Chapter 4: Coastal Issues

Summary

Oregon's coastline is expected to face greater coastal flooding and erosion hazards as sea levels rise. At Newport, sea level is projected to rise by 12 to 47 inches under the high emissions pathway by the end of the 21st century. Such sea levels would place thousands of people and homes, and over 100 miles of roads, in Oregon at risk of inundation from annual flood events that reach four feet above high tide. Multiple changes in the ocean environment—warmer temperatures, less oxygen, greater ocean acidity—are expected to result in substantial ecosystem shifts in Oregon's coastal waters. Ocean acidification is already affecting Oregon, caused in part by increasing greenhouse gas concentrations.

Introduction

The ocean, often overlooked, in fact bears a great burden due to global climate change. The ocean retains the majority of the extra heat trapped by the Earth due to extra greenhouse gases emitted by the burning of fossil fuels. It receives half of the extra water that melts from ice on land. It absorbs nearly one-third of the extra carbon dioxide emitted to the atmosphere. But, bearing this burden comes at a cost. Warmer temperatures can alter ecosystems; more water raises global sea levels; more carbon dioxide acidifies the ocean (Stocker, 2015). These effects, already seen in Oregon, are projected to increase in the future, likely threatening coastal habitats, food supply, economic livelihood, and development.

Sea level rise

Changes in global sea levels occur due to ocean thermal expansion, glacier and ice sheet mass loss, and land water storage. Regional and local sea levels on the Pacific Northwest's coast are governed by the global mean sea level, but also by natural variability (El Niño–Southern Oscillation affects ocean currents and wind fields), by vertical land motions from subducting ocean plates, and by post-glacial isostatic adjustment (Reeder *et al.*, 2013).

Past Trends

Global mean sea level rose about 7.5 inches during 1901–2010. Of that rise, 75% since the 1970s was due to melting glaciers and thermal expansion of sea water (IPCC, 2013). Sea level rise has been accelerating: most analyses suggest that global mean sea level rose at a rate of 1.7 mm/year during 1901–2010, 2.0 mm/year during 1971–2010, and 3.2 mm/year during 1993–2010 (IPCC, 2013). However, a recent reanalysis of global sea level rise suggests that sea level rise rates during 1901–1990 were smaller (1.2 mm/year) than previous estimates, bringing it in line with the sum of contributions from glacier and ice sheet mass loss, ocean thermal expansion, and changes in land water storage during that period (Hay *et al.*, 2015). These adjusted estimates in sea level rise imply even greater acceleration in recent decades. Trends in global and regional sea level changes beyond natural variability are now detectable. At a minimum, anthropogenic sea level rise very likely contributed about 1 mm/year to global sea level rise during 1880–2002, or more than half the observed trend (Becker *et al.*, 2014). There is, however, regional variability; the minimum anthropogenic sea level change signal at Seattle during 1899–2012 was only 15% of the observed trend (Becker *et al.*, 2014). In parsing out the contributions to global and regional sea level change as detected by satellite altimetry and gravity observations, one study found that sea level during 2002–2014 along the West Coast changed very little, with the cooling ocean trend (lack of thermal expansion) balancing contributions from melting ice sheets and glaciers (Rietbroek *et al.*, 2016). However, local tectonics was not accounted for in this study but is important for local sea level analysis.

Future Projections

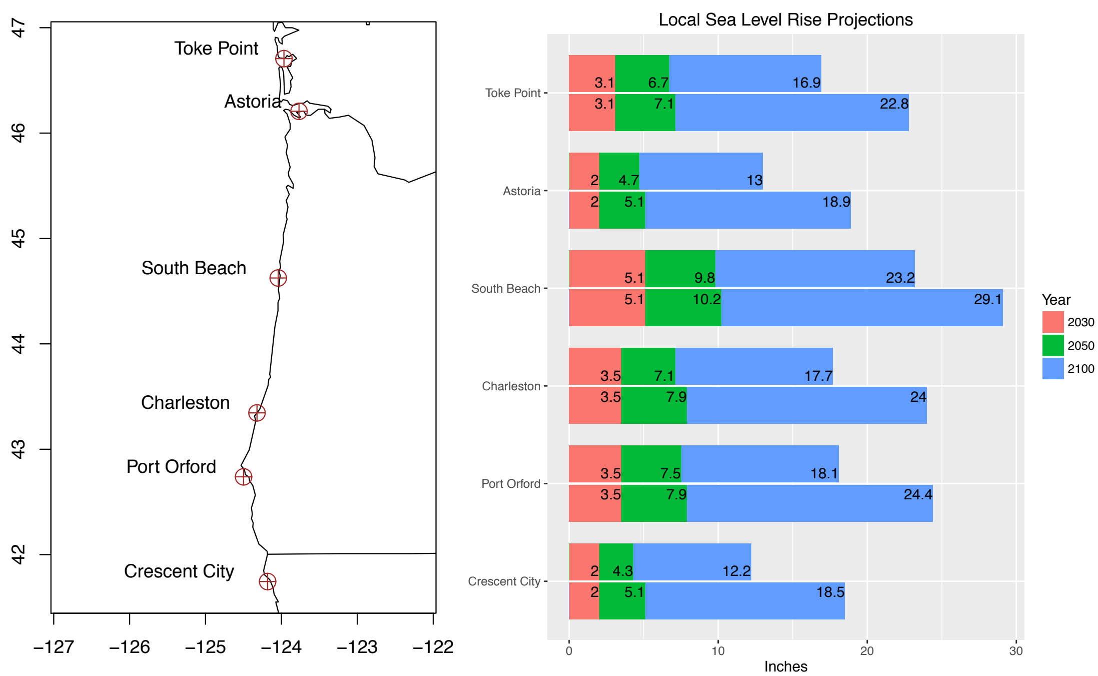
Global mean sea level is expected to continue to rise throughout this century at a faster pace than observed over the past several decades (IPCC, 2013). Under the high emissions pathway (RCP 8.5), sea levels will likely rise by 17.7–32.3 inches between the periods 1986–2005 and 2081–2100, and this rise will vary across regions (IPCC, 2013). Loss of the West Antarctic ice sheet would result in much higher sea level rise estimates than these (Clark *et al.*, 2016; DeConto and Pollard, 2016; Hansen *et al.*, 2016). In a large ensemble of simulations coupling climate and ice sheet dynamics, the West Antarctic Ice Sheet is projected to collapse within 250 years for the high emissions pathway (RCP8.5) and within 500 years for the low emission pathway (RCP4.5), contributing about 30.3 inches and 12.6 inches of global sea level rise by 2100, but 40.4 feet and 16.4 feet by 2500, respectively (DeConto and Pollard, 2016).

Local sea level change projections for the West Coast from the National Research Council 2012 report were quoted in the previous Oregon Climate Assessment Report (Reeder *et al.*, 2013). Based on the range of the previous generation of models (CMIP3) and scenarios (SRES), local sea level at Newport, Oregon, relative to the year 2000 was projected to change -1.4 to +8.9 inches by the 2030s, -0.8 to +18.9 inches by the 2050s, and +4.6 to +56.1 inches by 2100 (Reeder *et al.*, 2013). Local sea level change projections from the latest generation of models (CMIP5) and scenarios (RCP), taking into account glacial isostatic adjustment, tectonics, and other non-climatic local effects for gages in or near Oregon, are shown in figure 4.1 and listed in table 4.1 (see Chapter 2 for a description of scenarios). These local projections correspond to “very likely” (90% probability range) global sea level projections between 2000 and 2100 of 15.7 to 35.4 inches under the low emission pathway (RCP 4.5) and 19.7 to 47.2 inches under the high emissions pathway (RCP 8.5) (Kopp *et al.*, 2014).

Table 4.1 The 90% probability range of local sea level change projections across the low (RCP 4.5) and high (RCP 8.5) emissions pathways for each time period in inches (Data source: Kopp *et al.*, 2014)

	2030	2050	2100
Toke Point	1.2–5.1	2.8–11.8	5.9”–40.2”
Astoria	<0–3.9	0.8–9.8	2.4–35.8
South Beach	2.8–7.1	5.9–15.0	12.2–46.5
Charleston	1.2–5.5	3.1–12.6	6.7–41.7
Port Orford	1.2–5.9	3.1–12.6	6.7–42.5
Crescent City	-0.4–3.9	0.4–9.4	0.8–36.6

Figure 4.1 Median sea level projections in inches for Oregon Coast locations for a low (RCP 4.5, top bar) and a high (RCP 8.5, bottom bar) emissions pathway for 2030, 2050, and 2100. (Figure source: Meghan Dalton; data source: Kopp *et al.*, 2014)



Extreme storms and wave climate

Tall waves, intense storms, and El Niño–Southern Oscillation (ENSO) events can combine with sea level rise to produce coastal erosion and inundation hazards (Reeder *et al.*, 2013). During El Niño events the Pacific Northwest's coast can experience elevated sea levels, but both the top six El Niño and top five La Niña events during 1979–2016 amplified coastal erosion and wave energy in the Pacific Northwest (Barnard *et al.*, 2015, 2017). If ENSO becomes more extreme (see Chapter 2), coastal erosion may increase in the future irrespective of sea level rise (Barnard *et al.*, 2015).

Upward trends were seen in storm frequency and intensity during the cold season across the Northern Hemisphere since 1950, but these trends were significant only in some areas and not off the Pacific Northwest's coast (Vose *et al.*, 2014). Twenty-first century projections of changes in storm intensity are still inconclusive, although storm tracks are expected to shift slightly poleward (Vose *et al.*, 2014).

Wave heights have increased in the northeast Pacific over the past several decades (Reeder *et al.*, 2013), as have extreme wave events (Bromirski *et al.*, 2013); such waves have been largely responsible for recent increases in coastal flooding and erosion (Ruggiero, 2013). However, attributing increasing wave heights to climate change may not be possible until the second half of the 21st century because natural variability is quite large (Dobrynin *et al.*, 2014). Future projections of average and extreme wave heights along the West Coast are mixed (Erikson *et al.*, 2015; Wang *et al.*, 2014) as they rely on predictions that are difficult to make about extratropical storms and extreme winds (Vose *et al.*, 2014).

Coastal Hazards Vulnerability

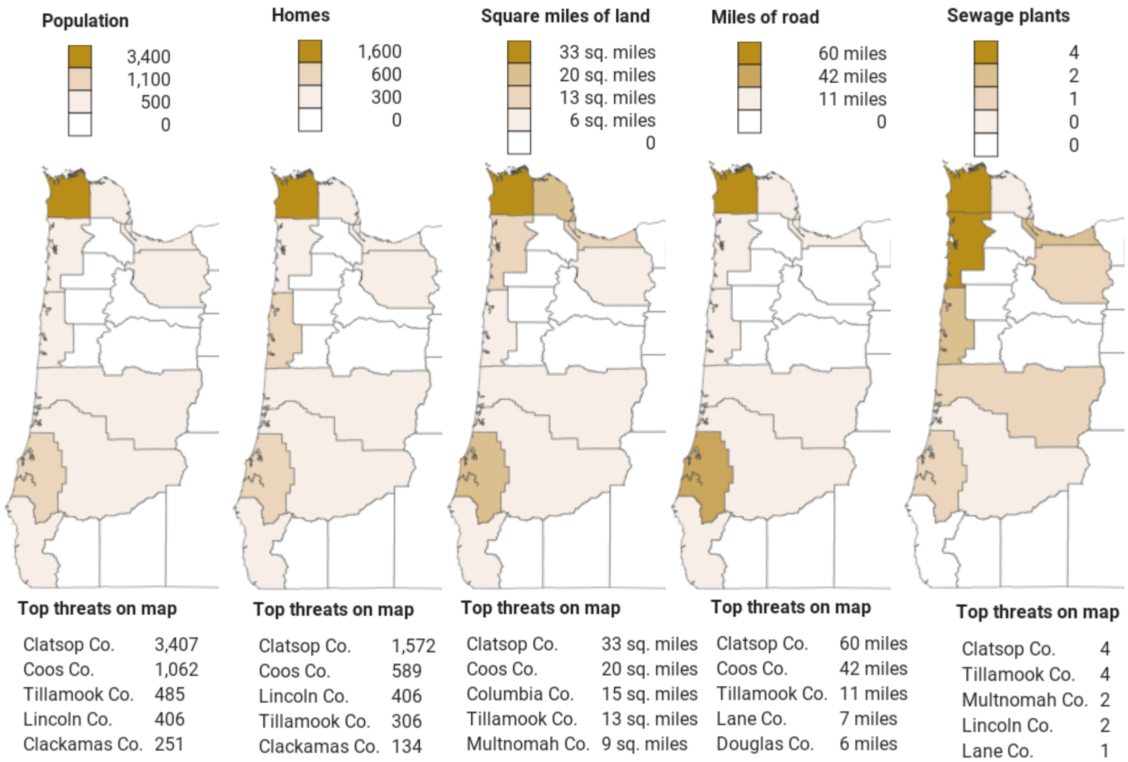
In US coastal communities, more than 2.2 million people currently live in areas within reach of the mean highest high tide projected for 2100 if global sea levels rise 35.4 inches (Hauer *et al.*, 2016). In Oregon, more than 7,400 people currently live in this inundation zone, but accounting for population growth could place more than 12,700 people at risk by 2100 (Hauer *et al.*, 2016). Nuisance flooding events, in which water levels exceed local thresholds for minor impacts, are also projected to increase, placing even more people and property at risk of frequent inundation. In Seattle, for example, the projected likely range of local sea level rise of 19.7–35.4 inches by 2100 (Kopp *et al.*, 2014) would result in 30 nuisance flooding days per year by the 2040s or 2050s (Sweet and Park, 2014). Coastal risk is amplified when considering other factors that influence extreme sea levels, such as storm surge, sea level anomalies, and intense rainfall (Serafin and Ruggiero, 2014; Wahl *et al.*, 2015). Accounting only for changes in mean sea level, for example, may be inadequate for ensuring that coastal infrastructure projects remain safe for the lifetime of the structure (Wahl and Chambers, 2015).

By 2100, assuming median local sea level projections under the high emissions pathway (RCP 8.5) of 18.9, 29.1, and 24 inches for Astoria, South Beach, and Charleston (fig. 4.1) (Kopp *et al.*, 2014), respectively, there is a 70%, 100%, and 86% risk of at least one flood per year reaching 4 feet above the current high tide line (Strauss *et al.*, 2014). At this level, 6118 people, 3346 homes, $779 million in property value, 138 miles of roads, 15 sewage plants, and 110 square miles of land would be at high risk of annual flooding in Oregon by 2100 (Strauss *et al.*, 2014). Figure 4.2 breaks these numbers down by county.

Globally, under 9.8–48.4 inches of global mean sea level rise, 0.2–4.6% of the population would experience annual flooding leading to losses of global gross domestic product of 0.3–9.3% by the end of the 21st century (Hinkel *et al.*, 2014). The adaptation cost of protecting coasts is estimated to be $12–$71 billion per year, a much lower total than the cost of avoided damages (Hinkel *et al.*, 2014). In the United States, the total cost of adaptation (including armoring, nourishment, abandoned property, and elevating) increases when considering storm surge on top of sea level rise and is estimated to range from $930 billion to $1.1 trillion through 2100 under a very high emissions pathway (REF 10). Low (POL 4.5) and very low (POL 3.7) emissions pathways have the potential to lower this cost by $84–$140 billion (Neumann *et al.*, 2015). In Oregon, the cost of adaptation to sea level rise and storm surge may be on the order of $1.5 billion through 2100; consideration of storm surge makes little difference for Oregon (Neumann *et al.*, 2015), but adding wave climate variability might.

Perhaps the greatest coastal hazard facing the West Coast this century is the possibility of a large magnitude Cascadia Subduction Zone earthquake. The latest estimate gives a 16–22% chance of a magnitude 8 or higher earthquake off the central and northern Oregon coast in next 50 years (Goldfinger *et al.*, 2016). Should the earthquake and subsequent tsunami occur, significant loss of life and profound damage to coastal development and infrastructure is anticipated (*Oregon Natural Hazards Mitigation Plan*, 2015).

Figure 4.2 Exposure of assets below 4 feet above mean high tide level in Oregon
http://riskfinder.climatecentral.org/state/oregon.us?comparisonType=county&forecastType=NRC_Medium&level=4&unit=ft



Ocean acidification and hypoxia

The world's oceans have absorbed about a third of the carbon dioxide (CO_2) emitted as a result of human activity. Absorption of this CO_2 has led to increased ocean acidity, a fundamental shift in ocean chemistry that is a growing concern for coastal ecosystems and the people that depend on them. The West Coast Ocean Acidification and Hypoxia Science Panel recently issued a scientific consensus report on the state of ocean acidification and hypoxia along the West Coast and recommended actions for managing and reducing their effects (Chan *et al.*, 2016). Ocean acidification and hypoxia tend to co-occur, as they are both driven by increased atmospheric CO_2 levels and local nutrient and organic carbon inputs, and together they comprise a challenge that can be managed synergistically (Chan *et al.*, 2016).

Ocean acidification (OA) is often expressed in terms of a decrease in pH or increase in acidity. OA also reduces the concentration of carbonate ions, which impairs the ability of calcifying organisms, such as oysters and crabs, to build shells. By 21st century's end assuming the current rate of global CO_2 emissions, the surface ocean's average acidity is expected to double (Chan *et al.*, 2016). But although it negatively affects some physiological processes, pH may not be the most useful number by which to monitor the biological effects of OA, particularly on calcifying organisms (Chan *et al.*, 2016; Waldbusser *et al.*, 2015). Furthermore, biologically-relevant thresholds of mineral carbonate saturation state are expected to be crossed much sooner than pH thresholds for some organisms (Waldbusser *et al.*, 2015). Even before it declines enough to corrode calcium carbonate shells, a lowered carbonate saturation state can "make it more difficult and energetically costly for larval bivalves to build shells" (Waldbusser *et al.*, 2015). Reductions in calcifying organisms at the base of the marine food web could have cascading effects on higher trophic marine fish, birds, mammals, and the people who rely on this resource. In a simple projection of ocean water saturation state changes, the mean annual surface seawater aragonite saturation state off the Oregon coast is projected to reach a threshold known to disrupt calcification and development in larval bivalves by the 2030s (Ekstrom *et al.*, 2015). However, the West Coast has already reached a threshold and negative impacts are already evident, such as dissolved shells in pteropod populations (Feely *et al.*, 2016) and impaired oyster hatchery operations (Barton *et al.*, 2012) (see box 4.1). Furthermore, 60% of the dissolved inorganic carbon in surface waters off Oregon's coast in 2013 is attributed to increasing greenhouse gas concentrations (Feely *et al.*, 2016).

Hypoxia—low oxygen levels—tend to accompany high ocean acidity, and the combined effects can be worse than the effects either of hypoxia or acidification independently (Chan *et al.*, 2016). Hypoxic waters along the West Coast have expanded upward into shallower depths and are already affecting marine ecosystems (Somero *et al.*, 2016). Natural climate variability exercises strong control on dissolved oceanic oxygen levels, but detection of a deoxygenation trend beyond natural variability may be possible by the 2030s and 2040s in the north Pacific Ocean and along the US West Coast according to earth system modeling results (Long *et al.*, 2016).

The West Coast of North America is one of the first places in the world to experience severe environmental, ecological, and economic consequences of OA and hypoxia largely due to the naturally occurring CO_2-enriched, low-oxygen deep water that wells up along the continental shelf of the West Coast (Chan *et al.*, 2016). How the region manages these ongoing changes will likely influence management choices of other coastal regions of the world. OA is a global problem, and reducing global levels of CO_2 emissions will be the most effective strategy to lessen the effect of OA (Chan *et al.*, 2016). However, better management of local nutrient and organic matter inputs to the coastal environment can lessen exposure to OA where those local stressors are having impacts. Furthermore, managing ecosystems to increase resilience—the ability to withstand impacts—to OA represent an important path for local adaptation actions. Time is of the essence because delayed action will reduce management options in the future and more greatly diminish ecosystem services (Chan *et al.*, 2016).

Ocean temperature

Most of the greenhouse-gas-driven warming of the Earth since the late 18th century has occurred in the ocean, consistent with previous interglacial warming periods (Rosenthal *et al.*, 2013). Since 1970, more than 90% of the extra heat taken up by the Earth has accumulated in the ocean (Gleckler *et al.*, 2016). Ocean warming is accelerating, particularly in the deep ocean: half of the increase in ocean heat content since the late 18th century occurred in recent decades (Gleckler *et al.*, 2016). By absorbing vast amounts of heat, the deep ocean provides a buffer to greenhouse gas warming experienced by land ecosystems, but at the cost of highly vulnerable biodiversity in ocean ecosystems (Levin and Bris, 2015).

There is, however, considerable regional variability in ocean temperature trends as ocean currents redistribute heat throughout the world ocean. Surface waters off the West

Coast have warmed and are expected to continue warming in the future; however, there will continue to exist large annual variability via seasonal upwelling and interannual variability from ENSO-related changes in wind patterns (Reeder *et al.*, 2013).

Coastal Upwelling

Coastal upwelling in the California eastern boundary upwelling system, which runs along the West Coast from Victoria to Baja, occurs during the spring and summer when the wind predominately blows southward and interacts with the Earth's rotation to push surface waters offshore, allowing cold, nutrient-rich waters at depth to well up toward the surface, spurring productivity that supports the marine food web. Observed evidence suggests that upwelling-favorable winds have intensified in the California upwelling system over the past 60 years (Sydeman *et al.*, 2014). However, the majority of climate models project future weakening of upwelling-favorable winds along the California upwelling system by the end of this century under a high emissions pathway (RCP 8.5) (Rykaczewski *et al.*, 2015). This projection is in contrast to a projected intensification of upwelling-favorable winds in other eastern boundary upwelling systems of the world. Theory suggests that upwelling in eastern boundary currents would intensify under climate change due to strengthening ocean high-pressure systems and greater relative warming over the land than over the ocean, which could produce upwelling-favorable winds locally, although there will continue to be large year-to-year variability in upwelling (Bakun *et al.*, 2015). The lack of upwelling intensification projected for the California upwelling system suggests that other regional controls are at play (Wang *et al.*, 2015). If upwelling does intensify, the cooler waters could potentially counteract the effects of habitat warming; however, that water would likely be more acidic and with less oxygen (Bakun *et al.*, 2015).

Impacts to Marine & Coastal Ecosystems

Ocean acidification (OA)—decreasing pH, increasing partial pressure of CO_2 dissolved in water (pCO_2), and decreasing aragonite saturation—in combination with changes in ocean temperature and dissolved oxygen levels will have varying effects on the physiology of marine species from the microscopic plants and bugs (i.e., plankton) at the base of the marine food web to shellfish, fish, and larger mammals, leading to substantial and potentially irreversible changes in marine ecosystems species assemblages (Somero *et al.*, 2016; Wittmann and Pörtner, 2013). Such ecosystem shifts will likely affect the coastal economy and the communities that rely on traditional coastal resources. In Oregon, commercial fishing and seafood manufacturing accounted for 0.2% of Oregon jobs and $614 million in sales in 2013 (Sorte *et al.*, 2016). The range of organisms for which evidence of sensitivity to OA exists has continued to grow, but more research is still needed to understand the complex interactions and outcomes of multiple changing stressors on multiple interconnected species within the marine environment (Busch and McElhany, 2016).

Phytoplankton

Warmer oceans will likely alter the metabolic functioning of some phytoplankton (Toseland *et al.*, 2013), and OA is expected to favor some types over others (Eggers *et al.*, 2014). The thousands of phytoplankton species at the base of the marine food web will likely each respond a little differently to these climate stressors spurring competition among species and resulting in substantial changes in phytoplankton community composition (Dutkiewicz *et al.*, 2015). This in turn would lead to the alteration of ocean biogeochemical nutrient cycling, with cascading effects on the marine food web as different phytoplankton types perform different and essential functions.

Zooplankton

Pteropods—tiny sea snails with aragonite shells that serve as a major food source for many commercially important fishes (Somero *et al.*, 2016)—are strong indicators of the cumulative effects not only of OA, but also of warming and of declining oxygen levels (Bednaršek *et al.*, 2016). Suitable habitat for pteropods is already declining off the West Coast (Bednaršek *et al.*, 2014). OA, by increasing the extent of aragonite undersaturation, has already increased severe pteropod shell dissolution incidences along the West Coast compared with pre-industrial conditions (Bednaršek *et al.*, 2014; Feely *et al.*, 2016). By mid-21st century such dissolution incidences are expected to triple (Bednaršek *et al.*, 2014). Such impacts to pteropods will alter available food sources for a number of commercially-important species of fish along the West Coast (Somero *et al.*, 2016).

Invertebrates

OA threatens the growth and survival of most classes of shell-forming invertebrates, including bivalves and crabs, although some are more sensitive than others, and sensitivity varies among species (Busch and McElhany, 2016). During the larval stage, bivalves—clams, mussels, oysters—are highly sensitive to reduced carbonate saturation during the crucial hours or days in which initial shells are formed (Waldbusser *et al.*, 2015). Changes in pH and pCO_2 can also affect invertebrate physiology (Somero *et al.*, 2016). Cephalopods (e.g., octopus, squid) that spend time in both shallow oxygen-rich water and deep oxygen-poor waters are generally considered tolerant of increasing pCO_2, as they can tolerate a wide range of water chemistry conditions, but this tolerance varies with water temperature (Doubleday *et al.*, 2016; Somero *et al.*, 2016). In addition, other classes of squid may be more sensitive to declining ocean pH (Busch and McElhany, 2016).

Fishes

Fishes will exhibit varied responses to changing water conditions (e.g., temperature, OA, hypoxia, food source) depending on differences in vulnerability and adaptive capacity (Pörtner *et al.*, 2014). Increases in pCO_2 has been found to be a relevant indicator for many fish: higher pCO_2 affects fish behavior and their ability to navigate (Chan *et al.*, 2016), with little capacity for some fish to acclimate (Welch *et al.*, 2014). The eggs and larvae of some north Pacific commercial flatfish species are also affected by elevated CO_2 levels (Hurst *et al.*, 2016). OA and hypoxia can also affect the metabolism of fish species; slow swimming and larval stages are particularly vulnerable, as they are less able to move away from such impaired conditions (Somero *et al.*, 2016).

For salmon, warmer ocean waters could alter their ranges and migration, could lead to thermal stress and susceptibility to disease and predation, and could increase stratification that would change the habitat structure and reduce food supply (Wainwright and Weitkamp, 2013). During warmer Pacific ocean regimes when food availability is generally lower, returning Chinook salmon (*Oncorhynchus tshawytscha*) were smaller and fewer, but they appeared to need to eat more in order to maintain energy to forage for the lower food availability (Daly and Brodeur, 2015). Increases in ocean acidity would also disrupt food supply and shift the ecosystem, while changes in upwelling could result in greater nutrients but a desynchronization between food supply and arrival to the ocean (Wainwright and Weitkamp, 2013).

As temperatures warm, the range of many marine fishes is projected to shift poleward in the northeast Pacific, and an influx of warm water species along the Oregon coast is expected (Cheung *et al.*, 2015). Species assemblages are projected to change, potentially resulting in mis-matches between co-evolved species, which could cause cascading effects up the marine food web and a shifting of traditional fishing grounds (Cheung *et al.*, 2015). Declines in northeast Pacific fisheries catch is projected under climate change; however, poleward range shifts may open new recreational and commercial fishing opportunities (Weatherdon *et al.*, 2016a).

Indigenous fishing communities are particularly vulnerable as climate change has the potential to reduce their capacity to harvest traditional marine resources for their economic and cultural livelihood (Weatherdon *et al.*, 2016a). Ranges of the many commercially and culturally important marine fishes for First Nations in coastal British Columbia are projected to shift north by about 6–112 miles per decade by 2050, with accompanying projected declines in abundance of -15% to -21%, with the greatest impacts toward the south (Weatherdon *et al.*, 2016b). Under such projections, catch potential is expected to decline for most commercial fisheries, leading to revenue reductions of 16% to 29% by 2050 (Weatherdon *et al.*, 2016b).

Mammals

Climate change is likely to impact marine mammals indirectly through alteration in food availability and prey communities over time (Okey *et al.*, 2014). For example, migrating Humpback whales seem to be spending more time in Arctic ice-free waters where the warmer waters appear to be benefitting krill blooms (Groc, 2016). Such indirect responses are potentially long-lasting, but difficult to predict (Sydeman *et al.*, 2015).

Estuaries

Oregon's estuaries are crucial habitat for many species, including juvenile salmon and shellfish larvae. West Coast estuarine managers are most concerned about how sea level rise and OA will affect conservation of tidal wetland habitat and threatened species (Thorne *et al.*, 2016). Climate change is expected to alter estuarine habitat through changes in sea level, OA, water temperature, upwelling, freshwater runoff, and sedimentation. Higher sea levels would reduce wetland habitat for salmonid, and warmer waters would increase thermal stress and susceptibility to disease and predation (Wainwright and Weitkamp, 2013). In the Tillamook Bay estuary, for example, changes in relative sea level, wind, waves, and freshwater input were projected to result in higher total water levels everywhere, with some areas more exposed than others (Cheng *et al.*, 2015). Increases in coastal marsh vegetation due to fertilization by increasing CO_2 may provide some resilience to relative sea level rise inundation (Ratliff *et al.*, 2015). In the Yaquina Estuary at Newport, a 5.4°F increase in air temperature was projected to result in 1.3–2.9°F warming in the estuarine waters, with the upper portion experiencing up to 40 more days not meeting water temperature criteria for the protection of rearing and migrating salmonids (Brown *et al.*, 2016).

Box 4.1: West Coast Shellfish Industry Adapting to Ocean Acidification

Oregon's coastal waters are highly exposed to global ocean acidification (OA). Already, naturally occurring deep acidic waters upwell seasonally along the coast, which will be amplified by additional absorption of atmospheric carbon dioxide (CO_2) by the ocean. The Pacific Northwest's coastal waters are some of the first to experience the severe impacts of OA, exemplified during the repeated production failures experienced by the West Coast shellfish industry in the mid-2000s in which economic losses were substantial (Chan *et al.*, 2016; Mabardy *et al.*, 2015). For example, overall production at the Whisky Creek Shellfish Hatchery in Netarts Bay, Oregon, was 25% of normal in 2008 (Barton *et al.*, 2015).

Shellfish production is important to the West Coast economy, including the northern Oregon coast (Ekstrom *et al.*, 2015). Oregon's Whiskey Creek Shellfish Hatchery in Netarts Bay is one of three major commercial hatcheries in the Pacific Northwest that supplies shellfish larvae to the West Coast shellfish industry (Barton *et al.*, 2015). In Oregon, shellfish production in 2009 generated more than $3 million in sales (Barton *et al.*, 2015). For many Indigenous coastal communities, shellfish and traditional clam beds are integral to their culture, economy, and diets (Weatherdon *et al.*, 2016a).

In a 2013 survey of West Coast shellfish producers, the vast majority believed that OA is occurring, more than 80% noted that OA will have consequences today, and about half have already personally experienced its negative impacts (Mabardy *et al.*, 2015). More than half of West Coast shellfish producers in the 2013 survey felt they would be able to adapt, at least in the short-term (Mabardy *et al.*, 2015).

In response to OA impacts in the mid-2000s, the West Coast shellfish industry partnered with academic researchers to understand and implement strategies to mitigate OA effects (Barton *et al.*, 2015). As a global problem, the long-term solution to ocean acidification is global reductions in CO_2 emissions, but until then local adaptation measures will be necessary (Ekstrom *et al.*, 2015). Adaptation strategies for the shellfish industry have included: 1) monitoring water quality and understanding the influence of water chemistry on shellfish production, 2) treating water to improve water chemistry for production, 3) moving hatchery operations away from the highly exposed coastal waters of the Pacific Northwest—to Hawaii in one case, and 4) an emerging strategy to selectively breed for oyster strains more resistant to OA (Barton *et al.*, 2015; Chan *et al.*, 2016). In addition, several coastal tribes in the Pacific Northwest are beginning to investigate impacts and adaptation strategies of OA on their traditional shellfish harvests, including the Confederated Tribes of the Siletz Indians on Oregon's coast (Kathy Lynn, pers. comm.).

"The Pacific Northwest shellfish industry cannot treat the entire coastal ocean, and the general deterioration of coastal water quality is a pressing concern for the entire industry" (Barton *et al.*, 2015).

References

Bakun A, Black BA, Bograd SJ, García-Reyes M, Miller AJ, Rykaczewski RR, Sydeman WJ. 2015. Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems. *Current Climate Change Reports* **1**(2): 85–93. DOI: 10.1007/s40641-015-0008-4.

Barnard PL, Hoover D, Hubbard DM, Snyder A, Ludka BC, Kaminksy GM, Ruggiero P, Gallien T, Gabel L, McCandles D, Weiner HM, Cohn N, Anderson DL, Serafin KA. 2017. Extreme oceanographic forcing and coastal response due to the 2015–2016 El Niño. *Nature Communications* **In Press**.

Barnard PL, Short AD, Harley MD, Splinter KD, Vitousek S, Turner IL, Allan J, Banno M, Bryan KR, Doria A, Hansen JE, Kato S, Kuriyama Y, Randall-Goodwin E, Ruggiero P, Walker IJ, Heathfield DK. 2015. Coastal vulnerability across the Pacific dominated by El Nino/Southern Oscillation. *Nature Geoscience* **8**(10): 801–807. DOI: 10.1038/ngeo2539.

Barton A, Hales B, Waldbusser GG, Langdon C, Feely RA. 2012. The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography* **57**(3): 698–710. DOI: 10.4319/lo.2012.57.3.0698.

Barton A, Waldbusser G, Feely R, Weisberg S, Newton J, Hales B, Cudd S, Eudeline B, Langdon C, Jefferds I, King T, Suhrbier A, McLauglin K. 2015. Impacts of Coastal Acidification on the Pacific Northwest Shellfish Industry and Adaptation Strategies Implemented in Response. *Oceanography* **25**(2): 146–159. DOI: 10.5670/oceanog.2015.38.

Becker M, Karpytchev M, Lennartz-Sassinek S. 2014. Long-term sea level trends: Natural or anthropogenic? *Geophysical Research Letters* **41**(15): 2014GL061027. DOI: 10.1002/2014GL061027.

Bednaršek N, Feely RA, Reum JCP, Peterson B, Menkel J, Alin SR, Hales B. 2014. Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proceedings of the Royal Society B: Biological Sciences* **281**(1785): 20140123–20140123. DOI: 10.1098/rspb.2014.0123.

Bednaršek N, Harvey CJ, Kaplan IC, Feely RA, Možina J. 2016. Pteropods on the edge: Cumulative effects of ocean acidification, warming, and deoxygenation. *Progress in Oceanography* **145**: 1–24. DOI: 10.1016/j.pocean.2016.04.002.

Bromirski PD, Cayan DR, Helly J, Wittmann P. 2013. Wave power variability and trends across the North Pacific. *Journal of Geophysical Research: Oceans* **118**(12): 6329–6348. DOI: 10.1002/2013JC009189.

Brown CA, Sharp D, Mochon Collura TC. 2016. Effect of climate change on water temperature and attainment of water temperature criteria in the Yaquina Estuary, Oregon (USA). *Estuarine, Coastal and Shelf Science* **169**: 136–146. DOI: 10.1016/j.ecss.2015.11.006.

Busch DS, McElhany P. 2016. Estimates of the Direct Effect of Seawater pH on the Survival Rate of Species Groups in the California Current Ecosystem. *PLOS ONE* **11**(8): e0160669. DOI: 10.1371/journal.pone.0160669.

Chan F, Boehm AB, Barth JA, Chornesky EA, Dickson AG, Feely RA, Hales B, Hill TM, Hofmann G, Ianson D, Klinger T, Largier J, Newton J, Pedersen TF, Somero GN, Sutula M, Wakefield WW, Waldbusser GG, Weisberg SB, Whiteman EA. 2016. *The West Coast Ocean Acidification and Hypoxia Science Panel: Major Findings, Recommendations, and Actions*. California Ocean Science Trust: Oakland, California, USA.

Cheng TK, Hill DF, Beamer J, García-Medina G. 2015. Climate change impacts on wave and surge processes in a Pacific Northwest (USA) estuary. *Journal of Geophysical Research: Oceans* **120**(1): 182–200. DOI: 10.1002/2014JC010268.

Cheung WWL, Brodeur RD, Okey TA, Pauly D. 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progress in Oceanography* **130**: 19–31. DOI: 10.1016/j.pocean.2014.09.003.

Clark PU, Shakun JD, Marcott SA, Mix AC, Eby M, Kulp S, Levermann A, Milne GA, Pfister PL, Santer BD, Schrag DP, Solomon S, Stocker TF, Strauss BH, Weaver AJ, Winkelmann R, Archer D, Bard E, Goldner A, Lambeck K, Pierrehumbert RT, Plattner G-K. 2016. Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change* **6**(4): 360–369. DOI: 10.1038/nclimate2923.

Daly EA, Brodeur RD. 2015. Warming Ocean Conditions Relate to Increased Trophic Requirements of Threatened and Endangered Salmon. *PLOS ONE* **10**(12): e0144066. DOI: 10.1371/journal.pone.0144066.

DeConto RM, Pollard D. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature* **531**(7596): 591–597. DOI: 10.1038/nature17145.

Dobrynin M, Murawski J, Baehr J, Ilyina T. 2014. Detection and Attribution of Climate Change Signal in Ocean Wind Waves. *Journal of Climate* **28**(4): 1578–1591. DOI: 10.1175/JCLI-D-13-00664.1.

Doubleday ZA, Prowse TAA, Arkhipkin A, Pierce GJ, Semmens J, Steer M, Leporati SC, Lourenço S, Quetglas A, Sauer W, Gillanders BM. 2016. Global proliferation of cephalopods. *Current Biology* **26**(10): R406–R407. DOI: 10.1016/j.cub.2016.04.002.

Dutkiewicz S, Morris JJ, Follows MJ, Scott J, Levitan O, Dyhrman ST, Berman-Frank I. 2015. Impact of ocean acidification on the structure of future phytoplankton communities. *Nature Climate Change* **5**(11): 1002–1006. DOI: 10.1038/nclimate2722.

Eggers SL, Lewandowska AM, Barcelos e Ramos J, Blanco-Ameijeiras S, Gallo F, Matthiessen B. 2014. Community composition has greater impact on the functioning of marine phytoplankton communities than ocean acidification. *Global Change Biology* **20**(3): 713–723. DOI: 10.1111/gcb.12421.

Ekstrom JA, Suatoni L, Cooley SR, Pendleton LH, Waldbusser GG, Cinner JE, Ritter J, Langdon C, van Hooidonk R, Gledhill D, Wellman K, Beck MW, Brander LM, Rittschof D, Doherty C, Edwards PET, Portela R. 2015. Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change* **5**(3): 207–214. DOI: 10.1038/nclimate2508.

Erikson LH, Hegermiller CA, Barnard PL, Ruggiero P, van Ormondt M. 2015. Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios. *Ocean Modelling* **96**, **Part 1**: 171–185. DOI: 10.1016/j.ocemod.2015.07.004.

Feely RA, Alin SR, Carter B, Bednaršek N, Hales B, Chan F, Hill TM, Gaylord B, Sanford E, Byrne RH, Sabine CL, Greeley D, Juranek L. 2016. Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal and Shelf Science* **183**, **Part A**: 260–270. DOI: 10.1016/j.ecss.2016.08.043.

Gleckler PJ, Durack PJ, Stouffer RJ, Johnson GC, Forest CE. 2016. Industrial-era global ocean heat uptake doubles in recent decades. *Nature Climate Change* **6**(4): 394–398. DOI: 10.1038/nclimate2915.

Goldfinger C, Galer S, Beeson J, Hamilton T, Black B, Romsos C, Patton J, Nelson CH, Hausmann R, Morey A. 2016. The importance of site selection, sediment supply, and hydrodynamics: A case study of submarine paleoseismology on the northern Cascadia margin, Washington USA. *Marine Geology* **In Press**. DOI: 10.1016/j.margeo.2016.06.008.

Groc I. 2016. *Some Whales Like Global Warming Just Fine*. *National Geographic News*.

Hansen J, Sato M, Hearty P, Ruedy R, Kelley M, Masson-Delmotte V, Russell G, Tselioudis G, Cao J, Rignot E, Velicogna I, Tormey B, Donovan B, Kandiano E, von Schuckmann K, Kharecha P, Legrande AN, Bauer M, Lo K-W. 2016. Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. *Atmos. Chem. Phys.* **16**(6): 3761–3812. DOI: 10.5194/acp-16-3761-2016.

Hauer ME, Evans JM, Mishra DR. 2016. Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change* **6**: 691–695. DOI: 10.1038/nclimate2961.

Hay CC, Morrow E, Kopp RE, Mitrovica JX. 2015. Probabilistic reanalysis of twentieth-century sea-level rise. *Nature* **517**(7535): 481–484. DOI: 10.1038/nature14093.

Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, Marzeion B, Fettweis X, Ionescu C, Levermann A. 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences* **111**(9): 3292–3297. DOI: 10.1073/pnas.1222469111.

Hurst TP, Laurel BJ, Mathis JT, Tobosa LR. 2016. Effects of elevated CO2 levels on eggs and larvae of a North Pacific flatfish. *ICES Journal of Marine Science: Journal du Conseil* **73**(3): 981–990. DOI: 10.1093/icesjms/fsv050.

IPCC. 2013. Summary for Policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

Kopp RE, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen DJ, Strauss BH, Tebaldi C. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* **2**(8): 2014EF000239. DOI: 10.1002/2014EF000239.

Levin LA, Bris NL. 2015. The deep ocean under climate change. *Science* **350**(6262): 766–768. DOI: 10.1126/science.aad0126.

Long MC, Deutsch C, Ito T. 2016. Finding forced trends in oceanic oxygen. *Global Biogeochemical Cycles* **30**(2): 2015GB005310. DOI: 10.1002/2015GB005310.

Mabardy RA, Waldbusser GG, Conway F, Olsen CS. 2015. Perception and Response of the U.S. West Coast Shellfish Industry to Ocean Acidification: The Voice of the Canaries in the Coal Mine. *Journal of Shellfish Research* **34**(2): 565–572. DOI: 10.2983/035.034.0241.

Neumann JE, Emanuel K, Ravela S, Ludwig L, Kirshen P, Bosma K, Martinich J. 2015. Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy. *Climatic Change* **129**(1–2): 337–349. DOI: 10.1007/s10584-014-1304-z.

Okey TA, Alidina HM, Lo V, Jessen S. 2014. Effects of climate change on Canada's Pacific marine ecosystems: a summary of scientific knowledge. *Reviews in Fish Biology and Fisheries* **24**(2): 519–559. DOI: 10.1007/s11160-014-9342-1.

Oregon Natural Hazards Mitigation Plan. 2015. State of Oregon.

Pörtner H-O, Karl D, Boyd PW, Cheung WWL, Lluch-Cota SE, Nojiri Y, Schmidt DN, Zavialov P. 2014. Ocean Systems. *Impacts, Adaptation and Vulnerability, Volume II: Contribution of Working Group II to the Fifth Assessment Report of the Integovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK.

Ratliff KM, Braswell AE, Marani M. 2015. Spatial response of coastal marshes to increased atmospheric CO2. *Proceedings of the National Academy of Sciences* **112**(51): 15580–15584. DOI: 10.1073/pnas.1516286112.

Reeder WS, Ruggiero P, Shafer SL, Snover AK, Houston LL, Glick P, Newton JA, Capalbo SM. 2013. Coasts: Complex Changes Affecting the Northwest's Diverse Shorelines: Chapter 4. In: Dalton MM, Mote PW and Snover AK (eds) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*. Island Press: Washington, DC, 67–109.

Rietbroek R, Brunnabend S-E, Kusche J, Schröter J, Dahle C. 2016. Revisiting the contemporary sea-level budget on global and regional scales. *Proceedings of the National Academy of Sciences* **113**(6): 1504–1509. DOI: 10.1073/pnas.1519132113.

Rosenthal Y, Linsley BK, Oppo DW. 2013. Pacific Ocean Heat Content During the Past 10,000 Years. *Science* **342**(6158): 617–621. DOI: 10.1126/science.1240837.

Ruggiero P. 2013. Is the Intensifying Wave Climate of the U.S. Pacific Northwest Increasing Flooding and Erosion Risk Faster Than Sea-Level Rise? *Journal of Waterway, Port, Coastal, and Ocean Engineering* **139**(2): 88–97. DOI: 10.1061/(ASCE)WW.1943-5460.0000172.

Rykaczewski RR, Dunne JP, Sydeman WJ, García-Reyes M, Black BA, Bograd SJ. 2015. Poleward displacement of coastal upwelling-favorable winds in the ocean's eastern boundary currents through the 21st century. *Geophysical Research Letters* **42**(15): 2015GL064694. DOI: 10.1002/2015GL064694.

Serafin KA, Ruggiero P. 2014. Simulating extreme total water levels using a time-dependent, extreme value approach. *J. Geophys. Res. Oceans* **119**: 6305–6329. DOI: 10.1002/2014JC010093.

Somero GN, Beers JM, Chan F, Hill TM, Klinger T, Litvin SY. 2016. What Changes in the Carbonate System, Oxygen, and Temperature Portend for the Northeastern Pacific Ocean: A Physiological Perspective. *BioScience* **66**(1): 14–26. DOI: 10.1093/biosci/biv162.

Sorte B, Rahe M, Lewin P. 2016. *Agriculture, Food, Forestry and Fishing in the Northwest U.S.: An Economic Overview*. Oregon State University and University of Idaho Extension Services.

Stocker TF. 2015. The silent services of the world ocean. *Science* **350**(6262): 764–765. DOI: 10.1126/science.aac8720.

Strauss B, Tebaldi C, Kulp S, Cutter S, Emrich C, Rizza D, Yawitz D. 2014. *California, Oregon, Washington and the Surging Sea: A vulnerability assessment with projections for sea level rise and coastal flood risk*. Climate Central Research Report, 29.

Sweet WV, Park J. 2014. From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future* **2**(12): 2014EF000272. DOI: 10.1002/2014EF000272.

Sydeman WJ, García-Reyes M, Schoeman DS, Rykaczewski RR, Thompson SA, Black BA, Bograd SJ. 2014. Climate change and wind intensification in coastal upwelling ecosystems. *Science* **345**(6192): 77–80. DOI: 10.1126/science.1251635.

Sydeman WJ, Poloczanska E, Reed TE, Thompson SA. 2015. Climate change and marine vertebrates. *Science* **350**(6262): 772–777. DOI: 10.1126/science.aac9874.

Thorne KM, Powelson KW, Bui TD, Freeman JY, Takekawa CM, Janousek CN, Buffington KJ, Elliott-Fisk DL. 2016. *Assessing coastal manager science needs and disseminating science results for planning. Data Summary Report Prepared for the California and North Pacific Landscape Conservation Cooperatives*. USGS Western Ecological Research Center: Vallejo, CA, 110.

Toseland A, Daines SJ, Clark JR, Kirkham A, Strauss J, Uhlig C, Lenton TM, Valentin K, Pearson GA, Moulton V, Mock T. 2013. The impact of temperature on marine phytoplankton resource allocation and metabolism. *Nature Climate Change* **3**(11): 979–984. DOI: 10.1038/nclimate1989.

Vose RS, Applequist S, Bourassa MA, Pryor SC, Barthelmie RJ, Blanton B, Bromirski PD, Brooks HE, DeGaetano AT, Dole RM, Easterling DR, Jensen RE, Karl TR, Katz RW, Klink K, Kruk MC, Kunkel KE, MacCracken MC, Peterson TC, Shein K, Thomas BR, Walsh JE, Wang XL, Wehner MF, Wuebbles DJ, Young RS. 2014. Monitoring and Understanding Changes in Extremes: Extratropical Storms, Winds, and Waves. *Bulletin of the American Meteorological Society* **95**(3): 377–386. DOI: 10.1175/BAMS-D-12-00162.1.

Wahl T, Chambers DP. 2015. Evidence for multidecadal variability in US extreme sea level records. *Journal of Geophysical Research: Oceans* **120**(3): 1527–1544. DOI: 10.1002/2014JC010443.

Wahl T, Jain S, Bender J, Meyers SD, Luther ME. 2015. Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Clim. Change* **5**(12): 1093–1097.

Wainwright TC, Weitkamp LA. 2013. Effects of Climate Change on Oregon Coast Coho Salmon: Habitat and Life-Cycle Interactions. *Northwest Science* **87**(3): 219–242. DOI: 10.3955/046.087.0305.

Waldbusser GG, Hales B, Langdon CJ, Haley BA, Schrader P, Brunner EL, Gray MW, Miller CA, Gimenez I. 2015. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nature Climate Change* **5**(3): 273–280. DOI: 10.1038/nclimate2479.

Wang D, Gouhier TC, Menge BA, Ganguly AR. 2015. Intensification and spatial homogenization of coastal upwelling under climate change. *Nature* **518**(7539): 390–394.

Wang XL, Feng Y, Swail VR. 2014. Changes in global ocean wave heights as projected using multimodel CMIP5 simulations. *Geophysical Research Letters* **41**(3): 1026–1034. DOI: 10.1002/2013GL058650.

Weatherdon LV, Magnan AK, Rogers AD, Sumaila UR, Cheung WWL. 2016a. Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. *Global Change and the Future Ocean* 48. DOI: 10.3389/fmars.2016.00048.

Weatherdon LV, Ota Y, Jones MC, Close DA, Cheung WWL. 2016b. Projected Scenarios for Coastal First Nations' Fisheries Catch Potential under Climate Change: Management Challenges and Opportunities. *PLOS ONE* **11**(1): e0145285. DOI: 10.1371/journal.pone.0145285.

Welch MJ, Watson S-A, Welsh JQ, McCormick MI, Munday PL. 2014. Effects of elevated CO2 on fish behaviour undiminished by transgenerational acclimation. *Nature Climate Change* **4**(12): 1086–1089. DOI: 10.1038/nclimate2400.

Wittmann AC, Pörtner H-O. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change* **3**(11): 995–1001. DOI: 10.1038/nclimate1982.