TECHNICAL SUPPLEMENT

The Oregon Conservation Strategy: Potential Impacts of Global Climate Change in Oregon's Nearshore Ocean

Introduction

Global atmospheric concentrations of carbon dioxide, the dominant greenhouse gas, have increased markedly since 1750 and now far exceed pre-industrial values[1]. The Intergovernmental Panel on Climate Change, an international working group of several thousand scientists, found that the Earth's climate is warming as a result of this increase in carbon dioxide concentrations[1]. The rapid increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea levels observed over the last century are evidence of these climatic changes[1]. A large portion of the carbon dioxide in the Earth's atmosphere is absorbed by the world's oceans[2,3]. Oceanic absorption of carbon dioxide temporarily slows atmospheric accumulation and its effect on climate[4]. This uptake of carbon dioxide changes the chemical equilibrium of seawater, making the oceans more acidic[1]. Evidence from all continents and almost all oceans show that many natural ecosystems are being affected by these impacts of increased carbon dioxide concentrations[1].

Impacts on the marine environment include, but are not limited to, increasing ocean temperatures, sea level rise, changing circulation and weather patterns, and changes in ocean chemistry[5]. Due to the complexity of the ocean and the relative scarcity of long-term or large-scale studies, the specific processes through which a changing climate will impact Oregon's nearshore are not entirely clear[6]. Scaling global climate change impacts to a local level can be problematic. Directly attributing changes observed locally to increased global carbon dioxide concentrations may be difficult[2]. Nevertheless, the significance of these potential impacts, especially along the dynamic Oregon coast[6], provides focus for scientific research efforts to document their effects.

Managing for a Changing Marine Environment

Sustainable resource management in a rapidly changing climate requires proactive planning for mitigation and adaptation at multiple scales. Physical and chemical changes are occurring in all habitats[1] and will affect local fish and wildlife resources[7] managed by the State of Oregon. Given that climate change is a complex and controversial issue, federally approved state wildlife action plans are useful platforms to guide statewide and regional planning efforts[8]. The Oregon Conservation Strategy[9] and its marine component the Oregon Nearshore Strategy[10] form the blueprint for the conservation of Oregon's fish, wildlife, and their habitats.

The Oregon Nearshore Strategy focuses on species and habitats in Oregon's nearshore marine environment[10]. Preparing for these impacts of a changing climate on Oregon's ecosystems is imperative[11]. Scientific information is available to guide initial planning efforts. This document, as a technical supplement to the Oregon Nearshore Strategy, synthesizes relevant information on Oregon's changing ocean. This information is intended to:

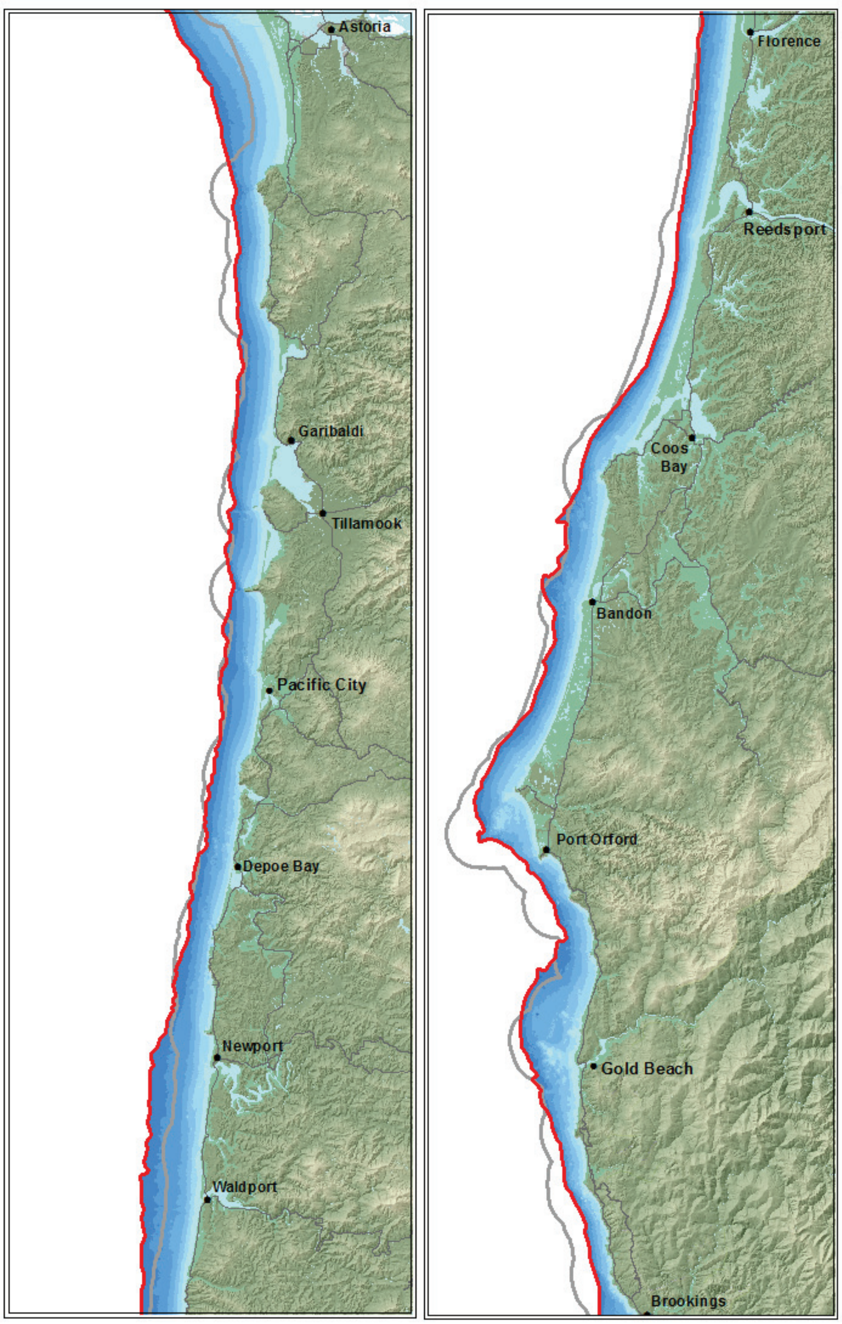
- Provide insight into potential impacts of a changing marine environment on Oregon's nearshore marine habitats and species;
- Guide future investigations and monitoring efforts in Oregon's nearshore environment; and
- Provide information and guidance for future refinement of the Oregon Nearshore Strategy.

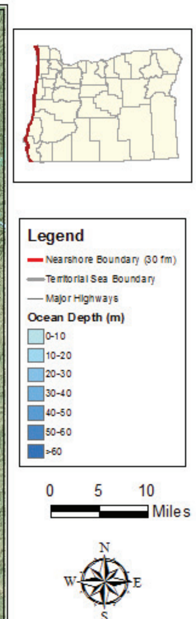
Oregon's Nearshore Marine Environment

Oregon's nearshore marine environment encompasses the area between the coastal high tide line offshore to the 30 fathom (180 feet or 55 meter) depth contour[10] (Figure 1). This area includes a variety of habitats and a vast array of fish, invertebrates, marine mammals, birds, algae, plants and micro-organisms[10]. The sandy beaches and rocky areas located between extreme high and low tides are the intertidal zone that links subtidal habitats and offshore marine waters to the terrestrial environment[10]. Oregon's nearshore subtidal habitats include all rocky and soft bottom areas below the low tide line to the 30-fathom depth contour[10]. Nearshore pelagic or open water habitats out to 30 fathoms are part of the ocean's neritic zone that extends beyond the nearshore out to approximately 650 feet (200 meters).

Many factors, including light, temperature, storms, circulation, currents, freshwater input, and offshore conditions affect Oregon's nearshore habitats and the species living there[10]. More than 40 estuaries and tidal creeks[6], including the influential Columbia River estuary, link the terrestrial environment to Oregon's

Figure 1: Oregon's Nearshore Ocean





Oregon's nearshore is defined as the area from the coastal high tide line out to 30 fathom (180 feet or 55 meter; red line) depth contour. The state's jurisdictional territorial sea boundary extends to three nautical miles (grey line).

marine waters. Nearshore habitats are connected to the offshore continental shelf and are affected by both local environmental forces and changes occurring elsewhere in the Pacific, primarily through linkages with the dynamic offshore waters of the California Current. Species in Oregon's nearshore respond to changes in their habitats in various ways. All of these habitats and species are integral parts of Oregon's complex nearshore ecosystem, and are interconnected through a multitude of biological, physical, and chemical factors that will be impacted by global climate changes.

Cyclic Patterns and Climatic Variability in Oregon's Nearshore

Oceans exhibit patterns and variability over a range of spatial and temporal scales. Ocean and climatic conditions are tightly linked, which influences the organisms that inhabit the marine environment[5]. Annual and interannual climatic patterns tend to be most variable in the nearshore and are highly responsive to a wide variety of physical drivers[6]. Patterns influencing Oregon's nearshore ocean include processes such as upwelling and downwelling processes, the El Niño Southern Oscillation, and the Pacific Decadal Oscillation.

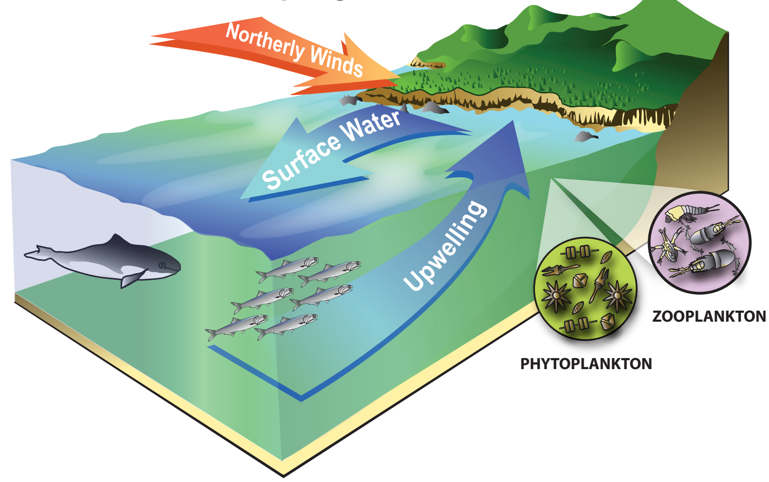
Upwelling/Downwelling: A large portion of the variability of Oregon's nearshore is closely related to local annual wind patterns[6], which exert drag on the surface of the ocean. The combination of the Earth's rotation and the dynamics of transferring the wind's energy downward into the water column results in net movement of the ocean's surface layer in a direction perpendicular to the wind. In the northern hemisphere, surface water moves 90 degrees to the right. Off the Oregon coast, when spring/summer northerly winds move surface waters away from shore, they are replaced by waters from depth in a process called upwelling (Figure 2a). Typically, this upwelled water is nutrient rich and supports strong productivity in the spring and summer.

Conversely, when fall/winter southerly winds move water towards shore, surface waters are pushed downward in a process called downwelling (Figure 2b). The transition from the fall/winter downwelling regime to the spring/summer upwelling period is called the spring transition, as it usually occurs in early spring. The winds that drive upwelling go through phases of acceleration and relaxation, and during relaxation periods, offshore waters bring planktonic food and

Figure 2. Upwelling and Downwelling

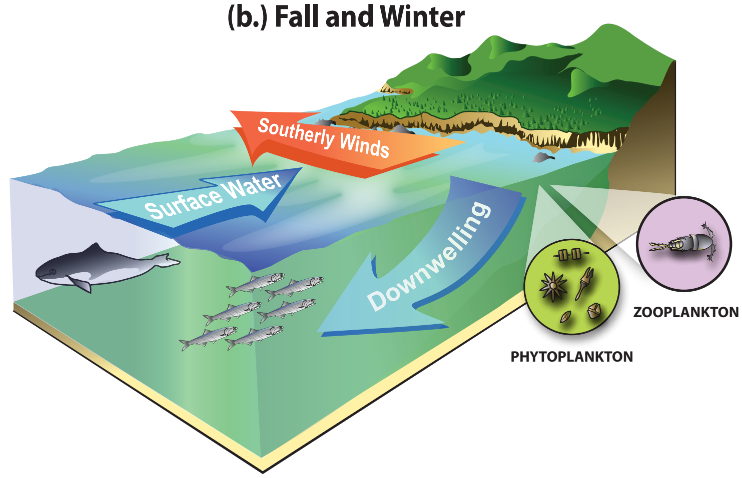
Spring and summer winds from the north move surface waters offshore. Surface waters move perpendicular to wind direction due the combined effects of earth's rotation and energy transfer downward through the water column. Surface waters are replaced by cold, nutrient rich, low oxygen waters from the deep offshore ocean in a process called upwelling. Production of nearshore plants and animals is highest during spring/summer upwelling.

(a.) Spring and Summer



Fall and winter winds from the south drive surface waters shoreward where they submerge in a process called downwelling. Downwelling transports nearshore surface waters to resupply deep offshore waters with oxygen. Storm activity is highest, and runoff from precipitation over land contributes to mixing nearshore waters and loading the environment with oxygen and freshwater inputs.

(b.) Fall and Winter



larvae into the nearshore. During upwelling surges, plankton is carried offshore and distributed along the coast. Both upwelling and downwelling events are important to maintaining the base of the marine food web, and this dynamic may become out of balance as ocean conditions become less predictable.

El Niño Southern Oscillation: Physical changes to Oregon's marine habitats on interannual scales include the ocean surface temperature changes associated with El Niño Southern Oscillation (ENSO) events, an irregular tropical cycle with connections to the Oregon coast. The tropical Pacific typically displays a large gradient in sea surface temperature, with a warm pool in the west and cooler temperatures along the equator in the east. Periodically, this warm pool surges eastward towards the American continents. These ENSO events, which include coupled El Niño and La Niña conditions, typically occur over a period of three to seven years with anomalous conditions persisting for six to 12 months at a time[12]. El Niño conditions along Oregon's coastline are characterized by the influx of warm tropical waters at the surface[12]. Severe El Niño events may move the colder and nutrient rich water deeper by as much as 165 feet (50 meters), affecting the quality of upwelled water in the nearshore and limiting nutrients brought to the surface[12]. La Niña conditions include cooler ocean surface temperatures off the Oregon coast, and generally exhibit smaller changes in the water properties[12,13]. This variability affects primary productivity, species distribution and abundances, and can drastically alter marine food web dynamics in Oregon's nearshore[12].

Pacific Decadal Oscillation: The Pacific Decadal Oscillation (PDO)[14] is considered the dominant driver of interdecadal (~20 – 30 years) variability in the North Pacific[15]. PDO is responsible for long-term changes that manifest in the California Current as changes in temperature and large-scale horizontal movement of water[16,17]. In general, the PDO alternates between two distinct phases[14]. During a positive phase of PDO, downwelling conditions off the west coast are prominent, leading to a transport of warm surface water northward from offshore California and toward the Pacific Northwest coast,whereas during the negative phase, upwelling conditions prevail and colder water is pulled southward[14,16,17]. This large-scale oceanic variability results in changes in species abundances, compositions, and distributions, and translates to impacts on the survival and distribution of salmonids[14] and multiple other marine fishes[18].

Many of these processes are controlled in part by physical climatic conditions and are altered as the Earth's climate changes due to increases in atmospheric carbon dioxide concentrations[6]. These sources of variability also interact with each other to produce additive or modulating effects over multiple time scales. Climatic variability introduces added complexity and makes it difficult to predict the consequences of a changing climate. However, the observed effects of climatic variability offer insight into how Oregon's dynamic nearshore ecosystem might respond to a changing climate.

Impacts from a Changing Marine Environment on Strategy Habitats and Species

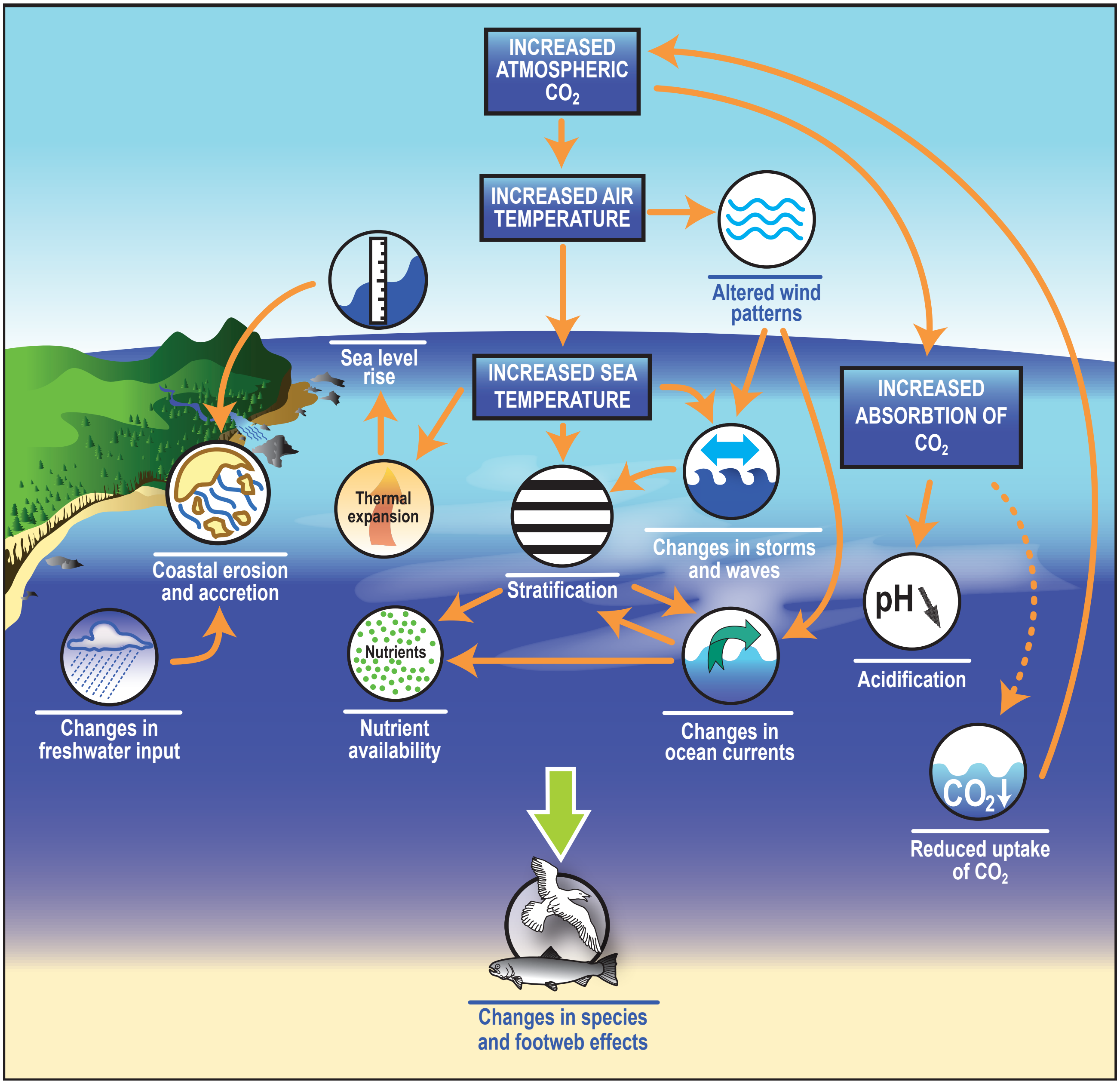
Understanding how atmospheric carbon dioxide concentrations may impact the marine environment has lagged behind that of terrestrial ecosystems[3]. No long-term (> 50 years) oceanic datasets off the Oregon coast exist and there are still many unanswered questions regarding how these effects will play out at the regional and local levels[11]. Despite the uncertainty, it is clear that Oregon's nearshore habitats and species are already experiencing changes consistent with the predicted effects of increased concentrations of atmospheric carbon dioxide[6] (Figure 3).

Changing Ocean Temperatures

The world's oceans are the main reservoir for heat energy retained in the Earth's atmosphere[2,19]. As atmospheric temperatures increase, over 90 percent of the added heat energy is absorbed by the ocean[2]. Most heat is stored in the upper water column[20]. During the latter half of the 20th century, average ocean temperatures have risen 0.2° F (0.1° C) in the

Figure 3: Oceanic Impacts of Increased Atmospheric Carbon Dioxide

The world's oceans are essential to regulating global climate, which is changing rapidly as carbon dioxide concentrations build in the atmosphere. As seen in this diagram, these impacts can interact and influence each other. Understanding the complexities of these impacts will inform managers attempting to address the impacts of a changing marine environment.



upper layers of the global ocean[2]. Oregon's coastal surface waters (< ~650 feet or 200 meters) have warmed an average of 0.5° F (0.3° C) per decade over this time period and are predicted to increase by approximately an additional 2.2 ° F (1.2° C) by the mid-21st century[6]. This estimate may be conservative, as observations over recent decades show that summertime water temperature increases have exceeded predictions[6].

Water temperature is a key factor in determining the strength of mixing in the nearshore, with higher temperatures inhibiting mixing because stratified layers of warm surface waters mix less easily with colder, deeper water. As the climate warms, the upper ocean will almost certainly be more stratified on average[21]. The thermocline (the relatively distinct layer of steep temperature gradient) is 32 – 65 feet (10 – 20 meters) deeper off Oregon in the early 21st century, compared with the middle of the 20th century[22].

Stronger stratification will make ocean mixing due to wind patterns less effective at bringing nutrients to the surface, thereby reducing primary productivity[3,21]. Increased stratification of nearshore waters may be partially mitigated[21] by predicted increases in the northerly winds that cause coastal upwelling off the Oregon coast[23].

Warming temperatures have a direct impact on the degree of environmental stress that organisms are subject to[24]. Some organisms respond by relocating to microhabitats with preferred conditions. For many immobile intertidal organisms, increased exposure and thermal stress may limit the range of suitable habitat or may reduce local populations[12,24]. Some species, such as the California mussel (*Mytilus califorinus*), grow larger or faster due to an accelerated metabolic response to warmer water temperatures[24]. In turn, this can alter competition and predation dynamics, changing the flow of energy through the food web and the structure of the ecosystem[24].

Warming ocean temperatures appear to be causing a northward shift in the distribution of fish and other mobile animals, likely associated with species-specific temperature requirements[25,26]. Poleward movement of marine fishes may actually increase species richness at temperate latitudes (e.g. the North Sea[26,27]). Species exhibiting these shifts or range expansions tend to be smaller[26,27], which will change the energy flow through the food web and alter the dynamics of the ecosystem[27]. Poleward population shifts may also be linked to temperature-associated food source availability[25]. Some fish species exhibit enhanced growth and survival when cool water zooplankton is available because this food base provides greater biomass and higher energy content[25]. Warming trends may be facilitating the ongoing range expansion of the Humboldt squid (*Dosidicus gigas*), an opportunistic predator with high consumption rates whose diet includes many commercially fished species[28].

Sea Level Rise

Global sea level is rising at an approximate rate of 0.07± 0.02 inches (1.8 ± 0.5 millimeters) per year, though this rate varies by region[2]. In the Pacific Northwest, the regional rate of sea level rise has been estimated to be slightly higher than the global average, at 0.1 inches (2.3 millimeters) per year during the 20th century[29]. Sea surface elevation rises when seawater expands as a result of increasing ocean temperatures and when land ice melts, increasing the amount of water in the ocean[2,20]. The thermal expansion of seawater currently contributes more to sea level rise than glacier and ice caps melting[20].

As sea level rises, the high-tide line migrates inland, increasing the potential for inundation, erosion, or other impacts to intertidal habitats. In Oregon, shoreline characteristics and elevation vary between steep hard substrate areas with low erosion potential to flat sandy dunes that could wash out easily as sea levels rise. Due to the variable rate of uplift on the Oregon coast, some areas may experience severe impacts sooner than others[29]. However, the projected acceleration in the rate of sea level rise will exceed all rates of uplift along the Oregon coast by the mid-21st century[29], affecting the entire Oregon coast. Natural climate variability can also affect sea levels during El Niño events[30] and during seasonal extreme high water levels occurring in the winter[31]. These combined effects on sea levels are projected to increase future coastal flooding and erosion of shoreline habitats[31,32].

Rising sea levels in rocky intertidal habitats may dramatically alter species interactions such as competition, predation, and reproduction[24]. For example, the upper range of the California mussel, a habitat engineer, continues to expand upwards in rocky shore elevation, competing with other attached invertebrates[24]. The vertical range of a keystone predator, the ochre sea star (*Pisaster ochreceus*), is also expanding with sea level rise, likely increasing predation rates on sessile intertidal invertebrates[24]. The spatial extent of intertidal sandy beaches will be reduced as sea levels rise, due to restricted inland migration imposed by coastal development and anthropogenic alteration of sediment dynamics[33]. Altered shorelines are subject to drastic increases in sand loss during large storm events, thus compounding the effects of sea level rise in sandy habitats[34]. Shoreline armoring and coastal development has been shown to reduce the ability of sandy beaches to respond to sea level rise through typical sediment dynamics[35]. The combined effects of sea level rise and coastal development on intertidal habitats will include impacts such as a reduction in the amount of spawning habitat available to species like surf smelt (*Hypomesus pretiosus*) and Pacific sandlance (*Ammodytes hexapterus*)[36].

Changes in Cycles

Oregon's nearshore ocean conditions vary on multiple time scales and to differing degrees. While some of these cycles are relatively well understood, for example, the annual cycle of upwelling and downwelling events, some, like the Pacific Decadal Oscillation[14], have only been described within the last 20 years. Understanding the underlying mechanisms responsible for these cycles is a necessary first step in understanding how they may be altered due to climate change[12]. Natural climate variability can change the biological and ecological characteristics of the nearshore, and these changes may offer clues to how habitats and species will react to a changing climate.

Annual Cycles: Increasing atmospheric carbon dioxide concentrations raise air temperatures over land more than over the ocean, leading to a greater pressure differential[23]. As a result, alongshore winds parallel to the coast could increase, which would intensify upwelling[23]. Within the California Current region, observations show that wind-driven upwelling has intensified over the last 30 years[37]. Multiple datasets off the Oregon coast indicate that summer upwelling is intensifying, particularly on the southern Oregon coast[6]. Upwelling intensification may lead to increased primary productivity though a greater delivery of nutrients to the nearshore[37]. However, this intensification could be offset by increased ocean stratification, potentially limiting the delivery of nutrients to the surface through wind-driven mixing[3,21]. The nearshore-offshore gradients in water temperature could become more pronounced as offshore waters warm and nearshore upwelling strength increases, creating stronger upwelling fronts that may impact distribution and abundances of marine organisms[21].

As a consequence of climate change, the timing of the spring transition could be delayed and followed by stronger upwelling effects later in the season[37,38]. The variability in wind stress has increased off the Oregon coast[6], leading to greater inconsistencies in upwelling patterns throughout the season. The intermittent wind relaxation periods may become less frequent, resulting in reduced transport of organisms and food into the nearshore[37]. Intensified coastal upwelling may enrich nearshore primary production of marine algae and phytoplankton[21,37] and could impact the marine food web through changes in species abundance and composition[21]. When the spring transition is delayed, primary production is also postponed[38]. Low levels of primary productivity early in the season, or delayed delivery of planktonic food sources, may lead to low recruitment of many organisms for which food availability is time-sensitive[21,38]. Planktonic fish and invertebrate larvae that are transported within the upwelling cycle may not reach inshore habitats in time for successful recruitment and replenishment of coastal populations[38]. Any changes in the primary productivity, the base of the ocean food web, will have profound implications for marine food webs[3]. Future predictions suggest greater seasonal variability in large-scale climatic cycles influencing the California Current region, possibly leading to increased interannual variation in the timing of spring transition[21].

A recent extreme event off the Oregon coast may provide insight on how the system could respond to changes in the spring transition. In 2005, there was a delay in the onset of coastal upwelling by two to three months[39,40]. This delay resulted in substantial changes in the physical environment during that season, including abnormally warm and fresh surface waters, trapping nutrient rich waters below[40]. Primary production was substantially lower prior to the delayed transition[41]. Pelagic fish and cephalopods were displaced poleward and towards shore and suffered reduced recruitment during early life stages[42]. Finally, marine mammals exhibited anomalous feeding patterns[43]. This example illustrates the importance of the annual cycle to Oregon's nearshore.

Interannual Cycles: ENSO is known to be sensitive to changes in background ocean surface temperatures and current temperature changes in the Pacific provide a mechanism to link changes in the frequency or magnitude of ENSO to climate change[44-46]. Over the last century, the observed behavior of ENSO has changed[47] and reconstructions to the early 1500's confirm that ENSO's 20th century behavior was unusual[48]. El Niño events have become more frequent in the last several decades[49-52]. The 1976-1977 climate shift, observed in the PDO index[14], is associated with dramatic changes in El Niño formation, including higher ocean surface temperatures and a tendency for more prolonged and stronger El Niño events[47]. Reconstructions of ENSO events back to 1525 indicate nearly half of all extreme ENSO events (including both El Niño and La Niña conditions) have occurred in the 20th century, with 30 percent in the latter half[48]. Nearly one third of all protracted ENSO events have occurred in the last century[48], though this has been suggested to be an artifact of increased frequency of events[53]. Based on observations of past events, changes in both the frequency and magnitude of ENSO events will impact Oregon nearshore waters[13,30].

Predicting how ENSO may change in a warmer climate is difficult. ENSO events are inadequately represented in global climate models used for projections[15,46]. Projections for future changes in the frequency and magnitude of ENSO events are inconsistent[21,46], possibly due to different responses to increased carbon dioxide concentrations among models[46]. Projections have also been complicated by the discovery of a novel and distinct variation of El Niño conditions that differs in the location of the maximum temperature anomalies and connections to the mid-latitude waters[45,54]. A recent study suggests that the frequency of the two variations of El Niño may change with climate change[54], however, further investigation of the connection between ENSO events and climate change is required[44,47,48].

If El Niño events continue to be stronger and more frequent, Oregon's nearshore habitats and species will be increasingly affected by those events. Extreme El Niño conditions in 1983 resulted in low overall primary productivity in Oregon and lead to longer and less productive food chains[55]. The 1997 strong El Niño dramatically affected zooplankton species compositions off the coast of Oregon, and replaced northern species with sub-tropical species of lower energy content[56]. This event also allowed multiple warm-water migratory fish species into Oregon waters, including the novel discovery of the Humboldt squid, though fewer warm water species were reported during this event than during the 1983 El Niño[57]. These two El Niño events (1983 and 1997) during a warm phase of the PDO produced the largest oceanographic anomalies off the Oregon coast in the latter half of the 20th century[13,30] and dramatic biological responses as a result[55-57].

Interdecadal Cycles: As one of the key components of North Pacific decadal variability, the PDO has dramatic impacts on the physical marine environment influencing Oregon's nearshore. There are climatic similarities in how the PDO and climate change impact the marine environment[47]. The lack of a long term observational record hinders scientists' ability to predict how a decadal source of variability, such as the PDO, may be impacted by future climate change. Only three shifts of the PDO occurred during the 20th century[14]. Currently, the PDO is not predicted to significantly change spatially or temporally during the 21st century[58]. However, models do not adequately capture the temperature dynamics associated with PDO and these results are still uncertain[58]. Warming trends over the North Pacific project an increase in winter ocean surface temperature as large as the amplitude of a PDO phase shift by mid-21st century, after which the temperature trend will dominate as the leading mode of variability in the North Pacific[15,21].

Species that are adapted to historic or recent PDO patterns may experience novel conditions with the combined effects of climate change and natural variation as soon as the first half of the 21st century[15]. Amplified by the global warming trend in temperatures, the California Current region will likely experience a greater frequency of years with lower primary productivity, such as those experienced during a positive PDO cycle[21]. Ongoing observations have shown that a positive PDO results in the dominance of warm-water zooplankton, which generally have lower energy content; this may have implications for the upper food chain[21], similar to conditions in strong El Niño years such as those shown in 1983[55]. Additional clarification is required to reduce these uncertainties and improve the accuracy of predictions in the context of future climate change[15,46,58].

Hypoxic/Anoxic Condition Changes

Seawater contains dissolved oxygen that is required for marine organisms to live. Oxygen is used when organisms respire and is replaced by contact with the sea surface, where oxygen can be exchanged with air (Figure 4). Since the middle of the 20th century, the concentration of dissolved oxygen has significantly decreased off Oregon's coast[6]. Severe inner shelf (< 230 feet or 70 meters) hypoxia (low oxygen) has been documented within the last decade[59,60] and the occurrence of hypoxia has expanded to regularly encompass approximately 80 percent of Oregon's nearshore water column between June and October during this time period[59]. In addition, 2006 marked the first documentation of anoxia (zero oxygen) in Oregon's nearshore[59]. Anoxic events are sporadic but potentially lethal for marine organisms[25,59].

Hypoxic conditions occur naturally in deeper water where organism respiration removes oxygen from seawater that cannot be easily replaced by contact with air[60]. Changes in coastal upwelling could boost the delivery of deep, low oxygen waters into nearshore waters[23,61], where respiration can further deplete the available oxygen and subject nearshore coastal ecosystems to hypoxic or anoxic events[59,60]. Upwelling intensity is projected to increase with climate change[6,23,37], which may have negative repercussions on the availability of oxygen in the nearshore.

Increased water column stratification as a result of warmer temperatures could reduce oxygen exchange with deeper waters and contribute to hypoxic conditions[62]. Consistent with predicted impacts of climate change, declines in dissolved oxygen have been documented offshore in the California Current region[62]. Wind-induced mixing can potentially improve hypoxic conditions in the shallow nearshore through the addition of oxygen at the surface[60]. However, strong upwelling favorable winds in the Oregon nearshore appeared to be insufficient to reduce stratification and the cold, oxygen-depleted waters transported shoreward decreased net oxygen concentrations further during a severe hypoxic event in 2002[60]. Severe storm events and wave heights increasing with climate change on the Oregon coast[32,63] may moderate hypoxic conditions by inducing strong mixing and oxygen exchange between the sea surface and the air. Changes in circulation can affect oxygen concentrations in the nearshore, such as the anomalous influx of water from the sub-Arctic off Oregon in 2002[64]. This change in source water substantially increased available nutrients and resulted in higher than normal respiration and hypoxic conditions in the nearshore[64]. ENSO events have also been shown to affect water temperatures and nutrients in upwelling areas[65]. Changes in the intensity and frequency of ENSO events as a result of climate change[49-52] may also impact oxygen concentrations in the nearshore.

When oxygen levels decrease, marine organisms may suffer stunted growth, slowed metabolic rates, or death[66] (Figure 4). Responses of individual organisms to hypoxic and anoxic conditions depend on the duration and intensity of the oxygen depletion[61]. Responses vary by species and depend in part on how well organisms recognize and avoid undesirable conditions[61]. Crustaceans[61,67] and echinoderms have been shown to be more sensitive to lower oxygen thresholds than annelids, molluscs, and cnidarians[61]. Hypoxic areas generally have higher mortality of sessile organisms and greater displacement of mobile species[25,60,61,66]. Both the physical conditions and the catch of multiple marine fish species and Dungeness crab deteriorate as oxygen levels decrease[68]. Some fish exhibit sub-lethal effects of hypoxia that include increased energy spent supporting respiration[67], potentially reducing feeding or other essential activities.

Some hypoxic or anoxic events can have community level impacts. In severe conditions, most sessile invertebrates will die and be replaced by bacterial mats, and reefs known to support diverse fisheries will be completely devoid of fish[59,60]. Low oxygen areas are characterized by low species richness[61,68]. Community dynamics change as trophic structure and energy pathways shift in response to hypoxia[61]. Predation rates are reduced within hypoxic areas[69] and displacement of mobile species will put additional pressure on adjacent oxygenated habitats, where increased predation could alter a broad range of marine populations[61,66]. The extent of the marine ecosystems affected by current and future hypoxic events may also be underestimated, as the conventional definition of hypoxia (< 2 parts per million or 2 milligrams O_2/liter) is lower than sublethal and lethal thresholds for many benthic marine species[67].

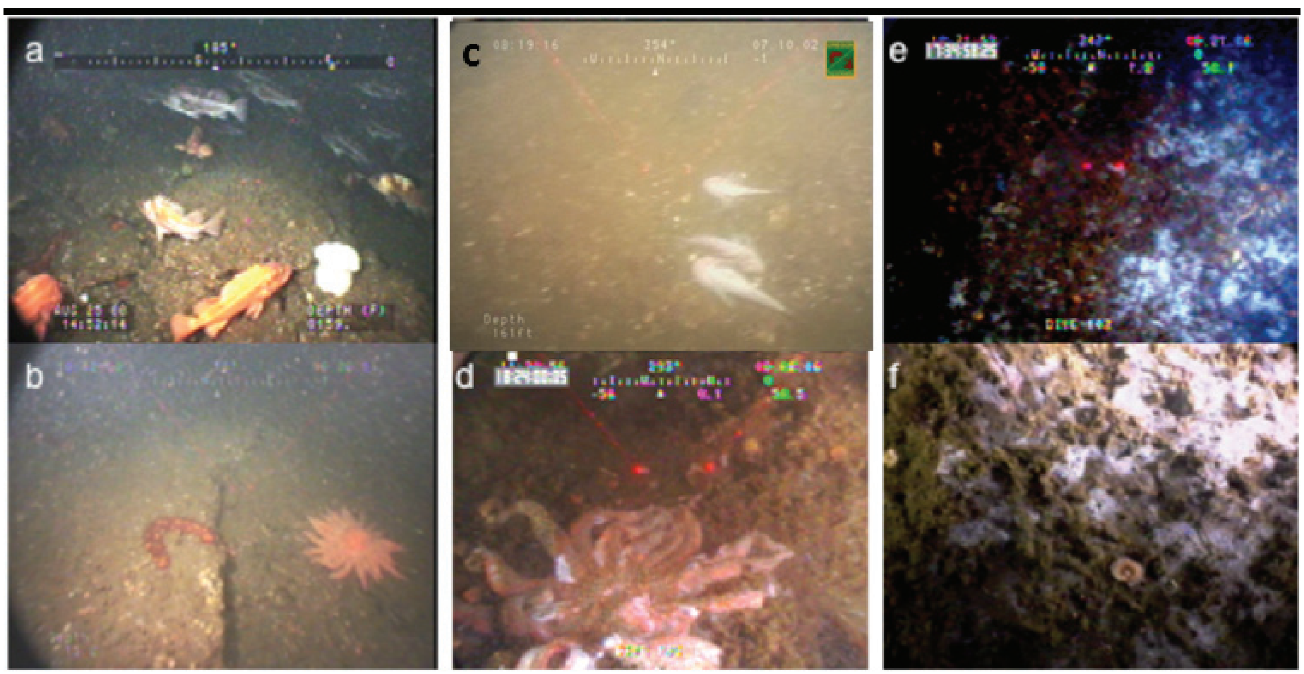
Extreme Wave Height and Storm Pattern Changes

Wave heights measured along the west coast are highest along the Oregon coastline[32]. Oregon wave heights have increased during the past 50 years[32,63]. Wave heights peak during El Niño events, but also result from background changes in warming water temperatures related to climate change[32,63]. Both the relatively low summer waves and the higher wave heights generated by winter storm events have been increasing off the Oregon coast since the mid-1970s[70]. The most extreme waves generated during winter storm events are also increasing at a higher rate than the winter average wave height[70].

As seawater warms, this thermal energy can result in storms with greater intensity, longer duration, earlier annual onset, and larger total area affected[71]. Storm intensity has also been increasing offshore of Oregon during the past 50 years and has been linked to warming water temperatures related to climate

Figure 4: Impacts of Hypoxic/Anoxic conditions in Oregon's Nearshore

Screen captures of ROV-based video transect surveys of nearshore rocky reefs off Cape Perpetua on the central Oregon coast. A) pre-anoxia rockfishes (Sebastes spp.); B) benthic invertebrates; C and D) mortality of fish and invertebrates during the 2006 anoxia event; E and F) formation of bacterial mats following 2006 anoxia event.



change[32,63]. In the North Pacific, winter storm intensity has increased but with a corresponding decrease in frequency, possibly resulting from a poleward shift in the storm track during the late 20th century[29]. The capacity for storm tracks to carry heat, precipitation, and surface wind stress toward the poles is intensified by climate change[72]. Changes in storm patterns resulting from climate change could also affect stratification persistence, wind- and wave-induced mixing, and oxygen availability in Oregon's nearshore. Though loosely associated with ENSO and PDO climatic variability, the storm intensities and track characteristics appear to be related to increasing upper atmospheric winds over the North Pole, which are strongly influenced by changes in sea surface temperature in the North Pacific[63].

Changes in storm patterns and larger wave heights correspond to greater erosion of shoreline habitats caused by increased breaker heights, wave action, and swash run-up levels[32]. The combination of sea level rise, increased storm intensity, larger wave heights and anthropogenic shoreline development reduces available sandy intertidal habitat [29,73]. This "coastal squeeze" also leads to decreases in biodiversity of invertebrates, recruitment, and prey availability for shoreline predators[73,74]. An increase in storminess may affect attachment strength of rocky inter-tidal organisms, though these have been shown in certain mussel species to vary seasonally[75]. Changes in wave action have also been shown to affect the size of intertidal algae and plants along the Oregon coast with those exposed to increased wave action being smaller with negative impacts on their reproductive capacity[76].

Changes in Sediment Movement

Sediment delivery and replenishment play key roles in shaping Oregon's nearshore sandy and soft bottom habitats. Sediment is stored, transported, and exchanged between the shoreline and ocean floor through upwelling[77], wave action, and the tides[78]. As storm intensity, wave heights, and sea levels increase due to climate change, sandy beaches are reduced between rising sea levels and adjacent upland areas[33,77,79]. Increased breaker heights and wave run-up levels can increase sediment suspension and change deposition rates[32]. Shoreline armoring and coastal development further restrict beach migration by limiting the available space for normal sediment dynamics to compensate for climate change impacts[33,34,79].

Sand tends to move rapidly away from shore during large storm events and gradually return during calm periods, thus protecting beaches from permanent erosion[33]. However, as storm patterns change as a

Shoreline impacts of climate change: Climate change impacts to shoreline habitats include rising sea levels, changes in wave heights and storm patterns, and changes to sediment movement and freshwater inputs. Low gradient sandy beaches, such as Beverly Beach on the central Oregon coast, may be at the greatest risk. ODFW Photo.

result of climate change, this delicate balance may be disrupted[33]. Shoreline armoring drastically increases sand loss during large storm events[33,34], thus adding to the impacts of greater storm intensity on the Oregon coast. With summer wave heights increasing as well[70], Oregon beaches have been unable to rebuild during that season[29].

Changes in sediment transport may also result from changes in wave direction, or from anomalous wave angles associated with major El Niño or storm events[80]. El Niño events create natural pulses in sea level and alter wave directionality along the Oregon coast, both of which can affect sediment dynamics[29,80]. During El Niño years, winter storm tracks are further to the south, which changes the general direction of waves reaching the shore[9]. This produces a redistribution of sand on beaches, creating hot spots of beach erosion that have already been observed along the Oregon coast, indicating a current sediment deficit[29]. These impacts may be intensified if El Niños become more frequent off the coast of Oregon[49-52]. As North Pacific storm tracks shift as a result of climate change[72], this may impact the sediment budgets along the Oregon coast as well.

Physical properties of sandy beaches, such as slope, particle size, and tidal variation, have significant impacts on community structure and species distribution, including polychaete worms, clams, and amphipods[81]. These and other physical beach characteristics are correlated with species richness, abundance, and biomass[78]. Low gradient sandy beaches typically house the greatest biodiversity[33]. These types of beaches are at higher risk from climate change impacts due to their erosive nature and the greater wave run-up on their gentle gradients, which could lead to the total disappearance of the habitat in extreme cases[33]. The compounded impacts of climate change have the potential to dramatically alter beach communities in Oregon's nearshore habitats.

Changes in Freshwater Inputs

Surface salinity and nutrient levels in Oregon's nearshore marine waters are strongly affected by freshwater discharge cycles. Freshwater arrives in the nearshore from rain-dominant smaller coastal rivers and streams[82], which have more localized impact[83], and from the snow-fed Columbia River[22]. Coastal watersheds along Oregon's coast are predicted to experience extreme flood events more often as a result of climate change[84]. Flooding of freshwater systems can increase erosion of riparian and estuarine sediments and have direct impacts on the substrate structure and availability of light in nearshore habitats[12]. Climate models predict increased annual precipitation in the Pacific Northwest[6,21], which will raise discharge levels of freshwater from coastal rain-fed watersheds

Changes in freshwater inputs to Oregon's nearshore: The Columbia River influences the water properties of Oregon's nearshore. Changes in freshwater inputs resulting from climate change may affect the structure and stability of the Columbia River plume, seen here in the lighter blue. Dr. Richard Brodeur, NOAA Photo.

Smaller watersheds, such as the Nestucca River, strongly affect local water properties in Oregon's nearshore. These coastal rivers and streams may experience extreme flooding events more often as precipitation patterns change as a result of climate change. ODFW and Oregon Department of Land Conservation and Development Photo.

into the nearshore during the winter and spring. Freshwater delivers nutrients to the nearshore, such as carbon and nitrogen inputs on sandy beaches[85] and nitrogen and silicate inputs to nearshore waters[83]. Oregon's nearshore may be affected by changes in the quality, quantity, and the variability in freshwater inputs resulting from climate change[83,85].

The Columbia River plume stretches hundreds of miles, moving seasonally[86]. It spreads primarily south and offshore from the mouth in the summer, and to the north and adjacent to the shore in winter, depending on climate conditions in the nearshore and freshwater inputs[86]. The average annual discharge on the Columbia River shows no significant long-term trend during the 20th century, however, the average summer discharge has decreased by approximately 30 percent during the same period[6]. This trend results from a combination of dam construction, water management regimes, and climate change[6]. The fraction of precipitation coming from snow has been decreasing in the western United States, resulting in snowpack water storage reductions that affect snow-fed rivers[87], such as the Columbia. In addition, the timing of spring stream flows in snow-fed watersheds will occur earlier in the year, shifting by 30 to 40 days by the end of the 21st century[87].

Altered freshwater inputs will modify the stratification and mixing of coastal waters and will affect riverine plume formation and stabilization[6]. With a decrease in the summer discharge, the seasonally productive Columbia River plume will be less intense and its inshore boundary next to the coastal upwelling front more diffuse[6]. The fronts that form the boundary of the Columbia River plume concentrate organisms from particular planktonic communities that provide a unique and valuable resource for upper trophic level consumers, such as salmonids and other planktivorous fishes[88]. Altered freshwater discharge levels may affect the timing of anadromous and catadromous populations to and from the nearshore[21]. For example, timing of spawning and outmigration of green sturgeon (*Acipenser medirostris*) in Oregon appears to be strongly related to both water temperatures and flow[89,90]. Changes in freshwater inputs may also affect recruitment success of juvenile fishes[91] and possibly change feeding ecology of organisms resident in Oregon's nearshore[92].

Ocean Acidification

The ocean acts as a sink, absorbing significant amounts of atmospheric carbon dioxide[3,93,94], and becomes increasingly acidic as a result[25,95]. While this absorption has slowed the growth of carbon dioxide levels in the atmosphere[4,96], the ability of the ocean to continue absorbing carbon dioxide will decrease over time[93]. Oceanic uptake of carbon dioxide will induce

OCEAN ACIDIFICATION

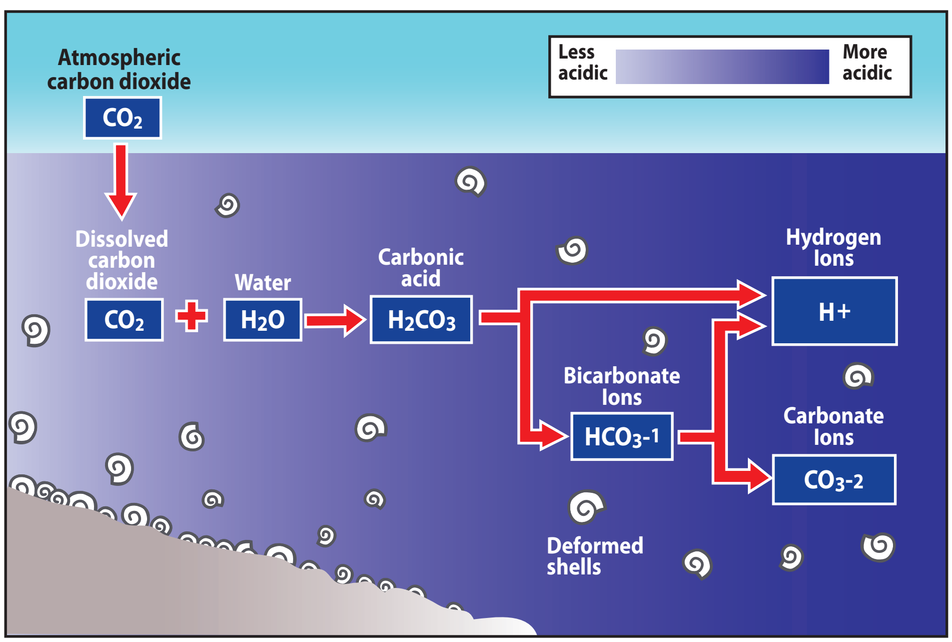


Figure 7: Ocean acidification

The absorption of carbon dioxide from the atmosphere reduces the availability of carbonate ions through a chemical reaction with seawater. These ions are necessary for the formation of skeletons and shells in many marine organisms. As more carbon dioxide is absorbed from the atmosphere, oceans will become more acidic.

fundamental changes in water chemistry that could have extreme impacts on biological ecosystems[96].

Seawater contains carbonate ions that are necessary for skeleton and shell formation of shellfish, corals, and planktonic food sources that support fisheries and upper trophic levels[71,95] (Figure 7). Ocean acidity affects the solubility and availability of the carbonate ions needed to form calcite and aragonite shells and skeletons[2], jeopardizing successful development and existence of many marine organisms[2,95]. These organisms are potentially vulnerable wherever the seawater saturation of aragonite or calcite is less than 100 percent[6]. Most of the global surface ocean is presently supersaturated for both calcite and aragonite, while deep ocean waters are typically undersaturated[2]. The boundary between these two states is called the saturation horizon, though the horizon depth varies by latitude and location[2]. The horizon depth is especially shallow (< 985 feet or 300 meters) in the northeast Pacific[95]. In the North Pacific, the calcite saturation horizon has moved ~ 130 – 330 feet (40 - 100 meters) towards the surface since pre-industrial times[2]. Recent surveys of the continental shelf off the Pacific Northwest show the saturation horizon at less than 330 feet (100 meters) below the surface, and during strong upwelling events, it can be at the ocean surface in the nearshore[95,97]. Seasonal variation in capacity of seawater to absorb carbon dioxide has been observed off the Oregon coast[98], which could lead to adverse conditions during the summer sooner in combination with upwelling events [95]. Spatial or temporal changes in the saturation state of these minerals are important for understanding how ocean acidification might impact biological systems[96].

The capacity for the ocean to continue absorbing carbon dioxide will decrease during the 21st century[2] and is projected to be more than 60 percent lower by 2100[94]. Acidity of ocean waters will continue to increase worldwide, though with some regional variation in the rate of change in the saturation horizon depth[94]. All saturation horizons are predicted to become more shallow with time[2,94] and at high latitudes, the aragonite saturation horizon may become extremely shallow within a few decades[94]. Predicted intensification of upwelling, which brings deep, naturally-acidic waters to the surface in Oregon's nearshore, may exacerbate the impacts of future ocean acidification[95]. Changes in primary productivity, water temperatures, and circulation can also affect carbonate ion availability[94]. Predicting the exact magnitude of acidification is problematic, primarily due to uncertainties with future atmospheric carbon dioxide concentrations[94].

Marine organisms may show differing responses to ocean acidification, particularly at local scales in nearshore waters, where the water characteristics are most variable and could buffer the effects of ocean acidification[99]. While some calcifying organisms require saturated conditions in order to form shells, others may be able to generate or maintain calcified structures in undersaturated conditions but at a bioenergeic cost[96]. California mussels (*Mytilus californius*) and gooseneck barnacles (*Pollicipes polymerus*) suffer reduced individual size and population abundance as waters become more acidic[25]. After only two days exposure to predicted levels of undersaturated seawater, live pteropods (pelagic gastropods) showed marked dissolution of their aragonite shells[94]. Ocean acidification may be associated with behavioral changes, such as difficulty with shell selection and slowed decision making in hermit crabs (*Pagurus bernhardus*)[100]. Exposure to acidic conditions during early life stages has been shown to disrupt recognition of predators in tropical marine fish species[101], though this has yet to be investigated for temperate fish species. The associated effects of water temperature interact with acidity to elicit complex responses with both abundance and diversity[102]. Molluscs showed the greatest reduction in abundance and diversity in response to higher acidity and warmer water temperatures, whereas nematodes increased in response to the same conditions, probably due to a reduction in predation and competition[102]. These complex responses to acidification may alter competition and predation dynamics, change species composition[25], reduce biodiversity, change community structure[102], or delay reproductive cycles[99].

Implications for Resource Management in Oregon's Nearshore

The chemical, physical, and biological changes occurring in the marine environment present major challenges for resource managers and policy makers[3]. As outlined above, many species and habitats will be affected by these changes, both positively and negatively, which may necessitate changes to current management actions[11]. New biological communities that form as species move and adapt may require a suite of new management techniques[11]. There are still many uncertainties regarding how climate change may affect Oregon's nearshore marine environment into the future[6].

Data gaps and Research Recommendations

Oregon's nearshore is a highly variable marine ecosystem that can benefit from research focused on the impacts of atmospheric carbon dioxide concentrations. Continuing to improve understanding of underlying mechanisms in variability is critical to refining predictions of the impacts on this ecosystem[71]. Research is needed to improve understanding of complex species responses and changes to habitats resulting from chemical and physical forcing[71]. Observational and monitoring networks need to be expanded in Oregon's nearshore ocean in order to continue to evaluate climate change impacts[6]. Continued investment in developing sampling capabilities should be a high priority, as well as maintaining facilities that support long term data collection[6].

A series of general research needs particularly relevant to Oregon's nearshore natural resources are listed below. These research recommendations are consistent among multiple adaptation guides available as resources for ODFW[11,103], and with the most recent assessment of climate changes related to carbon dioxide concentrations in Oregon[7]. These include:

- Climate change vulnerability assessments;
- Monitoring and evaluation of management actions;
- Long-term research on climate trends and ecosystem responses; and
- Regional downscaling of climate models.

General Recommendations for Future Management in a Changing Nearshore Climate

To address the changes occurring in Oregon's nearshore environment, resource management must remain flexible and adapt to sudden and unpredictable changes that are likely to characterize future marine ecosystems[3,104]. Adaptive management enables decision-makers to move forward with necessary actions without postponing decisions due to incomplete information[11]. Adaptation strategies will differ by the location and public preference for various alternatives. Therefore, it is important to develop site-based and goal oriented strategies for actions related to climate changes[11]. Assessments that incorporate risk exposure and vulnerability are needed to enable managers to prioritize species and habitats in need of the highest attention[3,97]. Management policies that restore and maintain critical ecological processes will play an increasingly important role[3,97] in maintaining resilience in marine environments.

Informing the Oregon Nearshore Strategy

Public participation is of the utmost importance when planning for climate change. The public process is a required element of federally-approved state wildlife action plans[11] and the controversy associated with climate change assessments could be high[11]. This supplemental document provides information for both the interested general public and for resource managers to better plan for the impacts of a changing marine climate.

Continuing to implement the Oregon Nearshore Strategy and its 16 recommendations is also considered a priority action, requiring additional resources[105]. These 16 recommendations identify some key management concerns regarding marine species and habitats[10]. While continuing to implement the recommendations from the Oregon Nearshore Strategy remains important, new actions or additional management measures may be necessary to address the unprecedented impacts of global climate change[11] and its impacts in Oregon's nearshore marine environment.

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ACKNOWLEDGEMENTS

Published in 2006, Oregon's statewide comprehensive conservation strategy is comprised of two documents: the Oregon Conservation Strategy and the Oregon Nearshore Strategy. In 2012 ODFW undertook efforts to further unify the two documents. Documenting the potential effects of climate change on species and habitats was among the tasks undertaken to better integrate the Oregon Conservation Strategy and the Oregon Nearshore Strategy. This work could not have been accomplished without the interactive efforts of the many individuals, agencies, and organizations that developed the Oregon Nearshore Strategy http://www.dfw.state.or.us/mrp/nearshore/index.asp

We would like to thank the following people and organizations that participated in the creation of supplements to the Oregon Conservation and Oregon Nearshore Strategy in 2012:

Project Funding

Funding for this project was through the Oregon Department of Fish and Wildlife State Wildlife Grant Program grant T-31-P-1 in cooperation with the U.S. Fish and Wildlife Service and Sport Fish Restoration Program.

Agencies and Institutions

James T. Carlton, Williams College; John Chapman, Oregon State University; Gayle Hansen, Oregon State University; Henry Lee, U.S. Environmental Protection Agency – Western Ecology Division; Sara O'Brien, Defenders of Wildlife, and Debbie Reusser, U.S. Geological Survey – Western Fisheries Research Center

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