessment Report (OCAR). Edited by K. D. Dello and P. W. Mote. Corvallis, OR: College of Oceanic and Atmospheric Sciences, Oregon State University. Available at <http://occri.net/ocar> (accessed December 2011).
- OCMP, Oregon Coastal Management Program. (2009). *Climate Ready Communities: A Strategy for Adapting to Impacts of Climate Change on the Oregon Coast (pdf)*. Oregon Department of Land Conservation and Development OR-DLCD. Available at http://www.oregon.gov/ENERGY/GBLWRM/docs/climate_ready_communities.pdf?ga=t (accessed December 15, 2010).
- Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R. G. Najjar, G-K. Plattner, K. B. Rodgers, C. L. Sabine, J. L. Sarmiento, R. Schlitzer, R. D. Slater, I. J. Totterdell, M-F. Weirig, Y. Yamanaka, and A. Yool. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*. 437: 681-686. Available at <http://www.nature.com/nature/journal/v437/n7059/full/nature04095.html> (accessed December 2011).
- Osgood, K. E. (Ed.). (2008). *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs*. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS-F/SPO-89. 118 pp. Available at <http://spo.nmfs.noaa.gov/tm/TM%20SPO%2089.pdf> (accessed December 2011).

- Otto-Bliesner, B. L., S. J. Marshall, J. T. Overpeck, G. H. Miller, A. Hu, and CAPE Last Interglacial Project members. (2006). Simulating Arctic climate warmth and icefield retreat in the last interglaciation. *Science*. 311: 1751-1753. Available at <http://www.sciencemag.org/content/311/5768/1751.abstract> (accessed December 2011).
- Overland, J. E., and M. Wang. (2007). Future climate of the North Pacific Ocean. *Eos*. 88(16): 178,182. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2007EO160003/abstract> (accessed December 2011).
- Overpeck, J. T., B. L. Otto-Bliesner, G. H. Miller, D. R. Muhs, R. B. Alley, and J. T. Kiehl. (2006). Paleoclimatic evidence for future ice-sheet instability and rapid sea level rise. *Science*. 311: 1747-1750. Available at <http://www.sciencemag.org/content/311/5768/1747.abstract> (accessed December 2011).
- Palacios, D. M., S. J. Bograd, R. Mendelssohn, and F. B. Schwing. (2004). Long-term and seasonal trends in stratification in the California Current, 1950-1993. *Journal of Geophysical Research*. 109 (C10016): 1-12. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2004JC002380/abstract> (accessed December 2011).
- Palacios, S. L., and R. C. Zimmerman. (2007). Response of eelgrass *Zostera marina* to CO₂ enrichment: possible impacts of climate change and potential for remediation of coastal habitats. *Marine Ecology Progress Series*. 344: 1-13. Available at <http://www.int-res.com/articles/feature/m344p001.pdf> (accessed December 2011).
- Papiez, C.. (2009). Climate Change Implications for the Quileute and Hoh Tribes. *The Evergreen State College: Environmental Studies/Natural Resources Case Subject*. Available at http://www.evergreen.edu/tribal/docs/Papiez%20Climate%20Change_Case%20Study%20Nov%208%202009.pdf (accessed April 7, 2011).
- Parks Canada. (2010). *Kluane National Park and Preserve of Canada Management Plan*. Available at <http://www.pc.gc.ca/eng/pn-np/yt/kluane/plan.aspx> (accessed December 2011).
- . *The Climate is Changing Our National Parks: Impacts on Pacific Parks*. April 15, 2009. Available at <http://www.pc.gc.ca/docs/v-g/ie-ei/cc/repercussions-impacts6.aspx> (accessed August 4, 2011).
- Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. (2007). Appendix I. Glossary. In *Climate Change 2007: Impacts, Adaptation, Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. pp. 869-883. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-app.pdf> (accessed December 2011).
- PAWG, Preparation and Adaptation Working Group. (2008). *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*. Olympia, WA: Washington State Department of Ecology. 84 pp. Available at <https://fortress.wa.gov/ecy/publications/publications/0801008c.pdf> (accessed December 2011).
- Peterson, G. D., G. S. Cumming, and S. R. Carpenter. (2003). Scenario planning: a tool for conservation in an uncertain world. *Conservation Biology*. 17(2): 358-366. Available at <http://www.cakex.org/virtual-library/3420> (accessed December 2011).
- Peterson, W. and F. Schwing. (2008). California Current Ecosystem. In *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs*. Edited by K. E. Osgood. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS-F/SPO-89. pp 44-63. Available at <http://spo.nmfs.noaa.gov/tm/TM%20SPO%2089.pdf> (accessed December 2011).
- Peterson, W. T., R. C. Hooff, C. A. Morgan, K. L. Hunter, E. Casillas, and J. W. Ferguson. (2006). Ocean conditions and salmon survival in the northern California Current. NOAA Fisheries Report. 52 pp. Available at <http://www.nwfsc.noaa.gov/research/divisions/fed/ecosysrep.pdf> (accessed December 2011).
- Pew Center on Global Climate Change. (2011). *The Greenhouse Effect*. Available at http://www.pewclimate.org/global-warming-basics/facts_and_figures/greenhouse.cfm (accessed March 16, 2011).
- Pew Center on Global Climate Change and Pew Center on the States. (2009). Climate Change 101: Understanding and Responding to Global Climate Change: Adaptation. Available at <http://www.pewclimate.org/docUploads/Climate101-Complete-Jan09.pdf> (accessed August 15, 2011).
- Philip Williams & Associates, Ltd. (March 11, 2009). California Coastal Erosion Response to Sea Level Rise - Analysis and Mapping. Available at <http://www.pwa-ltd.com/about/news-CoastalErosion/PWA OPC Methods final.pdf> (accessed June 10, 2011).

- Pierce, D. W. (2004). Future changes in biological activity in the North Pacific due to anthropogenic forcing of the physical environment. *Climatic Change*. 62: 389-418. Available at <http://cmbc.ucsd.edu/content/1/docs/pierce%20future.pdf> (accessed December 2011).
- Pike, R. G., K. E. Bennett, T. E. Redding, A. T. Werner, D. L. Spittlehouse, R. D. Moore, T. Q. Murdock, J. Beckers, B. D. Smerdon, K. D. Bladon, V. N. Foord, D. A. Campbell, and P. J. Tschaplinski. (2010). Climate Change Effects on Watershed Processes in British Columbia. In *Compendium of forest hydrology and geomorphology in British Columbia*. Edited by R. G. Pike, T. E. Redding, R. D. Moore, R. D. Winker and K. D. Bladon. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Manag. Handb. pp. 699-747. Available at http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66/Lmh66_ch19.pdf (accessed December 2011).
- PISCO, Partnership for Interdisciplinary Studies of Coastal Oceans. (2009). Hypoxia off the Pacific Northwest Coast. Corvallis: PISCO, Oregon State University. 2 pp. Available at http://www.piscoweb.org/files/hypoxia_general%20low-res.pdf (accessed December 2011).
- PRBO Conservation Science. (2011). Projected effects of climate change in California: Ecoregional summaries emphasizing consequences for wildlife. Version 1.0. Available at <http://data.prbo.org/apps/bssc/uploads/Ecoregional021011.pdf> (accessed March 1, 2011).
- PSNERP, Puget Sound Nearshore Ecosystem Restoration Project. (2010). *About the Nearshore Project*. Available at <http://www.pugetsoundnearshore.org/what.htm> (accessed December 22, 2010).
- PSNP, Puget Sound Nearshore Project. (August 2003). *Guidance for Protection and Restoration of Nearshore Ecosystems of Puget Sound*. Available at <http://www.pugetsoundnearshore.org/whatwedo/Guidance.pdf> (accessed December 11, 2010).
- PSWQAT, Puget Sound Water Quality Action Team. (October 2001). Sound Facts: Eelgrass. *Puget Sound Partnership Resource Center: Publications*. Available at http://www.psparchives.com/publications/our_work/misc/Fact_sheets/eelgrass.pdf (accessed April 13, 2011).
- Rahmstorf, S. (2007). A semi-empirical approach to projecting future sea level rise. *Science*. 315 (19): 368-370. Available at http://www.pik-potsdam.de/~stefan/Publications/Nature/rahmstorf_science_2007.pdf (accessed December 2011).
- Rahmstorf, S. (2003). The current climate. *Nature*. 421: 699. Available at http://www.pik-potsdam.de/~stefan/Publications/Nature/nature_concept_03.pdf (accessed December 2011).
- Raupach, M. R., G. Marland, P. Ciais, C. Le Quééré, J. G. Canadell, G. Klepper, and C. B. Field. (2007). Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National Academy of Science* 104(24): 10288-10293. Available at <http://www.pnas.org/content/104/24/10288.full.pdf+html> (accessed December 2011).
- RCS, Ramsar Convention Secretariat. (2007). Coastal management: Wetland issues in Integrated Coastal Zone Management. Available at http://www.ramsar.org/pdf/lib/lib_handbooks2006_e10.pdf (accessed April 14, 2011).
- Reed, T. E., P. Warzybok, A. J. Wilson, R. W. Bradley, S. Wanless, and W. J. Sydeman. (2009). Timing is everything: flexible phenology and shifting selection in a colonial seabird. *Journal of Animal Ecology* 78: 376-387. Available at <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2656.2008.01503.x/pdf> (accessed December 2011).
- Ries, J. B., A. L. Cohen, and D. C. McCorkle. (2009). Marine calcifiers exhibit mixed responses to CO₂-induced ocean acidification. *Geology*. 37(12): 1131-1134. Available at <http://geology.gsapubs.org/content/37/12/1131.full.pdf+html> (accessed December 2011).
- Rignot, E., and P. Kanagaratnam. (2006). Changes in the velocity structure of the Greenland Ice Sheet. *Science*. 311 (5763): 986-990. Available at <http://www.sciencemag.org/content/311/5763/986.short> (accessed December 2011).
- Rogers-Bennett, L., R. F. Dondanville, J. D. Moore, and L. I. Vilchis. (2010). Response of red abalone production to warm water, starvation, and dis ease stressors: implications of ocean warming. *Journal of Shellfish Research*. 29 (3): 599-611. Available at http://www.vetmed.ucdavis.edu/whc/about/bennett_pdfs/Rogers-Bennett-Red-Ab-2010.pdf (accessed December 2011).
- Rost, B., I. Zondervan, and D. Wolf-Gladrow. (2008). Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions. *Marine Ecology Progress Series*. 373: 227-237. Available at <http://www.int-res.com/articles/theme/m373p227.pdf> (accessed December 2011).

- Ruggiero, P., C. A. Brown, P. D. Komar, J. C. Allan, D. A. Reusser, and H. Lee II. (2010). Impacts of climate change on Oregon's coasts and estuaries. In *Oregon Climate Assessment Report*. Edited by K. D. Dello and P. W. Mote. Corvallis, OR: College of Oceanic and Atmospheric Sciences, Oregon State University. pp. 209-267. Available at <http://occri.net/wp-content/uploads/2011/04/chapter6ocar.pdf> (accessed December 2011).
- Ruggiero, P., P. D. Komar, and J. C. Allan. (2010). Increasing wave heights and extreme value projections: the wave climate of the U.S. Pacific Northwest. *Coastal Engineering*, 57(5): 539-552. doi: 10.1016/j.coastaleng.2009.12.005. Available at <http://www.sciencedirect.com/science/article/pii/S0378383909002142> (accessed December 2011).
- Rykaczewski, R. R. and J. P. Dunne. (2010). Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model. *Geophysical Research Letters*, 37 (L21606): 5 pp. Available at http://www.gfdl.noaa.gov/cms-filessystem-action/user_files/rrr/rykaczewski_dunne_grl_2010_wsupp.pdf (accessed December 2011).
- Sabine, C. L., R. A. Feely, N. Gruber, R. M. Key, K. Lee, J. L. Bullister, R. Wanninkhof, C. S. Wong, D. W. R. Wallace, B. Tilbrook, F. J. Millero, T-H. Peng, A. Kozyr, T. Ono, and A. F. Rios. (2004). The oceanic sink for anthropogenic CO₂. *Science*, 305(16): 367-371. Available at <http://www.sciencemag.org/content/305/5682/367.short> (accessed December 2011).
- Salathé Jr., E. P., L. R. Leung, Y. Qian, and Y. Zhang. (2010). Regional climate model projections for the State of Washington. *Climatic Change*, 102(1-2): 51-75. Available at http://www.atmos.washington.edu/~salathe/papers/full/Salathe_2010.pdf (accessed December 2011).
- Sanford, E.. (2002). Community responses to climate change: links between temperature and keystone predation in a rocky intertidal system. In *Wildlife Responses to Climate Change: North American Case Studies*. Edited by Stephen H. Schneider and Terry L. Root, pp. 165-200. Washington, DC: Island Press. Available at http://books.google.com/books/about/Wildlife_Responses_to_Climate_Change.html?id=auNVTJ6cePOC (accessed December 2011).
- Sarkar, N., T. C. Royer, and C. E. Grosch. (2005). Hydrographic and mixed layer depth variability on the shelf in the northern Gulf of Alaska, 1974-1998. *Continental Shelf Research*, 25: 2147-2162. Available at <http://www.sciencedirect.com/science/article/pii/S0278434305001615> (accessed December 2011).
- Sarmiento, J. L., R. Slater, R. Barber, L. Bopp, S. C. Doney, A. C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, V. Soldatov, S. A. Spall, and R. Stouffer. (2004). Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles*, 18: 23. Available at <https://darchive.mblwhoilibrary.org/bitstream/handle/1912/3392/2003GB002134.pdf?sequence=1> (accessed December 2011).
- Schultz, C. and E. Tretkoff. (May 2011). Research Spotlights. *Eos*, 92 (18): 160-162. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2011EO180020/pdf> (accessed December 2011).
- Sigler, M. F., R. J. Foy, J. W. Short, M. Dalton, L. B. Eisner, T. P. Hurst, J. F. Morado, and R. P. Stone. (2008). *Forecast fish, shellfish and coral population responses to ocean acidification in the north Pacific Ocean and Bering Sea: An ocean acidification research plan for the Alaska Fisheries Science Center*. AFSC Processed Rep. 2008-07, 17109 Point Lena Loop Road, Juneau AK 99801: Alaska Fisheries Science Center, NOAA, National Marine Fisheries Service. 35 pp. Available at <http://www.afsc.noaa.gov/Publications/ProcRpt/PR2008-07.pdf> (accessed December 2011).
- Sigler, M., J. Napp, and A. Hollowed. (2008). Alaska Ecosystem Complex. In *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs*. Edited by K. E. Osgood. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS-F/SPO-89. pp. 64-75. Available at <http://spo.nmfs.noaa.gov/tm/TM%20SPO%2089.pdf> (accessed December 2011).
- Snover, A. K., P. W. Mote, L. Whitely Binder, A. F. Hamlet, and N. J. Mantua. (2005). Uncertain Future: Climate Change and its Effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group (Center for Science in the Earth System, Joint Insititute for the Study of the Atmosphere and Oceans)." Seattle: University of Washington. Available at <http://cses.washington.edu/cig/outreach/files/psat1005.shtml> (accessed December 2011).
- Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell. (2003). Future climate change and upwelling in the California Current. *Geophysical Research Letters*, 30(15): 1-4. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2003GL017647/abstract> (accessed December 2011).

- Somero, G. N. (2010). The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers'. *The Journal of Experimental Biology*. 213: 912-920. Available at <http://jeb.biologists.org/content/213/6/912.abstract> (accessed December 2011).
- Sorte, C. J. B., S. L. Williams, and R. A. Zerebecki. (2010). Ocean warming increases threat of invasive species in a marine fouling community. *Ecology*. 91(8): 2198-2204. Available at http://cascadesorte.org/wp-content/uploads/2011/09/Sorteetal2010_Ecology.pdf (accessed December 2011).
- Spear, L. B., and D. G. Ainley. (1999). Migration routes of sooty shearwaters in the Pacific Ocean. *The Condor*. 101(2): 205-218. Available at <http://www.jstor.org/discover/10.2307/1369984?uid=3739960&uid=2&uid=4&uid=3739256&sid=21102022752091> (accessed December 2011).
- Stafford, J. M., G. Wendler, and J. Curtis. (2000). Temperature and precipitation of Alaska: 50 year trend analysis. *Theoretical and Applied Climatology*. 67: 33-44. Available at <http://climate.gi.alaska.edu/researchprojects/Stafford2000.pdf> (accessed December 2011).
- State of Oregon. (2010). The Oregon Climate Change Adaptation Framework. Available at http://www.oregon.gov/LCD/docs/ClimateChange/Framework_Final.pdf?ga=t (accessed January 13, 2010).
- Steinacher, M., F. Joos, T. L. Frölicher, L. Bopp, P. Cadule, V. Cocco, S. C. Doney, M. Gehlen, K. Lindsay, J. K. Moore, B. Schneider, and J. Segschneider. (2010). Projected 21st century decrease in marine productivity: a multi-model analysis. *Biogeosciences*. 7: 979-1005. Available at <http://www.biogeosciences.net/7/979/2010/bg-7-979-2010.pdf> (accessed December 2011).
- Stewart, I. T. (2009). Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*. 23: 78-94. Available at <http://onlinelibrary.wiley.com/doi/10.1002/hyp.7128/abstract?deniedAccessCustomisedMessage=&userIsAuthenticated=false> (accessed December 2011).
- Stewart, I. T., D. R. Cayan, and M. D. Dettinger. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*. 18: 1136-1155. Available at http://tenaya.ucsd.edu/~dettinge/stewart_timing.pdf (accessed December 2011).
- Swinomish Indian Tribal Community. (October 2010). Swinomish Climate Change Initiative: Climate Adaptation Action Plan. *Swinomish Climate Change Initiative*. Office of Planning and Community Development: La Conner, WA. 144 pp. Available at http://www.swinomish-nsn.gov/climate_change/Docs/SITC_CC_AdaptationActionPlan_complete.pdf (accessed March 8, 2011).
- TAG, WA Department of Ecology Topic Advisory Groups. *Integrated Climate Change Response Plan: Draft Topic Advisory Group Work Plan*. November 3, 2009. Unpublished document.
- Tallis, H. M. (2006). Japanese Eelgrass. In *Invasive Species in the Pacific Northwest*, by P. Dee Boersma and Amy N. Van Buren, 26-27. Seattle, WA: University of Washington Press. Available at <http://www.washington.edu/uwpress/search/books/BOEINV.html> (accessed December 2011).
- The Wildlife Society. (2004). *Global climate change and wildlife in North America: Technical review 04-2*. Technical Review, Bethesda: The Wildlife Society. 34 pp. Available at <https://store.wildlife.org/ScriptContent/TechnicalReviews/> (accessed December 2011).
- Thom, R. M., A. B. Borde, S. Rumrill, D. L. Woodruff, G. D. Williams, J. A. Southard, and S. L. Sargeant. (2003). Factors influencing spatial and annual variability in eelgrass (*Zostera marina* L.) meadows in Willapa Bay, Washington and Coos Bay, Oregon, *Estuaries*. 26(4B): 1117-1129. Available at <http://www.jstor.org/discover/10.2307/1353389?uid=3739960&uid=2134&uid=2&uid=70&uid=4&uid=3739256&sid=21102022752091> (accessed December 2011).
- Thomas, R., E. Rignot, G. Casassa, P. Kanagaratnam, C. Acuña, T. Akins, H. Brecher, E. Frederick, P. Gogineni, W. Krabill, S. Manizade, H. Ramamoorthy, A. Rivera, R. Russell, J. Sonntag, R. Swift, J. Yungel, and J. Zwally. (2004). Accelerated sea level rise from West Antarctica. *Science*. 306(8): 255-258. Available at <http://www.captura.uchile.cl/bitstream/handle/2250/1934/Thomas%20R.pdf?sequence=1> (accessed December 2011).
- Tohver, I., and A. F. Hamlet. (2010). Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. 21 pp. Available at http://www.hydro.washington.edu/2860/products/sites/r7climate/study_report/CBCCSP_chap7_extremes_final.pdf (accessed August 15, 2011).

- Tokay, A. (2009). *Chapter 13: Mid-latitude cyclones*. Available at <http://userpages.umbc.edu/~tokay/chapter13new.html> (accessed January 18, 2011).
- Trenberth, K.E., P. D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. K. Tank, D. Parker, F. Rahimzadeh, J. A. Renwick, M. Rusticucci, B. Soden, P. Zhai, et al. (2007). Observations: Surface and Atmospheric Climate Change. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental panel on Climate Change*. Edited by S. Solomon, et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. pp. Available at <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter3.pdf> (accessed December 2011).
- Trenberth, K. E., A. Dai, R. M. Rasmussen, and D. B. Parsons. (2003). The changing character of precipitation. *Bulletin of the American Meteorological Society* September 2003: 1205-1217. Available at http://portal.iri.columbia.edu/~alesall/ouagaCILSS/articles/trenberth_bams2003.pdf (accessed December 2011).
- Tulalip Tribes. (2006). *Climate Change Impacts on Tribal Resources*. Available at <http://www.tulalip.nsn.us/pdf.docs/FINAL%20CC%20FLYER.pdf> (accessed April 7, 2011).
- . *The Tulalip Spartina Control Project: 1998 Annual Report*. July 16, 2002. Available at <http://www.tulalip.nsn.us/htmldocs/spartinacontrolproject.htm> (accessed April 13, 2011).
- UK Royal Society. (2005). Ocean acidification due to increasing atmospheric carbon dioxide. Policy Document 12/05. The Royal Society. 68 pp. Available at http://dgs.stanford.edu/labs/caldeiralab/Caldeira%20downloads/RoyalSociety_OceanAcidification.pdf (accessed December 2011).
- UCAR, Univeristy Corporation for Atmospheric Research. (2010). *Community Earth System Model: About CESM 1.0*. (2010). Available at <http://www.cesm.ucar.edu/models/cesm1.0/> (accessed December 10, 2010).
- . *Community Earth Systems Model*. (2010). Available at <http://www.cesm.ucar.edu/models/> (accessed December 10, 2010).
- . *The Community Earth System Model: NCAR's latest step in the quest to model Earth's climate*. October 4, 2010. Available at <http://www2.ucar.edu/staffnotes/news/2746/community-earth-system-model> (accessed December 10, 2010).
- USAID, United States Agency for International Development. (2009). *Adapting to coastal climate change: A guidebook for development planners*. USAID. 148 pp. Available at <http://www.crc.uri.edu/download/CoastalAdaptationGuide.pdf> (accessed December 2011).
- USEPA, United States Environmental Protection Agency. (2009). *Adaptation Planning for the National Estuary Program*. U.S. Environmental Protection Agency. 19 pp. Available at <http://water.epa.gov/type/oceb/cre/upload/CREAdaptationPlanning-Final.pdf> (accessed December 2011).
- . *Environmental Justice Grant Recipients in the Pacific Southwest: Yurok Tribe Project*. March 24, 2011. Available at <http://www.epa.gov/region9/ej/ej-grants-projects.html> (accessed April 7, 2011).
- . National Estuary Program Coastal Condition Report. In *Chapter 6: West Coast National Estuary Program Coastal Condition, Puget Sound Action Team*. (2007). USEPA. 322-332. Available at http://water.epa.gov/type/oceb/nep/upload/2007_05_09_oceans_nepccr_pdf_nepccr_nepccr_west_partb.pdf (accessed December 2011).
- USFWS, U.S. Fish and Wildlife Service. (2010). *Landscape Conservation Cooperatives: Better Conservation through Partnerships in the Pacific Region*. Fact Sheet. 4 pp.
- . North Pacific Landscape Conservation Cooperative. (August 2010). 2 pp.
- . *North Pacific Landscape Conservation Cooperative High Resolution Map*. (2010). Available at <http://www.fws.gov/pacific/climatechange/pdf/NPLCCMap.pdf> (accessed December 15, 2010).
- . *Pacific Lamprey (Lampara tridentata) Draft Assessment and Template for Conservation Measures*. (2010). Portland, OR: U.S. Fish and Wildlife Service. 276 pp.
- . *Rising to the urgent challenge: strategic plan for responding to accelerating climate change*. In *Conservation in a Changing Climate: Climate Change Strategy*. (September 2010). Available at <http://www.fws.gov/home/climatechange/pdf/CCStrategicPlan.pdf> (accessed March 8, 2011).

- US-GCRP, US Global Change Research Program. (2009). Global Climate Change Impacts in the United States. *U.S. Global Change Research Program*. Edited by T. R. Karl, J. M. Melillo and T. C. Peterson. June 16, 2009. Available at <http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf> (accessed November 29, 2010).
- Vaquer-Sunyer, R., and C. M. Duarte. (2008). Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences* 105(40): 15452-15457. Available at <http://www.pnas.org/content/early/2008/09/26/0803833105.full.pdf+html> (accessed December 2011).
- Vermeer, M., and S. Rahmstorf. (2009). Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences* 106(51): 21527-21532. Available at <http://www.pnas.org/content/early/2009/12/04/0907765106.full.pdf+html> (accessed December 2011).
- Vincent, L. A., and É. Mekis. (2006). Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Atmosphere-Ocean*. 44(2): 177-193. Available at <http://www.tandfonline.com/doi/pdf/10.3137/ao.440205> (accessed December 2011).
- WA-DNR, WA Department of Natural Resources. (December 2007). Eelgrass Stressor-Response Project: 2005-2007 Report. Available at http://www.dnr.wa.gov/Publications/aqr_nrsh_05_07_biennial_report.pdf (accessed August 16, 2011).
- WA-ECY, Washington State Department of Ecology. (2009). Integrated Climate Change Response Plan: Draft Topic Advisory Group Work Plan. *Unpublished report*.
- . *Offshore Fault*. (2011). Available at <http://www.ecy.wa.gov/programs/sea/coast/waves/fault.html> (accessed January 17, 2011).
- . *Preparing for impacts: adapting to climate change*. (2011). Available at <http://www.ecy.wa.gov/climatechange/adaptation.htm> (accessed January 13, 2011).
- . *Topic Advisory Groups*. (2011). Available at <http://www.ecy.wa.gov/climatechange/2010TAG.htm> (accessed January 13, 2011).
- Wall, D. (2009). Indigenous Perspectives on Climate Change. *Tribes and Climate Change: Tribal Profiles: Traditional Knowledge*. Available at http://www4.nau.edu/tribalclimatechange/tribes/docs/tribes_IndigenousPers.pdf (accessed April 7, 2011).
- Wang, M., J. E. Overland, and N. A. Bond. (2010). Climate projections for selected large marine ecosystems. *Journal of Marine Systems*. 79: 258-266. Available at <http://www.sciencedirect.com/science/article/pii/S0924796309000839> (accessed December 2011).
- Ward, D. H., A. Reed, J. S. Sedinger, J. M. Black, D. V. Derksen, and P. M. Castelli. (2005). North American Brant: effects of changes in habitat and climate on population dynamics. *Global Change Biology*. 11: 869-880. Available at <http://www.humboldt.edu/wildlife/faculty/black/pdf/Ward%20et%20al.%202005%20GlobChBio.pdf> (accessed December 2011).
- Warren Pinnacle Consulting, Inc. (2010a). SLAMM Overview Powerpoint. *SLAMM: Sea Level Affecting Marshes Model*. December 23, 2010. Available at <http://warrenpinnacle.com/prof/SLAMM/index.html> (accessed April 2, 2011).
- . *SLAMM: Sea Level Affecting Marshes Model: SLAMM Version and Development History*. (2010b). October 20, 2010. Available at http://warrenpinnacle.com/prof/SLAMM/SLAMM_Versions.html (accessed April 2, 2011).
- WCGA, West Coast Governors' Agreement on Ocean Health. (May 2010). West Coast Governors' Agreement on Ocean Health: Climate Change Action Coordination Team Work Plan. *West Coast Governors' Agreement on Ocean Health: Action Teams*. Available at http://westcoastoceans.gov/Docs/Climate_Final_Work_Plan.pdf (accessed April 14, 2011).
- . *West Coast Governors' Agreement on Ocean Health: Action Teams*. (2011a). February 15, 2011. Available at <http://westcoastoceans.gov/teams/> (accessed April 14, 2011).
- . *West Coast Governors' Agreement on Ocean Health: Home*. (2011b). February 15, 2011. Available at <http://westcoastoceans.gov/> (accessed April 14, 2011).
- Wells, B. K., C. B. Grimes, J. G. Sneva, S. McPherson, and J. B. Waldvogel. (2008). Relationships between oceanic conditions and growth of Chinook salmon (*Oncorhynchus tshawytscha*) from California, Washington, and Alaska, USA. *Fisheries Oceanography*. 17(2): 101-125. Available at <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2419.2008.00467.x/abstract> (accessed December 2011).

- West, J. M., S. H. Julius, P. Kareiva, C. Enquist, J. J. Lawler, B. Petersen, A. E. Johnson, and M. R. Shaw. (2009). U.S. natural resources and climate change: concepts and approaches for management adaptation. *Environmental Management*. 44: 1001-1021. Available at <http://link.springer.com/content/pdf/10.1007%2Fs00267-009-9345-1> (accessed December 2011).
- West Coast EBM Network. (May 2010). Community-based management of coastal ecosystems: Highlights and lessons of success from the West Coast Ecosystem-Based Management Network. Available at http://www.westcoastebm.org/WestCoastEBMNetwork_EBMGuide_June2010.pdf (accessed April 14, 2011).
- Whitely Binder, L. C., J. K. Barcelos, D. B. Booth, M. Darzen, M. M. Elsner, R. Fenske, T. F. Graham, A. F. Hamlet, J. Hodges-Howell, and J. E. Jackson. (2010). Preparing for climate change in Washington State. *Climatic Change*. 102: 351-376. Available at <http://link.springer.com/article/10.1007/s10584-010-9850-5> (accessed December 2011).
- Whitney, F. A., H. J. Freeland, and M. Robert. (2007). Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. *Progress in Oceanography*. 75: 179-199. Available at <http://www.sciencedirect.com/science/article/pii/S0079661107001516> (accessed December 2011).
- Wolf, S. G., M. A. Snyder, W. J. Sydeman, D. F. Doak, and D. A. Croll. (2010). Predicting population consequences of ocean climate change for an ecosystem sentinel, the seabird Cassin's auklet. *Global Change Biology*. 16: 1923-1935. Available at http://bio.research.ucsc.edu/people/croll/pdf/Wolf_2010.pdf (accessed December 2011).
- Wootton, J. T., C. A. Pfister, and J. D. Forester. (2008). Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *Proceedings of the National Academy of Science*. 105(48): 18848-18853. Available at <http://www.pnas.org/content/early/2008/11/24/0810079105.abstract> (accessed December 2011).
- WorldWinds Inc. (2011). *About MM5*. Available at <http://www.worldwindsinc.com/aboutmm5.htm> (accessed July 29, 2011).
- Wright, N. (2002). *Eelgrass conservation for the B.C. coast: a discussion paper*. SeaChange. 16 pp.
- Yukon Government. (2011). *Executive Council Office: General Facts: Land*. July 29, 2011. Available at <http://www.eco.gov.yk.ca/stats/1467.html> (accessed August 4, 2011).
- . *Government of Yukon Climate Change Strategy*. (July 2006). Whitehorse: Yukon Department of Environment, Policy and Planning Branch. 20 pp. Available at <http://www.env.gov.yk.ca/publications-maps/documents/ygclimatechangestrategy.pdf> (accessed December 2011).
- . *Yukon Government Climate Change Action Plan*. (February 2009). Whitehorse: Environment Yukon, Environmental Programs Branch. 48 pp. Available at http://www.env.gov.yk.ca/publications-maps/documents/YG_Climate_Change_Action_Plan.pdf (accessed December 2011).