

IV. IMPLICATIONS FOR MARINE & COASTAL ECOSYSTEMS

Marine ecosystems are centrally important to the biology of the planet.⁶⁵⁵ Ecosystem production and structure respond to changes in ocean regimes.⁶⁵⁶ Although there is considerable uncertainty about the spatial and temporal details, climate change is clearly and fundamentally altering ocean ecosystems.⁶⁵⁷ Based on a search of the scientific and grey literature, the following implications of climate change for marine and coastal ecosystems in the NPLCC region have been identified:

1. Altered nutrient cycling
2. Altered ocean productivity
3. Altered food web dynamics
4. Multiple stressors and thresholds

Two large marine ecosystems (LME) are found in the NPLCC region – the Gulf of Alaska LME and the California Current Ecosystem (CCE).⁶⁵⁸ The Gulf of Alaska LME lies off the southern coast of Alaska and the western coast of Canada.⁶⁵⁹ The California Current is a ~621-mile-wide (1000 km), sluggish current spanning the North American Pacific Coast from ~20°N (near Guadalajara Mexico) to 50°N (northern Vancouver Island).⁶⁶⁰ The cold Subarctic Current, as it bifurcates towards the south, serves as the boundary between the Gulf of Alaska and the California Current LME.⁶⁶¹

Recent changes in Alaska's coastal waters include general warming of ocean surface waters, warming of the southeast Bering Sea bottom waters over the continental shelf, a more strongly stratified ocean, hypothesized decrease in ocean productivity, alteration of pelagic ocean habitat, and changes in the distribution of species.⁶⁶² These changes have the potential to affect the structure, function, productivity, and composition of Alaska's marine ecosystems, which may negatively impact the protected marine species that live or migrate through these ecosystems (e.g. North Pacific right whale).⁶⁶³ In the Gulf of Alaska, Sigler, Napp, and Hollowed (2008) identify ocean acidification, as well as climate regimes and ecosystem productivity, as major climate-related concerns.⁶⁶⁴

The northern end of the CCE is dominated by strong seasonal variability in winds, temperature, upwelling, plankton production, and the spawning times of many fishes, whereas the southern end of the CCE has much less seasonal variability in these parameters.⁶⁶⁵ For some groups of organisms, the

⁶⁵⁵ *Hoegh-Guldberg and Bruno. (2010, p. 1523)

⁶⁵⁶ *ISAB. *Climate change impacts on Columbia River Basin Fish and Wildlife*. (2007, p. 69)

⁶⁵⁷ *Hoegh-Guldberg and Bruno. (2010, p. 1523)

⁶⁵⁸ Osgood (ed.). *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs*. (2008, Fig. 1, p. 2); NOAA. *Gulf of Alaska: LME #2 (website)*. (2009); NOAA. *California Current: LME #3 (website)*. (2009)

⁶⁵⁹ *NOAA. *Gulf of Alaska: LME #2 (website)*. (2009)

⁶⁶⁰ *Hickey and Banas. (2008, p. 93)

⁶⁶¹ *NOAA. *Gulf of Alaska: LME #2 (website)*. (2009)

⁶⁶² *Sigler, M.; Napp, J.; Hollowed, A. *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs: Alaskan Ecosystem Complex*. (2008, p. 66). The authors refer the reader to Figure 2 in the cited report for Bering Sea information.

⁶⁶³ *Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 66).

⁶⁶⁴ Sigler, M.; Napp, J.; Hollowed, A. (2008, p. 66).

⁶⁶⁵ *Peterson, W. & Schwing, F. *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs: California Current Ecosystem*. (2008, p. 44)

northern end of the CCE is dominated by sub-arctic boreal fauna whereas the southern end is dominated by tropical and sub-tropical species.⁶⁶⁶ Higher trophic level organisms often take advantage of the strong seasonal cycles of production in the north by migrating to the region during the summer to feed.⁶⁶⁷ Animals exhibiting this behavior include pelagic seabirds such as black-footed albatross and sooty shearwaters, fishes such as Pacific whiting and sardines, and humpback whales.⁶⁶⁸ Overall, the climate-species linkages in the CCE are extremely complex.⁶⁶⁹ The five issues of greatest concern in the CCE are:

- Increased variability in climate forcing,
- Changes to the magnitude and timing of freshwater input,
- Changes in the timing and strength of the spring transition and their effect on marine populations,
- Ocean warming and increased acidification and their impact on pelagic habitat, and
- Changes in ocean circulation and their impact on species distribution and community structure.⁶⁷⁰

The following structure will be used to present information on the implications of climate change for the NPLCC region's marine and coastal ecosystems:

- **Observed Trends** – observed changes at the global level, for the Gulf of Alaska LME, and for the California Current Ecosystem. Section 3 (altered food web dynamics) also describes region-wide changes.
- **Future Projections** – projected direction and/or magnitude of change at the global level, for the Gulf of Alaska LME, and for the California Current Ecosystem. Section 3 (altered food web dynamics) also describes region-wide projections.
- **Information Gaps** – information and research needs identified by reviewers and literature searches.

Note: Section 4 (Multiple stressors and thresholds: Discussion) is presented as a discussion because the available information could not be classified as observed trends or future projections.

⁶⁶⁶ *Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁶⁷ *Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁶⁸ *Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁶⁹ *Peterson, W. & Schwing, F. (2008, p. 44)

⁶⁷⁰ *Peterson, W. & Schwing, F. (2008, p. 44-45)

1. ALTERED NUTRIENT CYCLING

Observed Trends

Global

Information needed.

Gulf of Alaska LME

Several recent studies have assessed nutrient cycling processes in the Gulf of Alaska:

- In a study of glacier runoff in freshwater discharge, Neal, Hood, and Smikrud (2010) conclude changes in timing and magnitude of freshwater delivery to the Gulf of Alaska could impact coastal circulation as well as biogeochemical fluxes in nearshore marine ecosystems and the eastern North Pacific Ocean.⁶⁷¹ Hood and Scott (2008) find that different levels of glacial coverage can alter the timing and magnitude of freshwater, dissolved organic matter, and nutrient yields.⁶⁷² Taken together, their results indicate that decreasing watershed glacial coverage leads to lower riverine yields of freshwater, inorganic phosphorus, and labile dissolved organic matter.⁶⁷³
- Hood et al. (2009) find that direct runoff from Gulf of Alaska glaciers produces a conservative dissolved organic carbon flux of 0.13 ± 0.01 Teragrams per year (Tg/yr) to downstream ecosystems.⁶⁷⁴ Furthermore, the dissolved organic carbon bioavailability value from the most heavily glaciated catchment suggests that ~ 0.1 Tg of the annual dissolved organic carbon derived from Gulf of Alaska glaciers is readily bioavailable.⁶⁷⁵ Because glacial streamwater turbidities are high and riverine transit times from glaciers to their estuaries are short across broad regions of the Gulf of Alaska, a substantial portion of this labile dissolved organic carbon is probably delivered to marine heterotrophic communities without biological or photochemical alteration.⁶⁷⁶ Thus, changes in riverine yields of dissolved organic matter and nutrients due to reductions in glacier extent in coastal watersheds may affect the productivity and function of nearshore coastal ecosystems.⁶⁷⁷ As stated above, the results of studies by Neal, Hood, and Smikrud (2010) and Hood and Scott (2008) indicate that decreasing watershed glacial coverage leads to lower riverine yields of freshwater, inorganic phosphorus, and labile dissolved organic matter.⁶⁷⁸

California Current Ecosystem

Information needed.

⁶⁷¹ *Neal, Hood and Smikrud. *Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska*. (2010, p. 1)

⁶⁷² *Hood and Scott. (2008, p. 583)

⁶⁷³ *Hood and Scott. (2008, p. 585)

⁶⁷⁴ *Hood et al. *Glaciers as a source of ancient and labile organic matter to the marine environment*. (2009, p. 1046)

⁶⁷⁵ *Hood et al. (2009, p. 1046)

⁶⁷⁶ *Hood et al. (2009, p. 1046)

⁶⁷⁷ *Hood and Scott. (2008, p. 583)

⁶⁷⁸ *Hood and Scott. (2008, p. 585)

Future Projections

Global

Information needed.

Gulf of Alaska LME

Iron is an essential micronutrient that limits primary productivity in much of the ocean, including the Gulf of Alaska.⁶⁷⁹ Dust is thought to be one of the most important sources of iron to the Gulf of Alaska, but as with most regions, there are few measurements.⁶⁸⁰ Crusius et al. (2011) recently described a potentially important but largely undocumented source of dust and iron to the Gulf of Alaska: glacial flour-rich riverbed sediments of coastal Alaska (results described in next section).⁶⁸¹ In their conclusion, they state it remains important to examine whether dust fluxes are increasing in high-latitude locations in response to glacial recession and climate change, and what the impact might be on marine ecosystems.⁶⁸² If glaciers continue their present-day pattern of increasing mass loss due to a warming climate, more glacial flour may be transported to the Gulf of Alaska by dust plumes and other mechanisms, affecting phytoplankton growth and Gulf of Alaska ecosystems.⁶⁸³

Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity and control of phytoplankton growth rates.⁶⁸⁴ Decreased freshwater inflows increase water residence time and decrease vertical stratification, and vice versa.⁶⁸⁵ For example, increased melting of glaciers in the Gulf of Alaska coupled with warmer sea surface temperatures will result in increased stratification of the Gulf.⁶⁸⁶ Areas with enhanced riverine input into the coastal ocean will also see greater vertical stratification.⁶⁸⁷

California Current Ecosystem

Since some of the source waters that supply the northern California Current originate in the Gulf of Alaska, more stratified source waters will contribute to increased stratification of coastal waters of the northern California Current.⁶⁸⁸

Comparing the 2081-2120 period to a 40-year period representative of 1860 climate conditions (A2 scenario), Rykaczewski and Dunne (2010) find that despite increased surface temperatures, associated increased stratification, and relatively modest changes in upwelling, nitrate concentration in the upper 200 m of the CCE is projected to increase eighty percent by year 2100.⁶⁸⁹ This significant increase in nitrate

⁶⁷⁹ *Crusius et al. (2011, p. 1)

⁶⁸⁰ *Crusius et al. (2011, p. 1)

⁶⁸¹ *Crusius et al. (2011, p. 1)

⁶⁸² *Crusius et al. (2011, p. 5)

⁶⁸³ *Eos "Research Spotlights" (2011, p. 18)

⁶⁸⁴ *Nicholls et al. (2007, p. 328)

⁶⁸⁵ *Nicholls et al. (2007, p. 328). The authors cite Moore et al. (1997) for this information.

⁶⁸⁶ *Peterson, W. & Schwing, F. (2008, p. 56)

⁶⁸⁷ *Peterson, W. & Schwing, F. (2008, p. 56)

⁶⁸⁸ *Peterson, W. & Schwing, F. (2008, p. 56)

⁶⁸⁹ *Rykaczewski and Dunne. *Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model.* (2010, p. 2). The authors refer the reader to Fig. S2b for

concentration is in opposition to the decreased concentration in the subtropical North Pacific (20°N to 45°N) that is expected given the increased stratification.⁶⁹⁰

Through the NPLCC region, the decrease in biodiversity in hypoxic areas will reduce ecosystem resilience and resistance and may decrease its function in nutrient cycling processes.⁶⁹¹

Information Gaps

Information is needed on observed patterns of nutrient cycling in the California Current Ecosystem, as well as observed trends and future projections for global patterns of nutrient cycling. Further, quantitative projections of nutrient cycling patterns under scenarios of future climatic change are needed for the NPLCC region.

information on increased stratification and to Fig. 1b for information on nitration concentration (both in cited report).

⁶⁹⁰ *Rykaczewski and Dunne. (2010, p. 2)

⁶⁹¹ *Ekau et al. *Impacts of hypoxia on the structure and processes in pelagic communities*. (2010, p. 1691)

2. ALTERED OCEAN PRODUCTIVITY

Observed Trends

Global

The annual primary production (accumulation of plant growth during a specified time period, typically by photosynthesizers such as phytoplankton) of the world's oceans has decreased by at least six percent since the early 1980s, with nearly seventy percent of this decline occurring at higher latitudes and with large relative decreases occurring within Pacific and Indian ocean gyres (see Chapter 3, Section 4 for further information on gyres).⁶⁹² Global declines in net primary production (as estimated from the SeaWiFS satellite sensor) between 1997 and 2005 were attributed to ocean surface warming.⁶⁹³

In a meta-analysis of the effects of ocean acidification on marine organisms, ocean acidification did not have a significant overall mean effect on photosynthesis.⁶⁹⁴ Although calcifying organisms had a more negative mean effect than non-calcifying organisms, the difference was not significant.⁶⁹⁵ The mean effect was different amongst taxonomic groups, with a significant negative mean effect on calcifying algae.⁶⁹⁶

Gulf of Alaska LME

Iron is an essential micronutrient that limits primary productivity in much of the ocean, including the Gulf of Alaska.⁶⁹⁷ In a study of hydrologic and meteorological controls and their importance as a source of bioavailable iron in glacial flour dust storms, Crusius et al. (2011) found that glacial flour (i.e., fine-grained sediment resulting from glacial erosion) dust plumes are transported several hundred kilometers beyond the continental shelf into iron-limited waters of the Gulf of Alaska.⁶⁹⁸ They estimated the mass of dust transported from the Copper River valley during one event in 2006 to be twenty-five to eighty kilotons.⁶⁹⁹ Based on conservative estimates, this equates to a soluble iron loading of 30 to 200 tons.⁷⁰⁰ Crusius et al. suggest the total amount from the entire Gulf of Alaska coastline is two to three times larger – comparable to the annual iron flux to Gulf of Alaska surface waters from eddies of coastal origin.⁷⁰¹

⁶⁹² *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.

⁶⁹³ *Janetos et al. (2008, p. 166)

⁶⁹⁴ *Kroeker et al. *Meta-analysis reveals negative yet variable effects on ocean acidification on marine organisms.* (2010, p. 1425)

⁶⁹⁵ *Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 2 in the cited report and provide statistics for this result: $Q_M = 0.30$, d.f. = 1, $P = 0.59$.

⁶⁹⁶ *Kroeker et al. (2010, p. 1425). The authors refer the reader to Fig. 3 in the cited report and provide statistics for taxonomic groups ($Q_M = 12.03$, d.f. = 3, $P = 0.02$) and calcifying algae ($\text{LnRR} = -0.33$, 95% bias-corrected confidence interval = -0.39 to -0.22).

⁶⁹⁷ *Crusius et al. (2011, p. 1)

⁶⁹⁸ *Crusius et al. (2011, p. 1)

⁶⁹⁹ *Crusius et al. (2011, p. 1)

⁷⁰⁰ *Crusius et al. (2011, p. 1)

⁷⁰¹ *Crusius et al. (2011, p. 1)

California Current Ecosystem

The vertical gradient in ocean temperature off California has intensified over the past several decades.⁷⁰² Roemmich and McGowan (1995) credited this change in temperature structure for the observed long-term decline in zooplankton biomass.⁷⁰³ In recent years, the northern California Current appears to have recovered from two summers of poor productivity (2005 and 2006) – the ocean was cold during the winter of 2006-07, the spring transition to upwelling conditions was very early (February), and zooplankton biomass returned to levels not seen since summer of 2004.⁷⁰⁴

Future Projections

Global

Sarmiento et al. (2004) examined six different coupled climate model simulations to determine the ocean biological response to climate warming between the beginning of the industrial revolution and 2050.⁷⁰⁵ Three different primary production algorithms were used to estimate the response of primary production to climate warming based on estimated chlorophyll concentrations.⁷⁰⁶ The three algorithms give a global increase in primary production of 0.7% at the low end to 8.1% at the high end, with very large regional differences.⁷⁰⁷

Steinacher et al. (2010), on the other hand, project decreases in global mean primary productivity and export of particulate organic carbon by 2100 relative to preindustrial conditions (A2 scenario; multi-model analysis).⁷⁰⁸

Finally, algae growth in lagoons and estuaries may respond positively to elevated dissolved inorganic carbon (DIC), though marine macroalgae do not appear to be limited by dissolved organic carbon levels.⁷⁰⁹

Region-wide

Beyond the coastal waters of the NPLCC region (i.e., farther out to sea than the California Current), production and chlorophyll concentration over most of the North Pacific are projected to decline with future warming, consistent with the changes in nutrient concentration discussed in the previous section.⁷¹⁰ The projected decline in production is greatest in the subtropical region (20% median decline by 2100 relative to 1860 levels between 20° and 45° N; A2 scenario) where primary production is limited by the supply of macronutrients.⁷¹¹ In the subarctic Pacific, where production is colimited by iron, light, and macronutrients, the relative decline in production is less (5% decline between 45° and 65° N); increased

⁷⁰² *Peterson, W. & Schwing, F. (2008, p. 56). The authors cite Palacios et al. (2004) for this information and refer the reader to Figure 4 in the cited report.

⁷⁰³ *Peterson, W. & Schwing, F. (2008, p. 56)

⁷⁰⁴ *Peterson, W. & Schwing, F. (2008, p. 45)

⁷⁰⁵ *Sarmiento et al. *Response of ocean ecosystems to climate warming*. (2004, p. 1)

⁷⁰⁶ *Sarmiento et al. (2004, p. 1)

⁷⁰⁷ *Sarmiento et al. (2004, p. 1)

⁷⁰⁸ *Steinacher et al. *Projected 21st century decrease in marine productivity: a multi-model analysis*. (2010, p. 979)

⁷⁰⁹ Nicholls et al. (2007, p. 329-330). The authors cite Beer and Koch (1996) for this information.

⁷¹⁰ *Rykaczewski and Dunne. (2010, p. 2). The authors refer the reader to Fig. 1c in the cited report.

⁷¹¹ *Rykaczewski and Dunne. (2010, p. 2)

stratification acts to reduce light limitation and thus iron demand in the subarctic, enhancing the efficiency of nitrate uptake.⁷¹²

Gulf of Alaska LME

If global warming results in shorter winters in the north Pacific, areas where production is light limited may see higher productivity.⁷¹³ For example, phytoplankton blooms are initiated currently as early as February off northern California in years when storm intensity is low.⁷¹⁴

California Current Ecosystem

The coastal plain estuaries of the Pacific Northwest, with the exception of the Columbia River, are relatively small, with large tidal forcing and highly seasonal direct river inputs that are low to negligible during the growing season.⁷¹⁵ Primary production in these estuaries is likely controlled not by river-driven stratification but by coastal upwelling and exchange with the ocean.⁷¹⁶

Future ocean productivity in the California Current is mediated by several mechanisms, each of which interacts to determine productivity. Available research on these mechanisms supports both increased and decreased ocean productivity. Increases in ocean productivity may occur in the following situations:

- Rykaczewski and Dunne (2010) examined changes in nutrient supply and productivity of the California Current Ecosystem under projected conditions of future global climate.⁷¹⁷ Comparing the 2081-2020 period to a 40-year period representative of 1860 (A2 scenario), they conclude primary production is projected to increase in the CCE with future warming (10% by 2100) in response to increased nitrate supply tempered by increased iron and light colimitation.⁷¹⁸
- Currently light limited areas (e.g., the northern California Current) may see higher productivity in the future.⁷¹⁹ Early blooms result in bursts in egg production by both copepods and euphausiids, initiating a cohort of animals that reach adulthood one-two months earlier than a cohort that is initiated with the onset of upwelling in March or April.⁷²⁰ The result would be a longer plankton production season.⁷²¹

Decreases in ocean productivity may occur in the following situations:

- Given that the future climate will be warmer, the upper ocean at the basin scale will almost certainly be, on average, more stratified.⁷²² This will make it more difficult for winds and upwelling to mix the upper layers of the coastal ocean, and will make offshore Ekman pumping less effective at bringing nutrients into the photic zone.⁷²³ The result will be lower primary

⁷¹² *Rykaczewski and Dunne. (2010, p. 2)

⁷¹³ *Peterson, W. & Schwing, F. (2008, p. 53)

⁷¹⁴ *Peterson, W. & Schwing, F. (2008, p. 53-54)

⁷¹⁵ *Hickey and Banas. (2003, p. 1010)

⁷¹⁶ *Hickey and Banas. (2003, p. 1010)

⁷¹⁷ *Rykaczewski and Dunne. (2010, p. 1)

⁷¹⁸ *Rykaczewski and Dunne. (2010, p. 2)

⁷¹⁹ Peterson, W. & Schwing, F. (2008, p. 53)

⁷²⁰ *Peterson, W. & Schwing, F. (2008, p. 54)

⁷²¹ *Peterson, W. & Schwing, F. (2008, p. 54)

⁷²² *Peterson, W. & Schwing, F. (2008, p. 53)

⁷²³ *Peterson, W. & Schwing, F. (2008, p. 53)

productivity everywhere (with the possible exception of the nearshore coastal upwelling zones).⁷²⁴

- Some global climate models predict a higher frequency of El Niño events, while others predict the intensity of these events will be stronger.⁷²⁵ If true, primary and secondary production will be greatly reduced in the CCE, with negative effects transmitted up the food chain.⁷²⁶ However, despite considerable progress in understanding the impact of climate change on many of the processes that contribute to El Niño variability, it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change.⁷²⁷

Information Gaps

Information is needed on observed patterns of ocean productivity in southcentral and southeast Alaska, as the research presented here is from a single study. Quantitative data on observed patterns of ocean productivity throughout the NPLCC region is also needed. For future projections, information is needed for the Gulf of Alaska LME as well as globally.

⁷²⁴ *Peterson, W. & Schwing, F. (2008, p. 53)

⁷²⁵ *Peterson, W. & Schwing, F. (2008, p. 45)

⁷²⁶ *Peterson, W. & Schwing, F. (2008, p. 45)

⁷²⁷ *Collins et al. *The impact of global warming on the tropical Pacific Ocean and El Niño*. (2010, p. 391)

3. ALTERED FOOD WEB DYNAMICS

Observed Trends

Global

Information needed.

Region-wide

In the Pacific Ocean, Chavez et al. (2003) report that air and ocean temperatures, atmospheric carbon dioxide, landings of anchovies and sardines, and the productivity of coastal and open ocean ecosystems have varied over periods of about fifty years.⁷²⁸ Sardine and anchovy “regimes” are associated with large-scale changes in ocean temperatures; for twenty-five years the Pacific is warmer than average (the warm, sardine regime) and then switches to cooler than average for the next twenty-five years (the cool, anchovy regime).⁷²⁹ In the northeast Pacific, an intensification (sardine) or relaxation (anchovy) of the Aleutian Low has also been observed.⁷³⁰ Instrumental data provide evidence for two full cycles.⁷³¹

- **Cool (anchovy) phases from about 1900 to 1925 and 1950 to 1975:**⁷³² A stronger and broader California Current, brought about during the anchovy regime, is associated with a shallower coastal thermocline from California to British Columbia, leading to enhanced primary production.⁷³³
- **Warm (sardine) phases from about 1925 to 1950 and 1975 to the mid-1990s:**⁷³⁴ The “sardine regime” of the 1930s and 1940s was most notable for the sardine fishery off California and its collapse.⁷³⁵ During the sardine regime from the late 1970s to the early 1990s, zooplankton and salmon declined off Oregon and Washington but increased off Alaska.⁷³⁶ Seabird populations decreased off California and Peru.⁷³⁷

As implied above, in the mid-1970s, the Pacific changed from a cool “anchovy regime” to a warm “sardine regime.”⁷³⁸ The mid-1970s change has been widely recognized in a myriad of North Pacific climatic and biological time series and has been referred to as the 1976–1977 regime shift, even though its precise timing is difficult to assess.⁷³⁹ Some indices suggest that the shift occurred rapidly whereas others

⁷²⁸ *Chavez et al. *From anchovies to sardines and back: multidecadal change in the Pacific Ocean.* (2003, p. 217)

⁷²⁹ *Chavez et al. (2003, p. 217)

⁷³⁰ *Chavez et al. (2003, p. 218). The authors cite Miller et al. (1994) for this information.

⁷³¹ *Chavez et al. (2003, p. 217)

⁷³² *Chavez et al. (2003, p. 217)

⁷³³ *Chavez et al. (2003, p. 218). The authors refer the reader to Figure 2 in the cited report.

⁷³⁴ *Chavez et al. (2003, p. 217)

⁷³⁵ *Chavez et al. (2003, p. 217). The authors cite Lluch-Cota, Hernández-Vázquez and Lluch-Cota (1997) and refer the reader to Figure 1E in the cited report for information on the sardine regime of the 1930s and 1940s.

⁷³⁶ *Chavez et al. (2003, p. 218). The authors cite Hare and Mantua (2000) and Benson and Trites (2002) for this information.

⁷³⁷ *Chavez et al. (2003, p. 218). The authors cite Veit, Pyle and McGowan (1996) for information on California.

⁷³⁸ *Chavez et al. (2003, p. 217)

⁷³⁹ *Chavez et al. (2003, p. 217). The authors cite Ebbesmeyer et al. (1991) for information on climatic time series, Hare and Mantua (2000) and Benson and Trites (2002) for information on biological time series, and Miller et al. (1994) and Frances and Hare (1994) for information on the 1976-1977 regime shift.

suggest a more gradual change, though all indicate a shift in the 1970s.⁷⁴⁰ Table 18 further describes the atmospheric, biological, and ecological changes associated with this regime shift.

Gulf of Alaska LME

Information needed.

California Current Ecosystem

Increasing hypoxia seems to benefit gelatinous plankton and/or squid as observed in the Benguela and California current regions.⁷⁴¹ Other components of the “classical” marine foodweb are negatively affected: certain copepods and fish.⁷⁴² Within these groups the response is very complex:⁷⁴³

- In general, small pelagic fish species, such as clupeids, could be more vulnerable than higher evolved and more adaptable species such as gobies or flat fish.⁷⁴⁴
- No systematic investigation exists on whether higher evolved fishes are more tolerant or adaptive to hypoxic conditions than less evolved ones.⁷⁴⁵

Jumbo squid (*Dosidicus gigas*) are opportunistic predators with high turnover rates and high consumption rates.⁷⁴⁶ Climate change has already been shown to force the range expansions of many marine species towards the poles, with animals with the greatest turnover rates showing the most rapid distributional responses to warming.⁷⁴⁷ Results from a food web study by Field et al. (2007) reflect the widely held perception of jumbo squid being a highly flexible predator with the ability to rapidly adapt to new environmental conditions during range expansions.⁷⁴⁸

Currently there is insufficient information to estimate plausible or possible impacts on California Current food webs, due to a lack of abundance information and incomplete knowledge of how movement and food habits may differ across seasons and between inshore and offshore waters.⁷⁴⁹ However, that jumbo squid are opportunistic predators with high turnover rates and high consumption rates, and that among their important prey are several of the current (and historically) largest fisheries (e.g., by volume along the U.S. West Coast, suggest that impacts are plausible.⁷⁵⁰ For example, stomach samples collected by Field et al. included Pacific hake (*Merluccius productus*), small flatfish, rockfish, Pacific sardine (*Sardinops sagax*), Northern anchovy (*Engraulis mordax*), and California market squid (*Loligo opalescens*).⁷⁵¹ Such impacts could drive changes at both higher and lower trophic levels.⁷⁵²

⁷⁴⁰ *Chavez et al. (2003, p. 217)

⁷⁴¹ *Ekau et al. (2010, p. 1690)

⁷⁴² *Ekau et al. (2010, p. 1690)

⁷⁴³ *Ekau et al. (2010, p. 1690)

⁷⁴⁴ *Ekau et al. (2010, p. 1690)

⁷⁴⁵ *Ekau et al. (2010, p. 1690)

⁷⁴⁶ *Field et al. *Range expansion and trophic interactions of the jumbo squid (*Dosidicus gigas*) in the California Current*. (2007, p. 143)

⁷⁴⁷ *Field et al. (2007, p. 142). The authors cite Perry et al. (2005) for this information.

⁷⁴⁸ *Field et al. (2007, p. 142)

⁷⁴⁹ *Field et al. (2007, p. 143)

⁷⁵⁰ *Field et al. (2007, p. 143)

⁷⁵¹ Field et al. (2007, Fig. 4, p. 138)

⁷⁵² *Field et al. (2007, p. 143)

Table 18. Synthesis of Pacific conditions during sardine and anchovy regimes.

Type of impact	Warm “sardine regime” (mid 1970s to mid 1990s)		Cool “anchovy regime” (1950s through early 1970s)	
	34 th to 48 th parallel*	North of 48 th parallel	34 th to 48 th parallel*	North of 48 th parallel
Atmospheric & Physical†	<ul style="list-style-type: none"> • Weaker upwelling • Slower CA Current & weaker CA Undercurrent • Lower precipitation in WA & lower salinity • Higher SST & stratification 	<ul style="list-style-type: none"> • Strong Aleutian Low • More downwelling • Higher precipitation & streamflow • Higher/strong stratification, higher SST 	<ul style="list-style-type: none"> • Stronger upwelling • Faster CA Current & stronger CA Undercurrent • Higher precipitation in WA & higher salinity • Lower SST & stratification 	<ul style="list-style-type: none"> • Weak Aleutian Low • Less downwelling • Lower precipitation & streamflow, • Lower/weaker stratification, lower SST
Biological & Ecological†	<ul style="list-style-type: none"> • More sardines • Less salmon, seabirds, rockfish, & anchovies • Lower nutrients, zooplankton, & PP 	<ul style="list-style-type: none"> • More salmon • Higher zooplankton, PP, & nutrients 	<ul style="list-style-type: none"> • More anchovies, salmon, seabirds, rockfish • Less sardines • Higher nutrients, zooplankton, & PP 	<ul style="list-style-type: none"> • Less salmon • Lower PP, nutrients, & zooplankton

*The 34th to 48th parallel is the area approximately between southern CA and the Strait of Juan de Fuca.
 † “SST” is sea surface temperature. “PP” is primary production.
 Source: Modified from Chavez et al. (2003, Fig. 3, p. 220) by authors of this report.

Future Projections

Global

Animal metabolism is temperature-dependent, and consequently ecological processes such as predator-prey interactions are likely to be altered as warming occurs.⁷⁵³ When combined with changing patterns of primary productivity and metabolic rate, these fundamental influences have the potential to substantially modify ocean food web dynamics, from coastal to open-ocean ecosystems:⁷⁵⁴

- Respiration is more sensitive than photosynthesis to changes in temperature, resulting in the caloric demands of consumers being potentially more strongly influenced by increased

⁷⁵³ *Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Hochachka and Somero (2002) for information on the temperature-dependence of animal metabolism and Sanford (1999) for information on predator-prey interactions.

⁷⁵⁴ *Hoegh-Guldberg and Bruno. (2010, p. 1525-1526)

temperature when compared to the temperature response of primary production.⁷⁵⁵ Energetic demands are increased at warmer temperatures, requiring increased consumption of prey to maintain a given growth rate.⁷⁵⁶ These findings have implications for the ability of pelagic (open-ocean) systems to capture and store carbon dioxide, with the potential for these critical ocean processes to decline as temperature increases.⁷⁵⁷

- Warming has also been found to decrease the size of individual phytoplankton, further altering the functioning and biogeochemistry of shallow pelagic ecosystems and, in particular, reducing their potential for carbon sequestration (see Chapter VII, Section 6 for further information).⁷⁵⁸

With regard to ocean acidification, the negative responses of corals and coccolithophores to ocean acidification could have profound repercussions for marine ecosystems, with scleractinian corals serving as habitat for coral reef ecosystems and coccolithophores serving as the foundation of its food web.⁷⁵⁹

Region-wide

Several reviewers requested information on whether the “sardine” or “anchovy” regime described previously is likely for the future. However, Chavez et al. (2003) do not make projections about which regime is more likely in the future. Instead, they note that studies of anthropogenic effects and management of ocean resources must consider natural, multidecadal oscillations.⁷⁶⁰ As an example, they state overfishing or global warming may alter the response of populations to natural multidecadal change.⁷⁶¹

Gulf of Alaska LME

With some assurance that oxygen levels will continue to decline (and nutrient levels increase), it is reasonable to project that continental shelf and slope ecosystems in the subarctic Pacific Ocean will lose oxygenated habitat if coastal upwelling strengthens.⁷⁶² For example:

- The few fish species such as sablefish and some rock fishes that tolerate low oxygen may expand their territory, but in general mid-water organisms will be forced to find shallower habitat or perish.⁷⁶³ This will increase competition for resources and may expose some species to greater predation from above.⁷⁶⁴

⁷⁵⁵ *Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite López-Urrutia et al. (2006) for information on the sensitivity of respiration to temperature, and refer the reader to Figure 3, A to F, in the cited publication.

⁷⁵⁶ *ISAB. (2007, p. 69)

⁷⁵⁷ *Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite López-Urrutia et al. (2006) for this information.

⁷⁵⁸ *Hoegh-Guldberg and Bruno. (2010, p. 1525). The authors cite Morán et al. (2010) for information on the size of individual phytoplankton.

⁷⁵⁹ *Kroeker et al. (2010, p. 1428)

⁷⁶⁰ *Chavez et al. (2003, p. 221)

⁷⁶¹ *Chavez et al. (2003, p. 221)

⁷⁶² *Whitney, Freeland and Robert. (2007, p. 191)

⁷⁶³ *Whitney, Freeland and Robert. (2007, p. 191)

⁷⁶⁴ *Whitney, Freeland and Robert. (2007, p. 191)

California Current Ecosystem

The source waters that feed into the California Current from the north and offshore can exert some control over the phytoplankton and zooplankton species that dominate the current.⁷⁶⁵ A particular biological concern is variability in the transport of organisms, which impacts zooplankton species composition and regional recruitment patterns for demersal (bottom-dwelling) fish stocks.⁷⁶⁶ Waters from the Gulf of Alaska carry large, lipid-rich copepods to the shelf waters, whereas waters coming from an offshore source carry small, oceanic lipid-poor copepods to the shelf waters.⁷⁶⁷ When the PDO is in the warm phase, a greater proportion of the water entering the northern end of the Current is sub-tropical in character rather than sub-Arctic (i.e. originating from offshore rather than the Gulf of Alaska).⁷⁶⁸ Based on ongoing observations, a positive PDO (corresponding to warmer ocean conditions in the California Current) results in dominance of small warm-water zooplankton (which are lipid-depleted) which may result in food chains with lower bioenergetic content.⁷⁶⁹

By about 2030, it is expected that the minima ocean temperatures due to decadal variability will be above the historical mean of the 20th Century (i.e., the greenhouse gas warming trend will be as large as natural variability).⁷⁷⁰ Thus changes reflected by PDO shifts may result in local food chains that have vastly different bio-energetic content.⁷⁷¹

Information Gaps

Information is needed on observed trends in the Gulf of Alaska LME and globally. Quantitative future projections for the NPLCC region are also needed, as the information presented here only discusses the possible direction and magnitude of future change. High-resolution coastal ocean/atmosphere models are needed to resolve important processes (e.g., coastal upwelling, eddies, coastal wind features) in conjunction with global models or as nested components of global models. Chavez et al. (2003) state that unraveling the processes behind multidecadal variability and how they affect ocean ecosystems and biogeochemical cycling will require a concerted and integrated observational and modeling effort.⁷⁷² Measurement networks, analogous to those established by meteorologists, will be required for ocean physics, ecology, and biogeochemistry.⁷⁷³ As longer time series are collected and integrated into a basin-scale or global view, longer period fluctuations may be uncovered.⁷⁷⁴ These time series will help answer many of the fundamental questions associated with regime shifts.⁷⁷⁵

⁷⁶⁵ *Peterson, W. & Schwing, F. (2008, p. 59). The authors refer the reader to Figure 5 in the cited report.

⁷⁶⁶ *Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁶⁷ *Peterson, W. & Schwing, F. (2008, p. 59)

⁷⁶⁸ *Peterson, W. & Schwing, F. (2008, p. 59)

⁷⁶⁹ Peterson, W. & Schwing, F. (2008, p. 45)

⁷⁷⁰ Peterson, W. & Schwing, F. (2008, p. 45)

⁷⁷¹ *Peterson, W. & Schwing, F. (2008, p. 59)

⁷⁷² *Chavez et al. (2003, p. 221)

⁷⁷³ *Chavez et al. (2003, p. 221)

⁷⁷⁴ *Chavez et al. (2003, p. 221)

⁷⁷⁵ *Chavez et al. (2003, p. 221)

Peterson and Schwing (2008) identify a number of information gaps for the California Current region:

- The combined impact of ocean warming and increased acidification on pelagic habitat requires data on the factors that contribute to upper ocean stratification.⁷⁷⁶ These include coastal wind (for estimating wind stress, mixing, and latent heat exchange), air-sea heat fluxes, and streamflow and freshwater discharge throughout the CCE region.⁷⁷⁷
- High-resolution synoptic mapping of ocean variables that define biological “hot spots” must be maintained to monitor changes in the pelagic habitat and relations to climate variability.⁷⁷⁸
- Regional models with reliable precipitation and stream flow projections are necessary to model future coastal pelagic ocean conditions.⁷⁷⁹
- IPCC projections of future temperature and stratification are needed to allow long-term estimates of changes in upper ocean structure and productivity, which will determine the pelagic habitat for many coastal species.⁷⁸⁰

⁷⁷⁶ *Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁷⁷ *Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁷⁸ *Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁷⁹ *Peterson, W. & Schwing, F. (2008, p. 58)

⁷⁸⁰ *Peterson, W. & Schwing, F. (2008, p. 58)

4. MULTIPLE STRESSORS AND THRESHOLDS: DISCUSSION

Although most of the ocean is undergoing impacts from multiple anthropogenic stressors, little is known about the potential for large-scale synergisms (or antagonisms).⁷⁸¹ Even additive effects have great potential to overwhelm key species and entire ecosystems.⁷⁸² Recent evidence suggests that there is now a growing risk that several thresholds will soon be exceeded.⁷⁸³ Carbon dioxide concentrations of 400 to 450 ppm or a +3.6°F (+2°C) increase in average global temperature above pre-industrial values have been identified as thresholds for key ocean components such as aragonite undersaturation of the Southern Ocean, loss of polar sea ice, and the melting of the Greenland and Western Antarctic ice sheets.⁷⁸⁴ From 2000 to 2004, the actual emissions trajectory was close to that of the high-emissions A1F1 scenario (nearly 1000 ppm⁷⁸⁵).⁷⁸⁶ A new study by Arora et al. (2011) suggests that limiting warming to roughly 3.6°F (2.0°C) by 2100 is unlikely since it requires an immediate ramp down of emissions followed by ongoing carbon sequestration after 2050.⁷⁸⁷

Multiple stressors and thresholds were identified as climate-related concerns for marine and coastal ecosystems globally⁷⁸⁸ and information specific to the NPLCC region was available for the California Current Ecosystem.⁷⁸⁹

Eastern boundary upwelling systems, such as the California Current System (CCS) are naturally more acidic than most of the rest of the surface ocean.⁷⁹⁰ Recent research suggests systems like the CCS are particularly vulnerable to future ocean acidification.⁷⁹¹ However, ocean acidification is just one of several stress factors, which include hypoxia, anomalous sea surface temperatures, pollution, and overfishing:⁷⁹²

- Increasing SST and stratification tend to enhance low-oxygen (i.e. potentially hypoxic) conditions in the CCS, adding another stressor, with resultant cascading effects on benthic (bottom-dwelling) and pelagic (open ocean) ecosystems.⁷⁹³
- Ocean deoxygenation due to the effects of reduced production of mineral ballast by calcifying organisms could substantially amplify the impact of ocean acidification on marine ecosystems in the CCS.⁷⁹⁴

⁷⁸¹ *Hoegh-Guldberg and Bruno. (2010, p. 1528). The authors cite Halpern et al. (2008) for information on multiple anthropogenic stressors and Darling and Côté (2008) for information on large-scale synergisms or antagonisms.

⁷⁸² *Hoegh-Guldberg and Bruno. (2010, p. 1528)

⁷⁸³ *Hoegh-Guldberg and Bruno. (2010, p. 1528). The authors cite Rockström et al. (2009) for this information.

⁷⁸⁴ *Hoegh-Guldberg and Bruno. (2010, p. 1528). The authors cite McNeil et al. (2008) for information on the Southern Ocean, Wang and Overland (2009) for information on polar sea ice, Gregory et al. (2004) for information on Greenland, and Naish et al. (2009) for information on Western Antarctica.

⁷⁸⁵ Meehl et al. (2007, p. 803). This information was extrapolated from Figure 10.26 by the authors of this report.

⁷⁸⁶ Raupach et al. *Global and regional drivers of accelerating CO₂ emissions*. (2007)

⁷⁸⁷ *Arora et al. *Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases*. (2011)

⁷⁸⁸ Hoegh-Guldberg and Bruno. (2010)

⁷⁸⁹ Hauri et al. (2009)

⁷⁹⁰ *Hauri et al. (2009, p. 60)

⁷⁹¹ *Hauri et al. (2009, p. 61)

⁷⁹² *Hauri et al. (2009, p. 68)

⁷⁹³ *Hauri et al. (2009, p. 68-69). The authors cited Bograd et al. (2008) for this information.

⁷⁹⁴ *Hauri et al. (2009, p. 69). The authors cited Brewer and Peltzer (2009) for this information.

However, when assessing the potential vulnerability of organisms and ecosystems to ocean acidification in the CCS, it is important to consider that organisms are already frequently exposed to water with low pH and saturation levels (of aragonite and calcite, important for shell formation), especially during upwelling events and in nearshore regions.⁷⁹⁵ Furthermore, the growth and success of an individual species in a changing ocean depends on many environmental factors.⁷⁹⁶

Information Gaps

Information is needed on observed trends and future projections for the Gulf of Alaska LME and the California Current Ecosystem, as the information presented here is a discussion only.

⁷⁹⁵ *Hauri et al. (2009, p. 66)

⁷⁹⁶ *Hauri et al. (2009, p. 66)