APPENDIX MS2013-01. SENSITIVITY OF THE CALIFORNIA CURRENT ECOSYSTEM TO CLIMATE CHANGE AND OCEAN ACIDIFICATION

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[King et al. (2011) article summarized with permission from Jacquelynne King, Department of Fisheries and Oceans, Canada]

CLIMATE CHANGE AND THE CALIFORNIA CURRENT ECOSYSTEM

King et al. (2011) review potential implications of climate change on the California Current. Their synthesis, augmented with several other recent studies, provides a backdrop for the quantitative modeling we present here. Overall, King et al. identify trends in recent decades that may be associated with climate change; they point to specific pathways by which changes in physics and biogeochemistry may impact particular species; and they identify predictions from ensembles of global circulation models that forecast potential biophysical changes. One example of such a biophysical change impacting upper trophic levels (Woodworth-Jefcoats et al. 2013) is that large fish abundance is projected to decrease in the broader north Pacific, while in the California Current large fish are predicted to increase.

King et al. summarize empirical trends from the last 50-60 years that indicate warming of surface waters, an increase in upwelling-favorable winds particularly in the north, but increased stratification, particularly in the south (Bakun 1990, Mendelssohn et al. 2003, Palacios 2004). Increased upwelling may therefore have not led to increased primary production (McGowan et al. 2003, Palacios 2004). The biophysical system responds strongly to El Niño events, which have been increasing in intensity and frequency (An and Wang 2000). El Niño events bring warm water to the coast, and generally reduce the productivity of many coastal stocks (Checkley and Barth 2009), though migratory species such as sardine and hake may increase in abundance in the northern extent of the California Current.

King et al provide conceptual diagrams illustrating the potential for climate change to lead to: warmer surface waters; increased upwelling-favorable winds; a deepening thermocline; and increased coastal stratification that may lessen the beneficial effects of upwelling. Increased upwelling often includes increased acidification and lower dissolved oxygen, which can result in further habitat compression for hypoxia sensitive species (Stramma et al. 2011) but also reduced maximum body sizes for fish species in the CCS (Cheung et al. 2012). King et al. predicted that southern species of copepods would move north, replacing boreal copepods that provide higher energy content to predators and have been linked to high salmon production. Migratory fish such as Pacific hake and sardine could expand northward and increase the extent of annual northerly migrations. Pelagic species such as albacore tuna and blue shark could increase movements to nearshore areas. Chinook salmon freshwater habitat may have low water flow during salmon spawning and rearing phases, decreasing spawner success and juvenile survival. On the other hand, King and colleagues suggest that some long-lived groundfish may be able to withstand prolonged periods of poor recruitment, and could increase in the northern extent of the California Current. However, seabirds often have poor hatchling survival and fledging success during warm El Niño events, and this may be persistent if warmer conditions continue in the future. As illustrated by the expansion of jumbo squid in the California Current and recruitment failures of Cassin's auklet and Chinook salmon in recent years (Sydeman et al. 2006, Lindley et al. 2009, Stewart et al. 2012), changing environmental conditions will most certainly result in some populations expanding in size and habitat while others decrease.

Overland and Wang (2007) summarize climate change predictions from an ensemble of 10 atmosphere-ocean global circulation models that best fit 20th century historical data of sea surface temperature and the Pacific Decadal Oscillation. This ensemble approach leads to estimates of slight warming of approximately 1.2-1.8°C by year 2050, across the North Pacific. King et al. (2011) use a similar model ensemble, and also report some minor increases in upwelling intensity, particularly in the northern California Current. Natural variability overshadowed climate signals for many important metrics, particularly through 2040, with more substantial deviation from long term means beginning in 2040-2050. The northeast Pacific was predicted to have increases of 1.2°C for 2040-2049, relative to 1980-1999, based on ten IPCC models. In addition, global climate models have predicted a pole-ward expansion of the less productive subtropical gyre in the future (Polovina et al. 2008, 2011). The more northward position of the boundary between the subtropical and subarctic gyres, known as the transition zone, will change important north Pacific migration corridors to and from the California Current (Polovina et al. 2011, Hazen et al. 2012). These warming trends and the poleward expansion of subtropical water in recent decades are consistent with King and colleagues' conceptual pathways from climate to plankton, fish, and birds.

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SENSITIVITY OF THE CALIFORNIA CURRENT ECOSYSTEM TO OCEAN ACIDIFICATION

CURRENT AND PROJECTED FUTURE OCEAN CARBON CHEMISTRY

Worldwide, ocean chemistry is changing due to increasing atmospheric carbon dioxide concentrations (Caldeira and Wickett 2003, Feely et al. 2004, Orr et al. 2005, Doney et al. 2009). About a third of all anthropogenically-released carbon dioxide has been absorbed by the oceans since the Industrial Revolution, though ocean carbon dioxide absorption has slowed over time and oceans currently absorb only about a quarter of annual carbon dioxide emissions (Sabine et al. 2004, Canadell et al. 2007, Le Quéré et al. 2010). When carbon dioxide dissolves in seawater, it forms carbonic acid, which lowers seawater pH. Due to the accumulation of carbon dioxide in marine waters over the past ~250 years, the concentration of H^+ has increased ~30% and the average pH of global oceans has dropped from ~8.2 to ~8.1, a phenomenon known as ocean acidification (Caldeira and Wickett 2003). The accumulation of carbon dioxide in seawater also decreases the concentration of carbonate ions, which affects how readily calcium carbonate structures accrete or dissolve. Increases in carbon dioxide can reduce the saturation state for calcium carbonate structures to the point at which dissolution is chemically favored (Feely et al. 2004), which has implications for the large number of marine species that form calcium carbonate shells, tests, and skeletons (Kroeker et al. 2010). Aragonite is a form of calcium carbonate used by many marine organisms that is relatively sensitive to changes in carbon chemistry conditions.

North Pacific waters, which include the California Current Ecosystem, have relatively low seawater pH values and shallow aragonite saturation horizons due to a variety of natural oceanographic processes (Feely et al. 2004, Jepson and Jacob 2007, Feely et al. 2008, Feely et al. 2009, Hauri et al. 2009). North Pacific waters are at the end of the ocean's global conveyer belt, meaning that the waters are "old" and have an accumulation of carbon dioxide from respiration processes. Sub-surface waters (150-300 m deep) which are naturally high in carbon dioxide and nutrients and also carry anthropogenic carbon dioxide absorbed from prior contact with the atmosphere commonly upwell along the US West Coast in the summer months (Feely et al. 2008). Upwelling events, while ephemeral, amplify the acidification experienced in this region. Near coast and estuarine waters in the California Current Ecosystem also experience acidification events induced by biological processes: high nutrient loads from rivers and run-off from the land can cause phytoplankton blooms that then die and are decomposed by respiring bacteria (but see

Borges and Gypens 2010, Cai et al. 2011, Sunda and Cai 2012). Respiration of organic carbon is estimated to drive over half of the acidification that occurs in the deep waters of Puget Sound's Hood Canal during summer months (Feely et al. 2010). This and a variety of other physical and biological drivers (*e.g.*, day-night cycle of photosynthesis and respiration, tidal cycle, freshwater contributions, pollution) contribute to the wide variation in carbon chemistry conditions observed in nearshore waters (Doney et al. 2007, Hofmann et al. 2011, Barton et al. 2012).

Similar to global estimates, ocean acidification has decreased pH in the California Current Ecosystem by ~ 0.1 unit (to ~8.04) and aragonite saturation state by about 0.4 (to ~2.3) (Hauri et al. 2009, Gruber et al. 2012). This change is ten times faster than any change in ocean carbon chemistry over the past 50 million years (Pelejero et al. 2010). Ocean carbon chemistry in the region is also influenced by changes in ocean circulation due to climate change, such as those induced by the increase in upwelling favorable winds (Bakun 1990, Feely et al. 2012). Over recent decades, offshore upwelling in the southern California Current Ecosystem has intensified (Rykaczewski and Checkley 2008). Water upwelled to the surface in some parts of the California Current Ecosystem is now undersaturated with respect to aragonite due to ocean acidification (Feely et al. 2008). Without ocean acidification, undersaturated waters would be 50 m deeper than they are today (Feely et al. 2008). If carbon dioxide emissions continue as expected, globally, average surface ocean pH will decrease by ~0.3-0.4, to its lowest value in over 40 million years, and carbonate ion concentration will decrease by about 50% (Caldeira and Wickett 2003, Orr et al. 2005, Solomon et al. 2007, Pelejero et al. 2010). This change would occur ~100 times faster than the changes in ocean pH during Earth's recent glacial-interglacial transitions (Pelejero et al. 2010). By 2050, models project that over half of the nearshore water mass in the central part of the California Current Ecosystem will be undersaturated with respect to aragonite (Gruber et al. 2012). The California Current Ecosystem is one of Earth's three hot spots for the progression of ocean acidification (Gruber et al. 2012).

SPECIES RESPONSE TO OCEAN ACIDIFICATION

Laboratory and field research has found that many organisms, especially calcifiers, respond negatively to ocean acidification (Hall-Spencer et al. 2008, Kroeker et al. 2010). These changes include decreased growth and survival and altered gene and protein expression and physiology, including acid-base balance and energy metabolism (Kroeker et al. 2010, Parker et al. 2013). However, there is strong variation in response to acidification between species and even within some species (Kroeker et al. 2010, Parker et al. 2011, Kelly et al. 2013). Some primary producers (*e.g.*, seagrasses, macroalgae, and phytoplankton with low-efficiency CO_2 concentrating mechanisms) will likely benefit from ocean acidification (Palacios and Zimmerman 2007, Swanson and Fox 2007, Reinfelder 2011). The fast rate of change in ocean carbon chemistry raises the potential that some marine species harmed by ocean acidification may not be able to adapt, evolve, or adjust quickly enough to persist. Geologically induced ocean acidification events in Earth's history are contemporaneous with extinction events in some taxa, suggesting that ocean acidification may overwhelm evolutionary processes and reorganize ecosystems (Hautmann et al. 2008, Kump et al. 2009, Pelejero et al. 2010). Marine communities near natural CO_2 vents are significantly different than neighboring communities that are not exposed to elevated CO_2 levels (Hall-Spencer et al. 2008, Fabricius et al. 2011, Kroeker et al. 2011). Furthermore, ecosystem modeling suggests that trophic interactions can cause the direct impacts of ocean acidification on sensitive species to ripple through food webs, positively or negatively affecting species to which they are tropically linked (Busch et al. 2013). While the literature on the biological and ecological impacts of ocean acidification is growing rapidly, how the vast majority of economically and ecologically important species in the California Current Ecosystem will respond to ocean acidification and how acidification will affect species interactions is largely unknown. However, we do know that production of Pacific oyster (*Crassostrea gigas*) larvae in Pacific Northwest shellfish hatcheries has already been negatively affected by changes in ocean carbon chemistry (Barton et al. 2012).

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