

## VII. IMPLICATIONS FOR KEY FISH, WILDLIFE, PLANTS, PLANKTON, & SHELLFISH

Based on a search of the scientific and grey literature, sufficient information is available to discuss observed trends and future projections in the NPLCC region for:

1. Sea and shorebirds
2. Pacific lamprey
3. Pacific salmon
4. Shellfish
5. Eelgrass
6. Plankton

The following structure will be used to present information on the implications of climate change for the NPLCC region's fish, wildlife, plants, plankton, and shellfish:

- **Observed Trends** – observed changes for the Gulf of Alaska Large Marine Ecosystem (LME) and the California Current Ecosystem (CCE).
- **Future Projections** – projected direction and/or magnitude of change for the Gulf of Alaska LME and the CCE.
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

## 1. SEA AND SHOREBIRDS

According to an assessment of relative vulnerability of U.S. bird species by the North American Bird Conservation Initiative (NABCI), across all habitats species of conservation concern showed higher levels of vulnerability to climate change than species not threatened by other factors.<sup>1089</sup> Vulnerability to climate change may hasten declines or prevent recovery.<sup>1090</sup> At the same time, increased conservation concern may be warranted for groups of birds, such as waterfowl and aerial insect-eating birds that are abundant now but that will be increasingly stressed as climate change impacts intensify.<sup>1091</sup>

### Observed Trends

#### Region-wide

Of the sixty-seven ocean birds assessed by NABCI, all have medium to high vulnerability to climate change; forty-three are at the highest level of vulnerability (Figure 25).<sup>1092</sup> For example, Reed et al. (2009) studied breeding and development timing in the common guillemot (also known as the common murre) on southeast Farallon Island (about twenty-seven miles off the California coast), concluding:

- Egg laying date responded to environmental variability in non-extreme years, suggesting that guillemots were able to maintain high breeding success across most of the range of environmental conditions by adjusting laying dates in line with cues.<sup>1093</sup>
- Breeding was earlier in years where SSTs were low and the Northern Oscillation Index (NOI, a large-scale atmospheric phenomenon) was positive.<sup>1094</sup>
- Enhanced upwelling of cold, nutrient-rich water from depth in such years would have made the seas around Southeast Farallon Island more productive, which likely influenced the availability and/or timing of fish prey.<sup>1095</sup>

Of the eighty-four coastal species assessed by the NABCI, the majority (74 of 84, or 88%) have medium or high vulnerability to climate change (Figure 26).<sup>1096</sup> Many of the coastal species that show medium or high vulnerability to climate change are coastal seabirds such as the Aleutian Tern and Kittlitz's Murrelet.<sup>1097</sup> These species are vulnerable to climate change because they rely on marine food webs and because they have low reproductive potential.<sup>1098</sup> Observed trends for coastal birds include:

- Kittlitz's murrelet (*Brachyramphus brevirostris*) has been reported to be experiencing an annual estimated decline of around eighteen percent, attributed primarily to climate change, although the

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<sup>1089</sup> \*North American Bird Conservation Initiative (NABCI). *The State of the Birds 2010 Report on Climate Change, United States*. (2010, p. 4). The vulnerability assessment was based on five biological aspects of sensitivity to climate change, as well as the exposure of each species' habitat to climate change in the near future.

<sup>1090</sup> \*NABCI. (2010, p. 4)

<sup>1091</sup> \*NABCI. (2010, p. 4)

<sup>1092</sup> NABCI. (2010, p. 6)

<sup>1093</sup> \*Reed et al. *Timing is everything: flexible phenology and shifting selection in a colonial seabird*. (2009, p. 384)

<sup>1094</sup> \*Reed et al. (2009, p. 384)

<sup>1095</sup> \*Reed et al. (2009, p. 384)

<sup>1096</sup> NABCI. (2010, p. 8)

<sup>1097</sup> \*NABCI. (2010, p. 8)

<sup>1098</sup> \*NABCI. (2010, p. 8)

specific causes of its decline have not been determined.<sup>1099</sup> Kittlitz's murrelet feeds in waters around tidewater glaciers and is considered a critically endangered species as glaciers recede.<sup>1100</sup>

- Recently published data confirms marbled murrelets (*Brachyramphus marmoratus*) are susceptible to domoic acid poisoning.<sup>1101</sup> During a *Pseudo-nitzschia* bloom in California in 1998, domoic acid poisoning was documented as the cause of death of two of seventeen radio-tagged murrelets.<sup>1102</sup> In addition, Peery et al. (2006b, p.83) showed murrelet survival was reduced in years with a *Pseudo-nitzschia* bloom.<sup>1103</sup> McShane et al (2004) acknowledged that biotoxins will affect murrelets in the near future.<sup>1104</sup>
- Beach-nesting black oystercatchers are among the most vulnerable coastal birds because they rely heavily on limited, low-elevation coastal habitats.<sup>1105</sup> Please see Chapter V Section 3 for further information on habitat loss, degradation, and conversion due to climate change.
- Black and western High Arctic brant of the Pacific Flyway are dependent on *Zostera* (eelgrass), and are undergoing a shift in winter distribution that is likely related to climate change and its associated effects on *Zostera* dynamics.<sup>1106</sup> Between 1980 and 2000 and during a period of population stability for black brant, inventories showed a negative trend in numbers of black brant wintering in Mexico ( $R^2=0.35$ ,  $F_{2,20}=10.59$ ,  $P<0.01$ ; Fig. 4a) and a positive trend in numbers in the United States and Canada ( $R^2=0.69$ ,  $F_{2,20}=44.71$ ,  $P<0.01$ ; Fig. 4b).<sup>1107</sup> Brant reductions in Mexico have largely occurred at the southern wintering sites where *Z. marina* reaches the southern extent of its range in the northern hemisphere and air and sea surface temperatures already limit *Z. marina* growth to low intertidal and subtidal areas.<sup>1108</sup>
- Variation in breeding propensity of Black Brant associated with winter location and climate strongly suggests that food abundance on the wintering grounds directly affects reproductive performance in these geese.<sup>1109</sup> In summer, salt marshes, especially those containing *Carex* (sedges) and *Puccinellia* (common saltmarsh grass), are key habitats for raising young.<sup>1110</sup> Availability and abundance of salt marshes has a direct effect on growth and recruitment of goslings (young geese) and ultimately, plays an important role in regulating size of local brant populations.<sup>1111</sup>

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<sup>1099</sup> \*Haufler, Mehl and Yeats. *Climate change: anticipated effects on ecosystem services and potential actions by the Alaska Region*, U.S. Forest Service. (2010, p. 17)

<sup>1100</sup> \*Haufler, Mehl and Yeats. (2010, p. 17)

<sup>1101</sup> \* U.S. Fish and Wildlife Service. *Marbled Murrelet (Brachyramphus marmoratus): 5-Year Review (Final)*. (June 12, 2009, p. 38)

<sup>1102</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 38). The authors cite Peery et al. (2006b, p. 83-84) for this information.

<sup>1103</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 38)

<sup>1104</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 38)

<sup>1105</sup> \*NABCI. (2010, p. 8)

<sup>1106</sup> \*Ward et al. *North American Brant: effects of changes in habitat and climate on population dynamics*. (2005, p. 869)

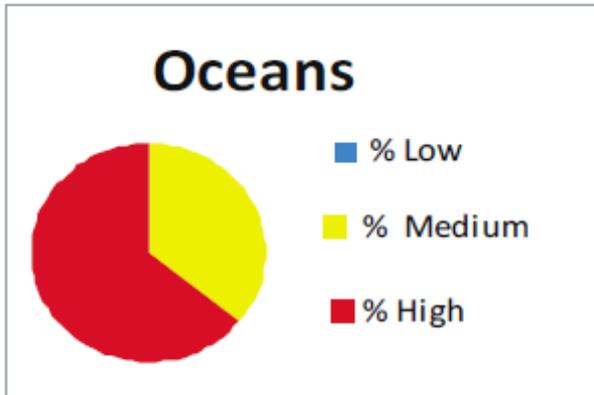
<sup>1107</sup> \*Ward et al. (2005, p. 876). The authors refer the reader to Fig. 4a and 4b for black brant in Mexico and the U.S./Canada, respectively. The authors provide statistics for data in Mexico ( $R^2 = 0.35$ ,  $F_{2,20} = 10.59$ ,  $P < 0.01$ ) and the U.S./Canada ( $R^2 = 0.69$ ,  $F_{2,20} = 44.71$ ,  $P < 0.01$ ).

<sup>1108</sup> \*Ward et al. (2005, p. 876). The authors refer the reader to Fig. 4a in the cited report and cite Meling-López & Ibarra-Obando (1999) and Cabello-Pasini et al. (2003) for this information.

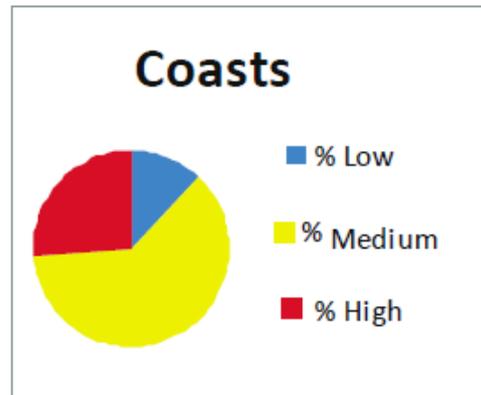
<sup>1109</sup> \*Ward et al. (2005, p. 869)

<sup>1110</sup> \*Ward et al. (2005, p. 869)

<sup>1111</sup> \*Ward et al. (2005, p. 869)



**Figure 25.** The 67 ocean birds assessed have medium to high vulnerability to climate change; 43 are at the highest level.  
*Source: NABCI (2010, p. 6)*



**Figure 26.** The great majority of coastal species (74 of 84 assessed) have medium or high vulnerability to climate change.  
*Source: NABCI (2010, p. 8)*

## Future Projections

### Region-wide

Ocean birds are slow to adapt or recover from adverse conditions and are vulnerable to climate change because of their low reproductive potential (advanced age of first breeding, production of one egg each year or every other year, and the high mortality rate for young birds).<sup>1112</sup> Many seabirds forage over vast areas of ocean and are highly sensitive to the availability of marine food.<sup>1113</sup> This sensitivity is especially pronounced during breeding, when providing food for chicks can place enormous physiological strain on the parents.<sup>1114</sup> In fact, reproductive failure of seabirds resulting from changes in marine productivity is a documented natural occurrence, such as when Pacific Coast seabird chicks starve during El Niño years (when sea surface temperatures are warmer than usual).<sup>1115</sup> If catastrophic events become more frequent, intense, or longer as a result of climate change, population recovery is less likely.<sup>1116</sup>

In the California Current region, significant ocean climate change is projected for the foraging range of Cassin's auklet by 2100, including a large increase in SST (~3.6°F, ~2°C) year-round and an intensification of spring upwelling followed by an overall decrease in summer and winter upwelling (using a mid-level emissions scenario and well-validated regional climate model for the California Current region).<sup>1117</sup> Because breeding success of Farallon Island auklets covaries with population parameters of other important predators in the California Current Ecosystem (i.e. return rates of

<sup>1112</sup> \*NABCI. (2010, p. 6)

<sup>1113</sup> \*NABCI. (2010, p. 6)

<sup>1114</sup> \*NABCI. (2010, p. 6)

<sup>1115</sup> \*NABCI. (2010, p. 6)

<sup>1116</sup> \*NABCI. (2010, p. 6-7)

<sup>1117</sup> \*Wolf et al. *Predicting population consequences of ocean climate change for an ecosystem sentinel, the seabird Cassin's auklet.* (2010, p. 1930)

Sacramento River fall Chinook salmon), climate change-related impacts to auklet populations may be harbingers of effects on other plankton predators in this system.<sup>1118</sup> For example:

- The Cassin’s auklet population growth rate at one breeding site on Farallon Island is projected to experience an absolute decline of 11–45% by the end of the century, which would lead to rapid population extirpation.<sup>1119</sup>

Warmer waters have apparently led to decreases in the abundance of fish in Prince William Sound, the Gulf of Alaska, and the California Current region, which is likely to reduce the abundance of fish-eating birds.<sup>1120</sup> In the future, seabirds such as Common Murres (also known as Common Guillemot) that time their breeding based on temperature cues may fail to raise any young if their chicks hatch at the wrong time, missing the window when food is abundant.<sup>1121</sup> Climate change may also cause prey to shift ranges, leading to declines in bird populations if the birds are unable to follow.<sup>1122</sup>

For coastal birds, losses of habitat and food sources due to climate change are the largest concerns.<sup>1123</sup> Some researchers suggest that, overall, sea level rise is expected to have minor impacts on waterfowl habitats along much of the Pacific Coast because of the abrupt topography of the coastline and continuing tectonic movements that counteract sea level rise.<sup>1124</sup> However, researchers have also noted the combined effects of habitat change on shorebird breeding areas and intertidal habitat loss at their wintering and migratory staging sites could, potentially, have even more severe effects than could be brought about by any one factor.<sup>1125</sup> Where landform or human development prevent the shoreward movement of coastal wetlands, the threat of loss is greater.<sup>1126</sup> Future projections for the marbled murrelet include:

- Within the marine environment, effects on the murrelet food supply (amount, distribution, quality) provide the most likely mechanism for climate change impacts to murrelets.<sup>1127</sup> The murrelet diet is not well studied, which hampers assessment of climate change effects related to prey, but effects on nutrient levels, and primary productivity are of concern, as are effects on prey abundances, quality, and distribution.<sup>1128</sup>
- While murrelets have likely adapted to occasional adverse ocean conditions, should strong El Niño events continue to be more frequent, the cumulative effects of repeated El Niño events in a short period with other threats “could contribute to serious population declines or extirpations”

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<sup>1118</sup> \*Wolf et al. (2010, p. 1931). The authors cite (Roth et al., 2007) for information on return rates of Sacramento River fall Chinook salmon.

<sup>1119</sup> \*Wolf et al. (2010, p. 1930)

<sup>1120</sup> \*NABCI. (2010, p. 7)

<sup>1121</sup> \*NABCI. (2010, p. 7)

<sup>1122</sup> \*NABCI. (2010, p. 7)

<sup>1123</sup> \*NABCI. (2010, p. 8)

<sup>1124</sup> \*The Wildlife Society. *Global climate change and wildlife in North America: Technical review 04-2*. (2004, p. 14). The authors cite Shaw et al. (1998) for this information.

<sup>1125</sup> \*Galbraith et al. (2005, p. 1121)

<sup>1126</sup> \*The Wildlife Society. (2004, p. 14). The authors cite Boesch et al. (2000) for this information.

<sup>1127</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 42)

<sup>1128</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 42)

(emphasis in original).<sup>1129</sup> As noted in Chapter IV Section 2, it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change.<sup>1130</sup>

- Given uncertainty about future variability in California Current ocean conditions (e.g., how increased upwelling and increased stratification will interact), positive changes (for murrelet food supply) appear rare in forecasts, with the possible exception of increased upwelling.<sup>1131</sup> While upwelling is generally associated with increased productivity, at some level increased winds and upwelling could negatively affect the coastal marine ecosystems, by reducing the concentration of marine organisms, through increased mixing and transport seaward of surface water and organisms (out of the murrelet's near-shore environment).<sup>1132</sup>
- The negative impacts of increased acidity on plankton may cause negative impacts on many other species which are important food-sources for murrelet and their prey.<sup>1133</sup>

*For further information on projected changes to the quantity of tidal marsh, mudflat, and other habitat types important for sea and shorebirds in specific locations throughout the geographic extent of the NPLCC, please see Section 3 in Chapter 5.*

### **Information Gaps**

Information is needed on impacts to sea and shorebirds in the NPLCC region, including information on the effects of climate change on feeding, breeding, migration, socialization, interspecies interactions, and other factors.

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<sup>1129</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 43). The authors cite USFWS (1997, p. 78-19) for the quoted information.

<sup>1130</sup> \*Collins et al. *The impact of global warming on the tropical Pacific Ocean and El Nino*. (2010, p. 391)

<sup>1131</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 44)

<sup>1132</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 44). The authors cite Snyder et al. (2003, p. 4) for this information.

<sup>1133</sup> \* U.S. Fish and Wildlife Service. (June 12, 2009, p. 45). The authors cite Ruckelshaus and McClure (2007, p. 55) for this information.

## 2. PACIFIC LAMPREY (*LAMPETRA TRIDENTATA*)

### Observed Trends

#### Gulf of Alaska LME

*Information needed.*

#### California Current Ecosystem

In recent decades, anadromous Pacific lampreys (*Lampetra tridentata*) along the west coast of North America, have experienced broad-based population declines and regional extirpations.<sup>1134</sup> These declines parallel those of Pacific salmonids (*Oncorhynchus spp.*), perhaps because the two groups share widely sympatric (i.e. occurring in the same or overlapping geographic areas) distributions and similar anadromous life histories.<sup>1135</sup> In light of these similarities, the Columbia River Inter-Tribal Fish Commission is conducting a preliminary assessment of climate change impacts on the estuarine habitat for salmon and lamprey as derived from “filtering” simulations of Columbia River flow scenarios.<sup>1136</sup>

Along the coasts of Oregon, southern Washington, and northern California, threats to lamprey are, overall, moderate to severe.<sup>1137</sup> Population decline over the last three generations (27 years) has been observed throughout the region:

- Up to seventy percent decline in two Puget Sound watersheds and the North Coast of Oregon, and
- A ten to thirty percent decline in some areas of coastal California, the Lower Columbia River region, and other areas of coastal Oregon.<sup>1138</sup>

### Future Projections

#### Gulf of Alaska LME

*Information needed.*

#### California Current Ecosystem

Climate change may exacerbate many existing threats to lamprey, especially water flow, ocean conditions, water quality, disease, predation, and stream conditions.<sup>1139</sup>

### Information Gaps

Research on Pacific lamprey marine life stages, including projected effects of climate change, is needed.

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<sup>1134</sup> \*Keefer et al. *Variability in migration timing of adult Pacific lamprey (*Lampetra tridentata*) in the Columbia River, U.S.A.* (2009, p. 254). The authors cite Beamish and Northcote (1989), Kostow (2002), and Moser and Close (2003) for this information.

<sup>1135</sup> \*Keefer et al. (2009, p. 254). The authors cite Scott and Crossman (1973), Simpson and Wallace (1978), and Moyle (2002) for information on sympatric distributions, and McDowall (2001) and Quinn and Myers (2004) for information on Anadromous life histories.

<sup>1136</sup> Pers. Comm. with Laura Gephart. (June 2011). Contact information: (503) 238-0667, [gepl@critfc.org](mailto:gepl@critfc.org)

<sup>1137</sup> \*U.S. Fish and Wildlife Service. *Pacific Lamprey (*Lampetra tridentata*) Draft Assessment and Template for Conservation Measures.* (2010, p. 42). This information is obtained from Figure 4-6b. Data for the Puget Sound region is not available. Data from California are incomplete.

<sup>1138</sup> U.S. Fish and Wildlife Service. (2010, p. 41, 43, 46, 48, 55)

<sup>1139</sup> \*U.S. Fish and Wildlife Service. (2010, p. 23)

### 3. PACIFIC SALMON (*ONCORHYNCHUS* SPP.)

Pacific salmon have complex life histories that span diverse environments across the Pacific Rim.<sup>1140</sup> Pacific salmon (*Oncorhynchus* spp) are an important ecological and economic species complex in the North Pacific Ocean.<sup>1141</sup> Their natural distribution extends from San Francisco Bay in California, northwards along the Canadian and Alaskan coasts to North American and Russian rivers draining into the Arctic Ocean, and southwards along the Asian coastal areas of Russia, Japan, and Korea.<sup>1142</sup>

Pacific salmon spawn in fall in fresh water and their embryos incubate in the gravel during the winter and emerge in spring.<sup>1143</sup> Juveniles then spend days to years in habitats ranging from small creeks to large rivers, and small ponds to large lakes.<sup>1144</sup> Most juveniles then migrate downriver, through estuaries and coastal waters, to the ocean.<sup>1145</sup> These “anadromous” individuals spend anywhere from a few months to as much as seven years at sea, before migrating back to spawn and die at their natal sites in fresh water.<sup>1146</sup>

This great diversity of environments and behaviors suggests that climate change could influence selection on multiple traits in multiple phases of the life cycle. Changes in the ocean associated with warming will affect salmonids and their ecosystems, both directly and indirectly.<sup>1147</sup> Physical changes associated with warming include: increases in ocean temperature, increased stratification of the water column, and changes in the intensity and timing of coastal upwelling.<sup>1148</sup> These changes in climate forcing will alter both primary and secondary productivity and the structure of marine communities, and in turn, the growth, productivity, survival and migrations of salmonids.<sup>1149</sup> Nearshore ecosystems also play critical roles for salmon and steelhead, many of which use coastal marshes for feeding and refuge as they transition from freshwater to the ocean.<sup>1150</sup>

#### Observed Trends

##### Region-wide

At the scale of the Pacific Coast of North America, salmon production is strongly influenced by decadal-scale changes in the phase of the PDO.<sup>1151</sup> For example, the PDO can change the timing and distribution of salmon predators such as Pacific mackerel, which are drawn to the region’s coastal waters by warmer sea surface temperatures.<sup>1152</sup>

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<sup>1140</sup> \*Crozier et al. *Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon*. (2008, p. 253). The authors cite Groot and Margolis (1991) and Quinn (2005) for this information.

<sup>1141</sup> \*Irvine and Fukuwaka. *Pacific salmon abundance trends and climate change*. (2011, p. 1122)

<sup>1142</sup> \*Irvine and Fukuwaka. (2011, p. 1122). The authors cite Groot and Margolis (1991) for this information.

<sup>1143</sup> \*Crozier et al. (2008, p. 253)

<sup>1144</sup> \*Crozier et al. (2008, p. 253-254)

<sup>1145</sup> \*Crozier et al. (2008, p. 254)

<sup>1146</sup> \*Crozier et al. (2008, p. 254)

<sup>1147</sup> \*ISAB. (2007, p. 57)

<sup>1148</sup> \*ISAB. (2007, p. 57)

<sup>1149</sup> \*ISAB. (2007, p. 57)

<sup>1150</sup> \*Martin and Glick. *A great wave rising: solutions for Columbia and Snake River salmon in the age of global warming*. (2008, p. 15). The authors cite Bottom et al. (2005) for this information.

<sup>1151</sup> \*Hare, Mantua and Francis. *Inverse production regimes: Alaska and West Coast Pacific Salmon*. (1999, p. 7)

<sup>1152</sup> \*Martin and Glick. (2008). The authors cite Percy, W.G. (1992) for this information.

Pacific salmon production in Alaska is inversely related to that on the West Coast (i.e., Washington, Oregon, California) and is climate-driven.<sup>1153</sup> The loadings on the British Columbia Pacific salmon catches suggest that those stocks occupy a transitional region, with Chinook and coho salmon of the same sign as the southern stocks and the three other species (sockeye, pink, chum) of the same sign, but in a smaller magnitude as do the Alaska stocks.<sup>1154</sup> For example, in the Pacific Northwest, the cool PDO years of 1947-1976 coincided with high returns of Chinook and coho salmon to Oregon rivers.<sup>1155</sup> Conversely, during the warm PDO cycle that followed (1977-1998), salmon numbers declined steadily.<sup>1156</sup>

Irvine and Fukuwaka (2011) estimated Pacific salmon abundance in the eastern North Pacific during five time periods:

- **1925-1946 and 1947-1976:** Mean catches declined between 1925-1946 and 1947-1976 for pink, chum, and sockeye salmon.<sup>1157</sup>
- **1977-1988:** Sockeye, pink, and coho salmon abundances increased; mean abundances for these species, as well as chum salmon, were higher in this period than in 1947-1976.<sup>1158</sup>
- **1989-1998:** Chum and pink salmon were more abundant in 1989-1998 than in 1977-1988.<sup>1159</sup> Chum salmon abundances increased, whereas sockeye and coho decreased.<sup>1160</sup>
- **1999-2009:** Chinook salmon were less abundant than in earlier years and abundances declined. In general, differences during this time period were inconsistent.<sup>1161</sup>

#### Gulf of Alaska LME

*Information needed.*

#### California Current Ecosystem

In the Pacific Northwest, salmonid species use the nearshore marine and estuarine environment throughout their life cycle (Table 21 and Figure 27).<sup>1162</sup> There is evidence that the growth rate of Chinook salmon in Washington, Oregon, and California is influenced by the environment, and that the relationship is region- and life-history specific.<sup>1163</sup>

- Growth of Puget Sound (WA) salmon with ocean-type behavior was negatively related to a stronger California Current.<sup>1164</sup> Specifically, ocean-type Puget Sound fish were negatively related to the Northern Oscillation Index and upwelling.<sup>1165</sup>

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<sup>1153</sup> \*Hare, Mantua and Francis. (1999, p. 7)

<sup>1154</sup> \*Hare, Mantua and Francis. (1999, p. 10)

<sup>1155</sup> \*Peterson et al. *Ocean conditions and salmon survival in the northern California Current*. (2006, p. 3). The authors cite Mantua et al. (1997) for this information.

<sup>1156</sup> \*Peterson et al. (2006, p. 3). The authors cite Mantua et al. (1997) for this information.

<sup>1157</sup> \*Irvine and Fukuwaka. (2011, p. 1126-1127)

<sup>1158</sup> \*Irvine and Fukuwaka. (2011, p. 1127)

<sup>1159</sup> \*Irvine and Fukuwaka. (2011, p. 1127)

<sup>1160</sup> \*Irvine and Fukuwaka. (2011, p. 1127)

<sup>1161</sup> \*Irvine and Fukuwaka. (2011, p. 1127)

<sup>1162</sup> \*Glick, Clough and Nunley. (2007, p. 13)

<sup>1163</sup> \*Wells et al. *Relationships between oceanic conditions and growth of Chinook salmon (*Oncorhynchus tshawytscha*) from California, Washington, and Alaska, USA*. (2008, p. 120)

<sup>1164</sup> \*Wells et al. (2008, p. 121)

<sup>1165</sup> \*Wells et al. (2008, p. 121)

- On the other hand, a strong, productive California Current promoted growth among California Chinook salmon.<sup>1166</sup> Specifically, growth of California Chinook was enhanced by cool temperatures, increased upwelling, a stronger North Pacific high pressure system, and reduced sea level height.<sup>1167</sup>
- In Oregon, cooler sea surface temperature during the winter prior to smolt migration contributes to higher survival of coho salmon.<sup>1168</sup> The mechanism for this link is suggested by correlations between ocean and atmospheric variables: relatively weak downwelling (poleward) winds in the winter, due to a weaker Aleutian Low, result in less onshore transport of warm oceanic water, and reduced upper ocean stratification the following spring.<sup>1169</sup> Cooler sea surface temperature during the winter following smolt migration also contribute to high coho survival.<sup>1170</sup> The mechanism may involve either improved feeding conditions or reduced predation.<sup>1171</sup>
- A later transition between winter downwelling and spring upwelling season appears to contribute to relatively poor coho survival in Oregon, perhaps due to a temporal mismatch between arrival of smolts to the sea and seasonal increases in ocean food production in the nearshore upwelling habitat.<sup>1172</sup>
- Lower spring sea level anomalies (below a threshold of around -100 mm) are correlated with higher coho survival in Oregon.<sup>1173</sup> The processes responsible for the anomalies are expected to result in enhanced feeding conditions due to the transport of nutrients from depth to the euphotic zone, and/or the equatorward transport of nutrients and boreal copepod species from subarctic waters.<sup>1174</sup>

In 2009, the decline of sockeye salmon stocks in the Fraser River in British Columbia led to the closure of the fishery for the third consecutive year, despite favorable pre-season estimates of the number of sockeye salmon expected to return to the river.<sup>1175</sup> The 2009 return marked a steady decline that could be traced back two decades.<sup>1176</sup> Although the two-decade decline in Fraser sockeye stocks has been steady and profound, in 2010 Fraser sockeye experienced an extraordinary rebound, demonstrating their capacity to produce at historic levels.<sup>1177</sup> A qualitative assessment of the likelihood that life-stage-specific survival of Fraser River sockeye salmon has been undergoing a trend in the past 20 years due to the recent trends in climate, particularly in temperature, concluded for the marine environment.<sup>1178</sup>

- Survival of immatures in the ocean has *possibly* decreased; and,

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<sup>1166</sup> \*Wells et al. (2008, p. 101)

<sup>1167</sup> \*Wells et al. (2008, p. 122)

<sup>1168</sup> \*Logerwell et al. *Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (Oncorhynchus kisutch) marine survival*. (2003, p. 564)

<sup>1169</sup> \*Logerwell et al. (2003, p. 564-565)

<sup>1170</sup> \*Logerwell et al. (2003, p. 565)

<sup>1171</sup> \*Logerwell et al. (2003, p. 565)

<sup>1172</sup> \*Logerwell et al. (2003, p. 565)

<sup>1173</sup> \*Logerwell et al. (2003, p. 565)

<sup>1174</sup> \*Logerwell et al. (2003, p. 565). The authors cite Chelton et al. (1982), Chelton and Davis (1982), Simpson (1984), and Huyer and Smith (1985) for this information.

<sup>1175</sup> \*Hinch and Martins. *A review of potential climate change effects on survival of Fraser River sockeye salmon and an analysis of interannual trends in en route loss and pre-spawn mortality*. (2011, Preface)

<sup>1176</sup> \*Hinch and Martins. (2011, Preface)

<sup>1177</sup> \*Hinch and Martins. (2011, Preface)

<sup>1178</sup> \*Hinch and Martins. (2011, p. 2)

- Survival of returning adults has *very likely* decreased (but not in all stocks).<sup>1179</sup>

A number of studies have identified the loss of wetlands in the lower Columbia River estuary due to reduced freshwater flows, diking, and other problems as limiting factors in recovery of Columbia and Snake River Basin salmon.<sup>1180</sup> As described in Chapter 5 Section 3 (Habitat loss, degradation, and conversion), Ducks Unlimited project a two percent loss of low tidal areas, nineteen percent loss of saltmarsh, eleven percent loss of freshwater tidal areas, and a 160% gain in transitional areas.<sup>1181</sup> The Lower Columbia River may be resilient to climate-induced changes to habitat because losses to low tidal, saltmarsh, and freshwater tidal habitats are minimized, while gains in transitional areas are substantial (Figure 19).<sup>1182</sup>

## Future Projections

### Region-wide

If the regional impacts of global warming are expressed in El Niño-like or PDO-like ways, warmer waters due to global warming are likely to promote increased production of salmon in Alaskan waters, at least initially, provided primary and secondary production does not decline, while promoting decreased salmon production for salmon populations in the Pacific Northwest region (and throughout the California Current System).<sup>1183</sup> A key uncertainty here is how global warming will influence the characteristics of atmospheric surface pressure and wind fields over the North Pacific because of the prominent role that wind forcing plays in structuring the upper ocean.<sup>1184</sup>

### Gulf of Alaska LME

Under a doubling of CO<sub>2</sub>, models predict that Pacific salmon would experience a range decline as they move northward into the Bering Sea and the Arctic.<sup>1185</sup> Many habitats used by juvenile coho salmon in the lower Taku River, Alaska would likely be inundated with a modest (3 ft, 0.9 m) increase in sea level.<sup>1186</sup> Rising sea levels will flood low elevation habitats converting freshwater habitats into brackish or saline environments.<sup>1187</sup> Habitats above the immediate effects of flooding will become intertidal and subject to periodic tidal flooding and pulses of saline water and will no longer provide viable freshwater habitat for juvenile Coho salmon.<sup>1188</sup> Predicted effects of climate change on pink salmon growth in the Gulf of Alaska are that a ten percent increase in water temperature will lead to a three percent drop in mature salmon body weight (physiological effect) and a ten percent decrease in pteropod production will lead to a twenty percent drop in mature salmon body weight (prey limitation).<sup>1189</sup>

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<sup>1179</sup> \*Hinch and Martins. (2011, p. 3)

<sup>1180</sup> \*Martin and Glick. (2008). The authors cite Fresh et al. (2005) for this information.

<sup>1181</sup> DU. (2010b)

<sup>1182</sup> DU. (2010b)

<sup>1183</sup> \*ISAB. (2007, p. 64)

<sup>1184</sup> \*ISAB. (2007, p. 64)

<sup>1185</sup> \*Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1*.

<sup>1186</sup> \*Kelly et al. (2007, p. 58). The authors cite Murphy et al. (1989) for this information.

<sup>1187</sup> \*Kelly et al. (2007, p. 59)

<sup>1188</sup> \*Kelly et al. (2007, p. 59)

<sup>1189</sup> \*Sigler et al. (2008, p. 7). The authors cite Aydin et al. (2005) for this information.

### California Current Ecosystem

Recent analyses of the potential effects of future climate change on Fraser River (BC) sockeye salmon all point to reduced survival and lower productivity if the climate continues to warm.<sup>1190</sup> Although there is some potential for tolerance to warm temperatures to evolve in Pacific salmon, further evolutionary change may already be restricted in populations that have historically experienced high temperatures, such as summer-run Fraser River sockeye salmon.<sup>1191</sup> Phenological (i.e. timing of events such as seaward migration and return migration) changes are likely to be one of the major responses of Pacific salmon to climate change.<sup>1192</sup>

Most climate models project the 21<sup>st</sup> century will feature greater annual precipitation in the Pacific Northwest, extreme winter precipitation events in California, and a more rapid spring melt leading to a shorter, more intense spring period of river flow and freshwater discharge.<sup>1193</sup> This will greatly alter coastal stratification and mixing, riverine plume formation and evolution, and the timing of transport of anadromous populations to and from the ocean.<sup>1194</sup> Likely impacts of climate change on Pacific salmon such as the salmon that use the Columbia, Klamath, and Sacramento River systems include the following:

- Altered stream flow and warmer temperatures will reduce the available habitat, life history diversity, and freshwater survival rates for juvenile salmon;
- Altered air temperatures will increase heating of mainstem reservoirs and affect juvenile and adult salmon survival and passage timing through sections of regulated rivers such as the Columbia, Klamath, and Sacramento; and,
- Changes in coastal ocean habitat quality due to changes in productivity and seasonal cycles of production, and food chain bioenergetics.<sup>1195</sup>

With less productive coastal waters and modifications in timing of ocean entry, early ocean survival rates for Columbia River salmon will likely decline, and as observed in past periods of poor ocean conditions, declines in adult return rates may be exacerbated by large releases of hatchery fish.<sup>1196</sup>

Scientists believe that historical loss of nearshore marine and estuary habitats regionwide has already contributed to the decline in salmon populations.<sup>1197</sup> In the Puget Sound, the general picture of climate change – increased winter flooding and decreased summer and fall stream flows, along with elevated warm season stream and estuary temperatures – would be especially problematic for instream and estuarine habitat for salmon.<sup>1198</sup> Juvenile chum and fall Chinook salmon, considered to be the most estuary-dependent species, are at special risk:

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<sup>1190</sup> \*Hinch and Martins. (2011, p. 3)

<sup>1191</sup> \*Hinch and Martins. (2011, p. 3)

<sup>1192</sup> \*Hinch and Martins. (2011, p. 3)

<sup>1193</sup> \*Peterson, W. & Schwing, F. (2008, p. 50). The authors refer the reader to Figure 3 in the cited report.

<sup>1194</sup> \*Peterson, W. & Schwing, F. (2008, p. 50)

<sup>1195</sup> \*Peterson, W. & Schwing, F. (2008, p. 50)

<sup>1196</sup> \*ISAB. (2007, p. 72). The authors cite Levin et al. (2001) for this information.

<sup>1197</sup> \*Martin and Glick. (2008, p. 15). The authors cite William and Thom (2001) for this information.

<sup>1198</sup> \*Snover et al. (2005, p. 30)

- A recent analysis in the Skagit Delta of Puget Sound estimates that the rearing capacity in marshes for threatened juvenile Chinook salmon would decline by 211,000 and 530,000 fish, respectively, for an 18- and 32-inch (0.45 m and 0.81 m) sea level rise.<sup>1199</sup>

In conclusion, it is unknown whether the predicted rapid rate of change of new selective forces induced by climate change on salmonids will allow natural selection to produce evolutionary responses that will ameliorate impacts and retain the viability of populations.<sup>1200</sup> Such changes have occurred: for example, in less than a century, ocean-type Chinook introduced to New Zealand colonized rivers and evolved significant differences in heritable traits.<sup>1201</sup> The advanced spawning times of hatchery reared salmon is another example of evolutionary change, in this case from artificial selection.<sup>1202</sup> In any event, the future will depend on adequate freshwater spawning and rearing habitats, the chain of habitats in the life histories of anadromous salmonids, and maintenance of populations with diverse life histories and phenotypic and genetic variability to provide resilience to future changes.<sup>1203</sup>

### Information Gaps

Information is needed on observed trends particular to the Gulf of Alaska LME. Information is also needed on future projections throughout the NPLCC region. For example, information is needed to understand the genetic adaptation and phenotypic plasticity of salmonids in response to climate change, and the consequences for abundance, distribution, and survival.

<i>Species</i>	Nearshore Marine and Estuary Use		
	<i>Adult Residence</i>	<i>Adult and Juvenile Migration</i>	<i>Juvenile Rearing</i>
Chinook Salmon	Extensive Use	Extensive Use	Extensive Use
Chum Salmon	Little or Unknown	Extensive Use	Extensive Use
Coho Salmon	Some Use	Extensive Use	Some Use
Sockeye Salmon	Little or Unknown	Extensive Use	Little or Unknown
Pink Salmon	Little or Unknown	Extensive Use	Extensive Use
Cutthroat Trout	Extensive Use	Extensive Use	Extensive Use
Steelhead	Little or Unknown	Extensive Use	Some Use
Bull Trout	Extensive Use	Extensive Use	Extensive Use

Source: Williams, G.D. and R.M. Thom. 2001. *Marine and Estuarine Shoreline Modification* (Sequim, WA: Battelle Marine Sciences Laboratory/Pacific Northwest National Laboratory, p. 14. Available online at [http://www.ser.org/sernw/pdf/WDFW\\_marine\\_shoreline\\_white\\_paper.pdf](http://www.ser.org/sernw/pdf/WDFW_marine_shoreline_white_paper.pdf) (accessed 12.13.2010)

*Note: Table reproduced from Glick et al. (2007), Table 3, p. 13 by authors of this report.*

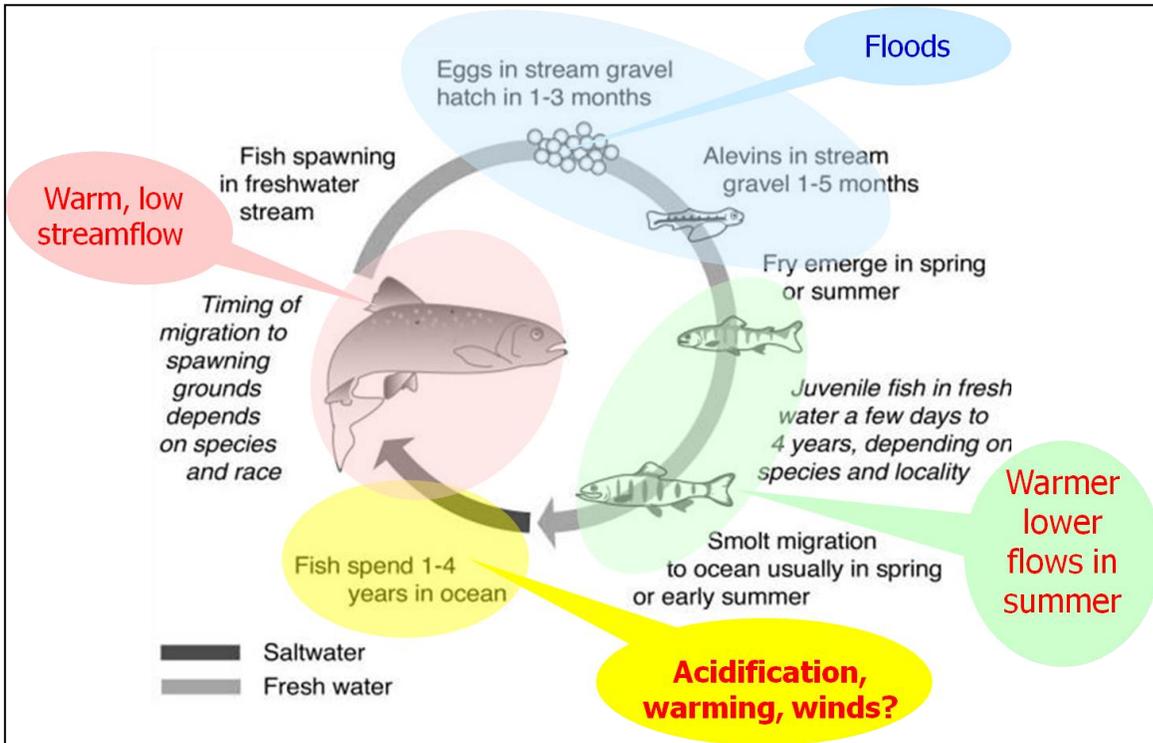
<sup>1199</sup> \*Martin and Glick. (2008, p. 15). The authors cite Hood, W.G. (2005) for this information.

<sup>1200</sup> \*ISAB. (2007, p. 72)

<sup>1201</sup> \*ISAB. (2007, p. 72). The authors cite Quinn et al. (2001) and Quinn (2005) for this information.

<sup>1202</sup> \*ISAB. (2007, p. 72)

<sup>1203</sup> \*ISAB. (2007, p. 72)



**Figure 27.** Climate change effects on the salmon life cycle. *Reproduced with permission from Nathan Mantua.*

## 4. SHELLFISH

### Observed Trends

#### Global

Kroeker et al. (2010) conducted a meta-analysis of the biological effects of ocean acidification on marine organisms. Calcification was the most sensitive process, and their analyses suggest calcifying organisms are more susceptible to ocean acidification across other response variables.<sup>1204</sup> This pattern was also highlighted in the differences in taxonomic groups, where survival and growth were negatively affected across most calcifiers.<sup>1205</sup> With the exception of crustaceans, these results suggest the effects of ocean acidification will be negative for most calcifying organisms, but that variation in life history characteristics will prove some organisms more resilient than others.<sup>1206</sup> Specific findings include:

- Calcifying organisms generally exhibited larger negative responses than noncalcifying organisms across numerous response variables, with the exception of crustaceans, which calcify but were not negatively affected.<sup>1207</sup>
  - Ocean acidification had significant negative mean effects on calcification in corals, and similar magnitude but non-significant negative mean effects on calcifying algae, coccolithophores and molluscs.<sup>1208</sup>
  - Ocean acidification had a significant positive mean effect on calcification on crustaceans, and a non-significant positive effect on calcification on echinoderms.<sup>1209</sup>
- The mean effect of ocean acidification on calcification varied amongst organisms with different mineral forms of calcium carbonate (CaCO<sub>3</sub>).<sup>1210</sup>
  - Organisms using aragonite and low-magnesium (low-Mg) calcite were negatively affected by ocean acidification, whereas organisms utilizing high-magnesium (high-Mg) calcite were not significantly affected.<sup>1211</sup>
  - These results are in contrast to the hypothesis that organisms utilizing high-Mg calcite will be more sensitive to ocean acidification because both crustaceans and coralline algae (which made up most of the calcifying algae category) utilize high-Mg calcite for calcified structures.<sup>1212</sup> This hypothesis, based on the solubility of the pure mineral forms in seawater, may fail to predict the sensitivity of marine organisms to ocean acidification because it does not account for biogenic calcification processes.<sup>1213</sup>

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<sup>1204</sup> \*Kroeker et al. (2010, p. 1427)

<sup>1205</sup> \*Kroeker et al. (2010, p. 1427)

<sup>1206</sup> \*Kroeker et al. (2010, p. 1427)

<sup>1207</sup> \*Kroeker et al. (2010, p. 1419)

<sup>1208</sup> \*Kroeker et al. (2010, p. 1424)

<sup>1209</sup> \*Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 3 in the cited report.

<sup>1210</sup> \*Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 5 in the cited report and provide statistics for this result:  $Q_M = 9.91$ , d.f. = 2,  $P = 0.05$ .

<sup>1211</sup> \*Kroeker et al. (2010, p. 1424)

<sup>1212</sup> \*Kroeker et al. (2010, p. 1428-1429)

<sup>1213</sup> \*Kroeker et al. (2010, p. 1429). The authors cite Pörtner (2008) for this information.

- The effect of ocean acidification on calcification did not differ significantly amongst taxonomic groups.<sup>1214</sup>

Ries, Cohen, and McCorkle (2009) conducted sixty-day laboratory experiments in which they investigated the effects of CO<sub>2</sub>-induced ocean acidification on calcification in eighteen benthic marine organisms.<sup>1215</sup> They observed variable responses among benthic marine species to acidified conditions:

- Ten of eighteen benthic marine species exhibited reduced rates of net calcification and, in some cases, net dissolution under elevated *p*CO<sub>2</sub> (partial pressure of carbon dioxide. At the air-sea interface, *p*CO<sub>2</sub> values indicate whether CO<sub>2</sub> will be absorbed by the ocean or emitted to the air).<sup>1216</sup>
- However, in seven species, net calcification increased under the intermediate and/or highest levels of *p*CO<sub>2</sub> and one species showed no response at all.<sup>1217</sup>
- A combination of factors, including the organisms' ability to regulate pH at the site of calcification, the extent of organic-layer coverage of their external shell, their biomineral solubility, and whether they utilize photosynthesis, may contribute to the disparity of these response patterns.<sup>1218</sup>

#### Gulf of Alaska LME

*Information needed.*

#### California Current Ecosystem

Some oyster hatcheries in the Pacific Northwest region have experienced mass mortalities of oyster larvae in association with a combination of circumstances including unusually saline surface waters and the upwelling of cold, CO<sub>2</sub>- and nutrient-rich waters, which contained high concentrations of the pathogenic bacteria, *Vibrio tubiashii*, and would also have low pH and aragonite saturation values.<sup>1219</sup> In Puget Sound, as may be the case for other coastal embayments and estuaries of the Pacific Northwest and elsewhere, the impacts of lowered seawater pH and hypoxia may have a synergistic or compounding impact on organisms.<sup>1220</sup>

During central Oregon's severe hypoxic event in summer 2002, significant mortality of Dungeness crab was observed.<sup>1221</sup> Rates of crab mortality varied by location, from less than twenty-five percent loss in most pots within two of four regions and greater than seventy-six percent loss in most pots in another

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<sup>1214</sup> \*Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 3 in the cited report and provide statistics for this result:  $Q_M = 16.24$ , d.f. = 5,  $P = 0.1$ .

<sup>1215</sup> \*Ries, Cohen and McCorkle. *Marine calcifiers exhibit mixed responses to CO<sub>2</sub>-induced ocean acidification*. (2009, p. 1132)

<sup>1216</sup> \*Ries, Cohen and McCorkle. (2009, p. 1132)

<sup>1217</sup> \*Ries, Cohen and McCorkle. (2009, p. 1132)

<sup>1218</sup> \*Ries, Cohen and McCorkle. (2009, p. 1132)

<sup>1219</sup> \*Feely et al. *The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary*. (2010, p. 447). The authors cite Elston et al. (2008) for information on the pathogenic bacteria, and Feely et al. (2008) for the information on low pH and aragonite saturation.

<sup>1220</sup> \*Feely et al. (2010, p. 447).

<sup>1221</sup> \*Grantham et al. (2004, p. 750)

region.<sup>1222</sup> During Oregon's anoxic event in 2006, surveys revealed the complete absence of all fish from rocky reefs that normally serve as habitats for diverse rockfish communities that are of current fishery management concern.<sup>1223</sup> Near-complete mortality of macroscopic benthic invertebrates was also observed.<sup>1224</sup>

Recent abundance observations have not indicated any significant decrease in CCS pteropod population size,<sup>1225</sup> whereas the Pacific oyster *Crassostrea gigas* exhibited recruitment failure during four consecutive years (2005–2008).<sup>1226</sup> *C. gigas* has an aragonitic larval stage, making it exceptionally vulnerable to decreasing aragonite saturation states.<sup>1227</sup>

Rogers-Bennett et al. (2010) examined the impacts of warm water, starvation, and disease on reproduction in red abalone (*Haliotis rufescens*; a harvested species).<sup>1228</sup> Wild abalone were gathered from sites in northern and southern California and subjected to a series of laboratory experiments.<sup>1229</sup> Rogers-Bennett et al. concluded both male and female red abalone responded negatively to warm water, starvation, and disease stressors, with declines in sperm formation among males and declines in egg production and quantity among females.<sup>1230</sup>

- At temperatures above 60.8°F (16°C) lasting for one year, total reproductive failure was observed in males irrespective of food treatment.<sup>1231</sup>
- Females exposed to 64.4°F (18°C) water for six months had diminished egg quantity, while those exposed to starvation did not produce any mature eggs.<sup>1232</sup>

## Future Projections

### Gulf of Alaska LME

*Information needed.*

### California Current Ecosystem

Secondary producers in the California Current System (CCS) can be affected both directly as a result of a change in seawater chemistry, and also indirectly by changes in food quality, prey disappearance, and altered timing of phytoplankton blooms.<sup>1233</sup> Limited experiments available today suggest that the aragonite-shelled pteropods, foraminifera, and planktonic life stages of bivalves and echinoderms are affected directly by ocean acidification as they experience either rapid shell dissolution and reduced

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<sup>1222</sup> Grantham et al. (2004, p. 750). Figure 1b displays crab mortality rates within four regions of the hypoxic zone. For example, in the region shown at top, crab mortality in most pots was recorded as one to twenty-five percent.

<sup>1223</sup> \*Chan et al. (2008, p. 920)

<sup>1224</sup> \*Chan et al. (2008, p. 920)

<sup>1225</sup> \*Hauri et al. (2009, p. 68). The authors cite Ohman and Lavaniegos (2008) for this information.

<sup>1226</sup> \*Hauri et al. (2009, p. 68). The authors cite Elston et al. (2008) for this information.

<sup>1227</sup> \*Hauri et al. (2009, p. 68). The authors cite Elston et al. (2008) for this information.

<sup>1228</sup> \*Rogers-Bennett et al. *Response of red abalone production to warm water, starvation, and disease stressors: implications of ocean warming.* (2010, p. 599)

<sup>1229</sup> Rogers-Bennett et al. (2010)

<sup>1230</sup> Rogers-Bennett et al. (2010)

<sup>1231</sup> \*Rogers-Bennett et al. (2010, p. 599)

<sup>1232</sup> \*Rogers-Bennett et al. (2010, p. 599)

<sup>1233</sup> \*Hauri et al. (2009, p. 67)

calcification ability or larvae develop with a temporal delay, build abnormal asymmetry, and often die before metamorphosis in aragonite undersaturated waters.<sup>1234</sup> However, one study points out that such negative responses are species specific, so that the primary effect in a future, more acidic ocean is likely to be a shift in species composition rather than the complete disappearance of an entire class of organisms.<sup>1235</sup> The recent meta-analysis by Kroeker et al. (2010), described previously, provides further insight on these topics.

Benthic organisms appear to be among those that will be most affected by the continuing acidification of the California Current System.<sup>1236</sup> Benthic organisms will be exposed to the lowest pH and aragonite saturation states in the nearshore, shallow areas, and many of them appear to be sensitive to ocean acidification.<sup>1237</sup> Moreover, their ability to migrate is limited.<sup>1238</sup> However, given limited understanding, this conclusion should be viewed as a preliminary assessment rather than a final conclusion.<sup>1239</sup> More accurate projections require special consideration of the integrated effects of ocean acidification, ocean warming, decreasing oxygen levels, and other processes that are expected with global change.<sup>1240</sup>

### Information Gaps

Information is needed on the Gulf of Alaska LME, both observed trends and future projections. For the California Current Ecosystem, additional experiments and quantitative future projections are needed. Kroeker et al. (2010) note the resilience of crustaceans and coralline algae requires further experimentation to understand the mechanisms for their responses.<sup>1241</sup>

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<sup>1234</sup> \*Hauri et al. (2009, p. 67-68). The authors cite Orr et al. (2005), Fabry et al. (2008), Kurihara et al. (2008), Dupont and Thorndyke (2009), and Lebrato et al. (in press) for this information.

<sup>1235</sup> \*Hauri et al. (2009, p. 68). The authors cite Dupont and Thorndyke (2009) for this information.

<sup>1236</sup> \*Hauri et al. (2009, p. 61)

<sup>1237</sup> \*Hauri et al. (2009, p. 68)

<sup>1238</sup> \*Hauri et al. (2009, p. 68)

<sup>1239</sup> \*Hauri et al. (2009, p. 68)

<sup>1240</sup> \*Hauri et al. (2009, p. 61)

<sup>1241</sup> \*Kroeker et al. (2010, p. 1429)

## 5. EELGRASS

Eelgrass is a flowering plant adapted to the marine environment that roots in sand or mud in shallow waters typically less than ten meters deep where waves and currents are not too severe.<sup>1242</sup> It is critical spawning and fertilization ground for Pacific herring eggs in southern British Columbia waters, which in turn is central to the marine food web, contributing thirty to seventy percent to the summer diets of Chinook salmon, Pacific cod, lingcod, and harbor seals in the area.<sup>1243</sup> A report from the Puget Sound provides additional detail on the role of eelgrass in the nearshore ecosystem: in greater Puget Sound, Z. marina also provides spawning grounds for Pacific herring (*Clupea harengus pallasii*), out-migrating corridors for juvenile salmon (*Oncorhynchus* spp.), and important feeding and foraging habitats for waterbirds such as the black brant (*Branta bernicla*) and great blue heron (*Ardea herodias*).<sup>1244</sup> Similarly, forty-two species of fish (mostly juvenile and including chum salmon and Pacific herring), as well as juvenile shrimp, hermit crabs, and juvenile Dungeness crabs, were found during nearshore habitat sampling in the City and Borough of Juneau, Alaska from 2004 to 2007.<sup>1245</sup>

### Observed Trends

#### Gulf of Alaska LME

*Information needed.*

#### California Current Ecosystem

At several sites in Willapa and Coos Bay (located in Washington and Oregon, respectively), Thom et al. (2003) observed plant density of eelgrass was positively correlated with summer estuarine salinity and inversely correlated with water temperature gradients in the estuaries from 1998 to 2001.<sup>1246</sup> Warmer periods can cause drying that concentrates mineral salts to levels that are stressful or toxic.<sup>1247</sup> Warmer winters and cooler summers associated with the transition from El Niño to La Niña ocean conditions during the study period corresponded with a substantial increase in eelgrass abundance and flowering in Willapa Bay, and less so in Coos Bay.<sup>1248</sup> The results suggest profound effects of climate variation on the abundance and flowering of eelgrass in Pacific Northwest coastal estuaries.<sup>1249</sup>

Non-native and invasive exotic plants, such as cordgrass *Spartina* spp, the brown algae *Sargassum muticum*, or the Japanese eelgrass *Zostera japonica* crowd and displace native plants.<sup>1250</sup> However, in

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<sup>1242</sup> \*Mumford. *Kelp and eelgrass in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-05.* (2007, p. v)

<sup>1243</sup> \*Wright. *Eelgrass conservation for the B.C. coast: a discussion paper.* (2002, p. 3)

<sup>1244</sup> WA DNR. *Eelgrass Stressor-Response Report: 2005-2007 Report.* (2007, p. 4). The authors cite Phillips (1984) and Simenstad (1994) for information on juvenile salmon, Wilson and Atkinson (1995) for information on black brant, and Butler (1995) for information on great blue heron.

<sup>1245</sup> \*Harris et al. *Eelgrass habitat and faunal assemblages in the City and Borough of Juneau, Alaska.* (2008, p. iii)

<sup>1246</sup> \*Thom et al. *Factors influencing spatial and annual variability in eelgrass (Zostera marine L.) meadows in Willapa Bay, Washington and Coos Bay, Oregon, Estuaries.* (2003, p. 1117)

<sup>1247</sup> Thom et al. *The influence of climate variation and change on structure and processes in nearshore vegetated communities of Puget Sound and other northwest estuaries.* (2001)

<sup>1248</sup> \*Thom et al. (2003, p. 1117)

<sup>1249</sup> \*Thom et al. (2003, p. 1117)

<sup>1250</sup> \*PSWQAT. (2001, p. 2)

most cases in the Pacific Northwest region, there is little opportunity for direct competition between the two *Zostera* species because they occupy different niches in the intertidal zone.<sup>1251</sup> Where they do overlap, neither species is clearly competitively dominant, since biomass and density of both species are reduced in the presence of the other.<sup>1252</sup>

## Future Projections

### Gulf of Alaska LME

*Information needed.*

### California Current Ecosystem

Previous short term studies demonstrated that carbon enrichment can sustain eelgrass growth under light limitation.<sup>1253</sup> Eelgrass has been projected to possibly benefit from acidification – in this case due to an enhancement of photosynthesis from an increased abundance of dissolved carbon dioxide.<sup>1254</sup> However, these benefits may be ultimately offset by water quality decline, and may have an upper threshold.<sup>1255</sup> Increased water temperature in rivers, for example, can harm or kill eelgrass close to the river mouth.<sup>1256</sup> In the Pacific Northwest, eelgrass variation may be related to sea level and temperature changes such that a decline under warmer, dryer conditions would be expected.<sup>1257</sup>

Kroeker et al. (2010) suggest another rationale for observed differences in seagrass response to ocean acidification and light: species-specific differences in response to ocean acidification may be more pronounced within certain taxonomic groups, and are likely responsible for the inability to detect strong effects of ocean acidification in photosynthesis in seagrasses (e.g., eelgrass).<sup>1258</sup> Some species of seagrass significantly increase photosynthesis under reduced pH, whereas other species are relatively immune to the changes due to differences in their carbon-concentrating mechanisms.<sup>1259</sup>

Palacios and Zimmerman (2007) show that long-term CO<sub>2</sub> enrichment derived from the flue gas of an electric power plant enhances the performance of eelgrass growing under natural light conditions over a year, resulting in significantly higher reproductive output, below-ground biomass and vegetative proliferation of new shoots.<sup>1260</sup> Three concentrations of carbon dioxide in solution [CO<sub>2</sub>(aq)] were used, representing current values (16 μM CO<sub>2</sub>(aq), pH 8.1) and three scenarios of higher concentration: pH 7.75

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<sup>1251</sup> \*Mach, Wyllie-Echeverria and Ward. *Distribution and potential effects of a non-native seagrass in Washington State: Zostera japonica workshop*. (2010, p. 8). The authors cite Shafer (2007) for this information.

<sup>1252</sup> \*Mach, Wyllie-Echeverria and Ward. (2010, p. 8)

<sup>1253</sup> \*Palacios and Zimmerman. *Response of eelgrass Zostera marina to CO<sub>2</sub> enrichment: possible impacts of climate change and potential for remediation of coastal habitats*. (2007, p. 1)

<sup>1254</sup> Guinotte and Fabry. *Ocean acidification and its potential effects on marine ecosystems*. (2008); Thom. *CO<sub>2</sub>-Enrichment effects on eelgrass (Zostera marina L.) and bull kelp (Nereocystis luetkeana (Mert.) P. & R.)*. (1996)

<sup>1255</sup> \*Thom. (1996, p. 88).

<sup>1256</sup> \*Puget Sound Water Quality Action Team (PSWQAT). *Sound Facts: Eelgrass (pdf)*. (2001, p. 2)

<sup>1257</sup> Thom et al. (2001)

<sup>1258</sup> \*Kroeker et al. (2010, p. 1430)

<sup>1259</sup> \*Kroeker et al. (2010, p. 1430). The authors cite Invers et al. (1997) for this information.

<sup>1260</sup> \*Palacios and Zimmerman. (2007, p. 1)

in 2100 (36  $\mu\text{M CO}_2(\text{aq})$ ), pH 7.5 in 2200 (85  $\mu\text{M CO}_2(\text{aq})$ ), and pH 6.2 (1123  $\mu\text{M CO}_2(\text{aq})$ ), which triples the light-saturated photosynthesis rate of eelgrass.<sup>1261</sup> Their findings include:

- **Shoot size and biomass accumulation:** Shoots growing at 36  $\mu\text{M CO}_2(\text{aq})$  were 25% larger than those in the unenriched treatment [16  $\mu\text{M CO}_2(\text{aq})$ ], at 85  $\mu\text{M CO}_2(\text{aq})$  shoots were 50% larger than those in the unenriched treatment and at 1123  $\mu\text{M CO}_2(\text{aq})$  shoots were almost twice as large as those in the unenriched treatment.<sup>1262</sup>
- **Flowering shoot production:** The proliferation of flowering shoots responded positively to  $\text{CO}_2(\text{aq})$  enrichment in the light-replete treatments.<sup>1263</sup> Flowering shoots appeared earlier in the year and matured more quickly in proportion to [ $\text{CO}_2(\text{aq})$ ].<sup>1264</sup> At 1123  $\mu\text{M CO}_2(\text{aq})$  in May 2001, 22% of the shoots differentiated into flowers, more than twice the flowering output of the other treatments at this light level.<sup>1265</sup>
- **Vegetative shoot abundance:** Shoot abundance was stable in the 16, 36, and 85  $\mu\text{M CO}_2(\text{aq})$  treatments under light-replete conditions through summer 2001.<sup>1266</sup> Abundance in the 1123  $\mu\text{M CO}_2(\text{aq})$  treatment dropped in late spring as flowering shoots matured and then died.<sup>1267</sup> However, the shoot population of this highest  $\text{CO}_2(\text{aq})$  treatment recovered subsequently through late spring and summer as a result of vegetative proliferation.<sup>1268</sup> Shoot numbers declined in all treatments in winter.<sup>1269</sup>

## Information Gaps

Information is needed on studies testing eelgrass under various environmental conditions in the NPLCC region to determine its potential reaction to the changing climate, including studies of interspecies interaction with other native and nonnative plant species. Information is also needed on observed trends in the Gulf of Alaska LME.

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<sup>1261</sup> \*Palacios and Zimmerman. (2007, p. 6). The authors cite Zimmerman et al. (1997) for the photosynthetic rate.

<sup>1262</sup> \*Palacios and Zimmerman. (2007, p. 6). The authors refer the reader to Fig. 4a in the cited report.

<sup>1263</sup> \*Palacios and Zimmerman. (2007, p. 8). The authors refer the reader to Table 3 and Fig. 7a in the cited report.

<sup>1264</sup> \*Palacios and Zimmerman. (2007, p. 8).

<sup>1265</sup> \*Palacios and Zimmerman. (2007, p. 8). The authors refer the reader to Fig. 8 in the cited report.

<sup>1266</sup> \*Palacios and Zimmerman. (2007, p. 8). The authors refer the reader to Fig. 9a in the cited report.

<sup>1267</sup> \*Palacios and Zimmerman. (2007, p. 8)

<sup>1268</sup> \*Palacios and Zimmerman. (2007, p. 8)

<sup>1269</sup> \*Palacios and Zimmerman. (2007, p. 8)

## 6. PLANKTON

Despite their microscopic size, marine phytoplankton are responsible for about half of the global primary production and represent the basis of the marine food web.<sup>1270</sup> This diverse group of organisms drives important biogeochemical cycles, exporting massive amounts of carbon to deep waters and sediments, and strongly influencing ocean-atmosphere gas exchanges.<sup>1271</sup> The distribution and abundance of

*Plankton are microscopic aquatic organisms that drift or swim weakly. Phytoplankton are the basis of the entire marine food web and are the dominant plants in the sea. These single-celled organisms are the principle agents of photosynthetic carbon fixation in the ocean. Zooplankton are the animal forms of plankton. They consume phytoplankton or other zooplankton.*

*Source: Parry et al. (2007); Rost, Zondervan, & Wolf-Gladrow. (2008)*

phytoplankton communities throughout the world, as well as their phenology and productivity, are changing in response to warming, acidifying, and stratifying oceans.<sup>1272</sup> The annual primary production of the world's oceans has decreased by at least six percent since the early 1980s (no end date provided), with nearly seventy percent of this decline occurring at higher latitudes and with large relative decreases occurring within Pacific and Indian ocean gyres.<sup>1273</sup> Overall, changes in the primary production of the oceans have profound implications for the marine biosphere, carbon sinks, and biogeochemistry of Earth.<sup>1274</sup> In the case of phytoplankton, these factors include nutrients and iron availability, temperature, light, and predation, and other factors.<sup>1275</sup> Essential fatty acids are produced exclusively by marine phytoplankton and transferred up the food

chain to fish through their zooplankton prey.<sup>1276</sup> Some of these lower trophic members such as coccolithophores, foraminifera, and pteropods may be particularly vulnerable to ocean acidification as calcium carbonate forms their biological structure.<sup>1277</sup> Changes in the production rates and community composition of phytoplankton and zooplankton could lead to changes in the fatty acid composition of prey that might not contain the essential fatty acids needed for optimal growth and survival of larval and juvenile fishes.<sup>1278</sup>

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<sup>1270</sup> \*Rost, Zondervan and Wolf-Gladrow. *Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions*. (2008, p. 227)

<sup>1271</sup> \*Rost, Zondervan and Wolf-Gladrow (2008, p. 227)

<sup>1272</sup> \*Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Doney et al. (2009) and Polovina et al. (2008) for this information.

<sup>1273</sup> \*Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Gregg et al. (2003) for information about higher latitudes and Polovina et al. (2008) for information about the Pacific and Indian oceans.

<sup>1274</sup> \*Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Falkowski et al. (2000) for this information.

<sup>1275</sup> \*Hauri et al. (2009, p. 66-67). The authors cite Hare et al. (2007) and Tortell et al. (1997, 2008) for this information.

<sup>1276</sup> \*Sigler et al. (2008, p. 12)

<sup>1277</sup> \*Sigler et al. (2008, p. 12)

<sup>1278</sup> \*Sigler et al. (2008, p. 12)

## Observed Trends

### Global

Declining ocean pH also affects plankton, particularly those with calcium carbonate shells.<sup>1279</sup> These changes are likely to be important to the food web, but in ways scientists cannot entirely predict.<sup>1280</sup> Meta-analysis of 251 unique experiments on the biological response of marine organisms revealed that ocean acidification had a significant negative effect on survival, calcification, growth, and reproduction, but no significant effect on photosynthesis.<sup>1281</sup> The negative effect of ocean acidification was most pronounced for calcification and survival.<sup>1282</sup> There was significant heterogeneity in the calcification and growth responses, but not for the other response variables.<sup>1283</sup> The results of this study are addressed in further detail in other sections of this report: for calcification, see Section 4 (Shellfish) in this Chapter; for survival, see Chapter VI Section 3 (Shifts in community composition, competition, and survival); for growth and developmental stages, see Chapter VI Section 2 (Altered phenology and development); and for photosynthesis, see Chapter IV Section 2 (Altered ocean productivity).

### Gulf of Alaska LME

*Information needed.*

### California Current Ecosystem

Along rocky intertidal zones of the Oregon coast, a study of the influence of climatic variation on phytoplankton abundance and mussel recruitment found that the North Pacific Gyre Oscillation had the strongest relationships with both phytoplankton and recruitment, while relationships between these factors and ENSO and PDO were weak.<sup>1284</sup> Despite the strong relationship between climate variation, phytoplankton concentration, and mussel recruitment, intertidal community dynamics have changed only in relatively subtle ways, suggesting a role for local ecological interactions in dampening the effects of dominant modes of climate forcings in coastal ecosystems.<sup>1285</sup>

## Future Projections

### Gulf of Alaska LME

With increasing SST, a northward shift by end-of-century of a region in the North Pacific that shows large seasonal cycles in phytoplankton and herbivore concentrations, roughly between 150°E and 140°W, 50°N and 60°N is projected.<sup>1286</sup> This is accompanied by a decrease in springtime primary productivity, which is

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<sup>1279</sup> \*Snover et al. (2005, p. 27)

<sup>1280</sup> \*Snover et al. (2005, p. 27)

<sup>1281</sup> \*Kroeker et al. (2010, p. 1424). The authors refer the reader to Fig. 1 in the cited report.

<sup>1282</sup> \*Kroeker et al. (2010, p. 1424)

<sup>1283</sup> \*Kroeker et al. (2010, p. 1424). The authors provide statistics for heterogeneity in calcification ( $Q_T = 116.33$ , d.f. = 62,  $P < 0.0001$ ) and growth responses ( $Q_T = 224.76$ , d.f. = 85,  $P < 0.0001$ ).

<sup>1284</sup> \*Menge et al. *Climatic variation alters supply-side ecology: impact of climate patterns on phytoplankton and mussel recruitment.* (2009, p. 379)

<sup>1285</sup> \*Menge et al. (2009, p. 379)

<sup>1286</sup> \*Pierce. *Future changes in biological activity in the North Pacific due to anthropogenic forcing of the physical environment.* (2004, p. 412). This region is bounded approximately by an east-west line through Strathcona Provincial Park on Vancouver Island (BC) in the south, a north-south line passing through Yakutat (AK) in the east,

partially counteracted by an increase in wintertime productivity.<sup>1287</sup> Changes in mixed layer temperature and depth account for almost all the changes in productivity; model-predicted changes in surface insolation (a measure of solar energy over a given surface and time period) and large-scale upwelling have little impact.<sup>1288</sup>

### California Current Ecosystem

In the California Current System (CCS), a preliminary assessment suggests that ocean acidification will cause a species shift in open ocean phytoplankton, with diatoms possibly profiting at the expense of calcifying phytoplankton.<sup>1289</sup> However, any conclusions about future phytoplankton compositions in the CCS remain speculative because factors such as nutrients and iron availability, temperature, light, and predation might change in parallel in the future, and because there is a lack of experiments that cover a combination of all factors.<sup>1290</sup>

### **Information Gaps**

Studies that specifically assess the current or potential response of planktonic species to climate change such as studies on potential changes to the occurrence and quantity of species, interspecies interactions, and food web interactions, are needed.

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a north-south line through the east coast of Australia in the west, and an east-west line through Seward AK in the north.

<sup>1287</sup> \*Pierce. (2004, p. 412)

<sup>1288</sup> \*Pierce. (2004, p. 389)

<sup>1289</sup> \*Hauri et al. (2009, p. 67)

<sup>1290</sup> \*Hauri et al. (2009, p. 67)