



Climate Change and Seabirds of the California Current and Pacific Islands Ecosystems: Observed and Potential Impacts and Management Implications

Final Report to the U.S. Fish and Wildlife Service, Region 1

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Contents

Executive Summary.....	3
Introduction	6
Climate Change and Seabirds	6
Geographic Scope	7
Natural Climate Variability and North Pacific Ecosystems.....	8
The California Current.....	9
Climate Change factors	10
Atmospheric circulation	10
Ocean Warming and Stratification.....	10
Ocean Chemistry	11
Potential Impacts on Seabirds	12
Surface feeding piscivores	12
Surface feeding planktivores	13
Diving piscivores	13
Diving planktivores.....	13
Sea level rise	14
Pacific Islands Ecosystem	15
Climate Change Factors	15
Atmospheric circulation	15
Ocean warming, stratification, and primary production	15
Ocean chemistry	16
Prey availability	16
Potential Impacts on Seabirds	17
Albatrosses.....	17
Species associated with predatory fishes	18
Solitary Pelecaniformes	18
Nocturnal procellariiformes.....	18
Neuston-feeding terns	18
Wind patterns and weather	19
Sea level rise	20
Conclusions	21
Literature Cited	23
Table 1.....	32

Executive Summary

Climate change is affecting marine and terrestrial systems worldwide, with impacts to biotic systems expected to intensify in the coming decades. In this report, we review observed and potential effects of climate change on breeding seabirds of the California Current System and Hawaii/Pacific Islands ecosystems, and recommend possible conservation actions to mitigate or facilitate species-level adaptation to environmental change. The California Current ecosystem covers approximately 32,000 km² of ocean habitat from British Columbia, Canada to Baja California, Mexico. Approximately 1-2 M seabirds representing ~30 species breed there. The Pacific Islands ecosystem covers approximately 518,000,000 km² including the offshore areas of Hawaii and the U.S. Pacific Island commonwealths, territories and possessions. Approximately 10-12 M seabirds representing 30 species breed in this system.

The expected impacts of climate change on these ecosystems and seabirds depend, in large part, on oceanographic responses to changing atmospheric conditions. Robust results from nearly all global climate models used by the Intergovernmental Panel for Climate Change in its 4th Assessment Report (IPCC 2007) include: (1) warming of the atmosphere and the oceans leading to increased stratification, (2) pole-ward shifts of the westerly winds at mid latitudes, and (3) sea level rise. Furthermore, the pH of the oceans is predicted to decline, indicating ocean acidification. It has been noted that the IPCC's 4th Assessment Report was deficient in considering climate change impacts on aquatic ecosystems, including marine and freshwater organisms.

Compared to the Pacific Islands ecosystem, the California Current is a highly productive system where upwelling and advection transport nutrients and drive primary productivity in the system. While the drivers of productivity in the Pacific Islands ecosystem is less clear, this is a system of generally low productivity but high biodiversity. Upwelling also occurs in certain regions of the Pacific Islands ecosystem, generally associated with features such as islands, which cause "wake effects", and shallow-water topographies (e.g., seamounts) which drive mechanisms of benthic-pelagic coupling. In both ecosystems, ocean warming and increasing stratification may reduce upwelling-driven mixing of the water column. However, upwelling-favorable winds may intensify which could counteract the effects of increasing stratification. Upwelling intensification is likely to be greater in the California Current than the Pacific Islands ecosystem due to the thermal and pressure gradient along the west coast of North America.

Ocean warming and increasing stratification could lessen primary productivity, thereby impacting seabird food webs in both ecosystems, but this potential effect is poorly understood, particularly for the Pacific Islands ecosystem where evidence of change in productivity is contradictory. Changes in winds and ocean structures such as currents, fronts, and eddies that are often important to seabird foraging habitat, are predicted for both systems. Winds are critical for seabird movements, particularly for procellariid seabirds such as albatrosses; therefore, changes in ocean structures and processes that concentrate prey may affect seabird foraging. Persistent sites of elevated food resources (e.g., foraging "hotspots") are known for both systems. "Hotspots" are associated with water mass convergences/divergences, shallow-water topographies, and coastal features (island wakes, coastal promontories); the impacts of climate change on these features are unknown, but could be significant.

Given variation in the oceanography of these systems, climate change will affect seabirds in each differently, but potential impacts could be similar. For example, seabird food resources and prey availability may diminish or be shifted farther from or closer to primary breeding colonies in both

systems, thus leading to positive or negative changes in demography (e.g., breeding success, survival, and recruitment) and population dynamics. Anticipated direct effects include potentially severe impacts of sea level rise and storm surges on breeding seabirds in the Pacific Islands ecosystem and its low-lying colonies. Ocean acidification may be more severe in the Pacific Islands system as well, owing to the importance of biogenic calcareous habitat (coral reefs), which may be degraded. Coral reef degradation may affect reef-associated prey seabird prey and atoll-forming processes which provide breeding habitat. Overall, though, the effects of climate change on ocean temperature, stratification, and upwelling may be more severe in the California Current, which is more 'sub-arctic' in character and may be more vulnerable to changes in the atmospheric-oceanic interactions that drive productivity.

A fundamental limitation we faced in reviewing observed and potential impacts of climate change on seabirds in these ecosystems is the lack of literature on long-term trends in seabird populations, demography, and life history characteristics (e.g., timing of breeding, survivorship), especially in the Pacific Islands, where we did not find a single published paper tackling observed effects of climate change on seabirds. This problem is not for lack of data; instead, available data are not being used to their full potential. Many long-term (20+ years) seabird data sets could be compiled, analyzed for several Pacific Islands sites (e.g. Tern, Midway, Kauai, Kure Islands), and examined for climate change impacts. Without such analyses, much of our understanding remains quite speculative. Documented or hypothesized effects of climate change on California Current and Pacific Islands seabirds include:

1. Inundation of breeding colonies from sea level rise and storm surge, especially for the many species using beaches, estuaries, or low-lying atolls in the Pacific Islands ecosystem, and for terns and gulls in the southern California Current.
2. Reductions or changes in the horizontal and vertical distribution of food resources due to ocean warming and changes in winds. Species with restricted diets and foraging ranges will be most vulnerable.
3. More variable demography (breeding success, survival, and recruitment) which could lead to population declines even if average rates of productivity remain constant.
4. Northward re-distribution of seabirds with changing winds and ocean structures thereby enhancing (or potentially initiating) breeding populations for species at the northern edge of their range and negatively affecting species at the southern edge of their range. This impact could be of equal importance in both ecosystems.
5. Increased mortality with increases in heat stress (air temperature), storm intensity, or harmful algal blooms that can negatively affect seabirds through acute toxicity, immuno-suppression, or various physiological effects. This impact could be similar between ecosystems.
6. Potential decrease in foraging success in a suite of Pacific Islands seabirds resulting from changes in the abundance and distribution of tunas and other schooling, predatory fishes (which concentrate prey for these seabird species).
7. Potential effects of a hypothesized increase in hypoxic conditions, which may enhance foraging opportunities (prey aggregating closer to the surface and away from oxygen depleted bottom water) or reduce food availability (through reduced prey abundance). This impact would likely be more substantial in the California Current due to greater anthropogenic nutrient sources and possible upwelling intensification.
8. Potential effects of changes in ocean chemistry (e.g., ocean acidification), though the impacts on seabirds are currently unknown.

Mitigation of these climate change impacts could include many common management actions that are known to support seabird populations. These include reduction of bycatch in fisheries, predator control on breeding colonies, habitat restoration at colonies, translocation to establish new breeding colonies and protection of prey species through ecosystem-based fisheries management.

Introduction

Climate change is affecting marine and terrestrial systems worldwide (Stenseth et al. 2002, Walther et al. 2002, Parmesan and Yohe 2003, Harley et al. 2006, Parmesan 2006, Hoegh-Guldberg and Bruno 2010), with effects on biological systems predicted to intensify in the coming decades. In the past 30 years, average global air temperatures have increased by $\sim 0.2^{\circ}\text{C}$ per decade (Hansen et al. 2006). Global circulation models (GCMs) used by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) project continued increases in air temperature of, on average, 1.1°C by the 2020s, 1.8°C by the 2040s, and 3.0°C by the 2080s as a result of rising greenhouse gas concentrations (IPCC 2007). Much of this heat is being absorbed by the world's oceans, and as a result the heat content of the ocean surface has increased dramatically (Levitus et al. 2001, 2005).

Given the capacity of the world's oceans to absorb heat and carbon dioxide (CO_2), coupled with sea level rise, increasing storminess and declines in sea ice, the need to understand and forecast the impacts of climate change on marine ecosystems and organisms has never been greater (IPCC 2007, Richardson and Poloczanska 2008, Hoegh-Guldberg and Bruno 2010). Marine organisms such as seabirds, which rely on the ocean for feeding and the land for breeding, may be particularly sensitive to the combined effect of climate change impacts on coastal and marine habitats. How different seabirds will respond to climate and ecosystem changes is related to many factors including their range, foraging behavior and diet composition, nesting habitat, and life history characteristics; some characteristics may facilitate adaptation whereas others will limit it. In short, some seabird species may fare well in a warming, more acidic ocean world; others may become locally or globally extinct.

Climate Change and Seabirds

Many aspects of climate change could affect seabirds of the California Current and Pacific Islands ecosystems. Several aspects that are likely to be most influential include:

1. Changes in wind patterns affecting productive oceanic frontal zones and coastal upwelling
2. Ocean warming and increasing thermal stratification
3. Increasing sea level, storm events, and coastal inundation
4. Changes in ocean chemistry (O_2) and ocean acidification (pCO_2 and pH)
5. Increased heat stress for breeding birds at terrestrial colony sites

These factors may lead to changes in primary and secondary productivity in the ocean and seabird prey (increase or decrease in zooplankton and forage fish populations), alterations in the oceanic structures that concentrate or disperse seabird prey, and changes to the terrestrial habitats that seabirds use for nesting and resting. For example, low-lying roosting and nesting habitat are likely to be vulnerable to flooding, erosion, and landslides as a result of sea level rise or increases in coastal inundation due to stronger and/or more frequent storms.

The purpose of this document is to review and evaluate how climate change may affect seabirds of the Pacific Region. The Pacific Region is vast, encompassing diverse marine and terrestrial habitats that support large and diverse seabird communities. We therefore divided our assessment into two general regions managed by the U.S. Fish and Wildlife Service (USFWS): the California Current and Pacific Islands ecosystems. Within these regions, we focused our review on the effects of climate change on ocean processes and on seabird responses to oceanographic change. Following Parmesan (2006), we consider how climate change might affect changes in seabird phenology (timing of breeding), breeding or roosting location, demographic traits (breeding success, survival, recruitment), distribution and range, physiology, and food habits (e.g., diet composition). We also review changes at the community level.

Long-term empirical data sets and retrospective analyses are central to assessing climate change effects on biological systems. Therefore, in our review we emphasize studies that linked trends in environmental conditions hypothesized to be affected by climate change (i.e., temperature and stratification, winds, sea level, pH) with changes in seabirds. Few studies in these systems or elsewhere clarified whether observed changes in seabirds resulted from natural climate variability or anthropogenic climate change (*cf.* Sydeman et al. 2009), but where possible we address this issue as well.

Geographic Scope

In this report, we review observed and anticipated effects of climate change on breeding seabirds of the California Current and Hawaii/Pacific Islands ecosystems and speculate on possible conservation actions to mitigate adverse effects or facilitate species-level adaptation to environmental change. The California Current ecosystem covers approximately 32,000 km² of ocean habitat from British Columbia, Canada to Baja California, Mexico (Figure 1). Approximately 1-2 M seabirds representing 30 different species breed in the California Current. The Pacific Islands ecosystem includes the coastal and offshore areas of Hawaii and the U.S. Pacific Island commonwealths, territories and possessions (Guam and the Commonwealth of the Northern Mariana Islands (CNMI) in the west; American Samoa in the south; Johnston Atoll; Wake Island in Micronesia; Palmyra Atoll, Kingman Reef and Jarvis Island in the Line Archipelago; Baker and Howland Islands in the Phoenix Archipelago). The area encompassed by these islands and atolls is massive, approximately 581,000,000 km². Approximately 10-12 M seabirds representing 30 different species breed in the Pacific Islands ecosystem.

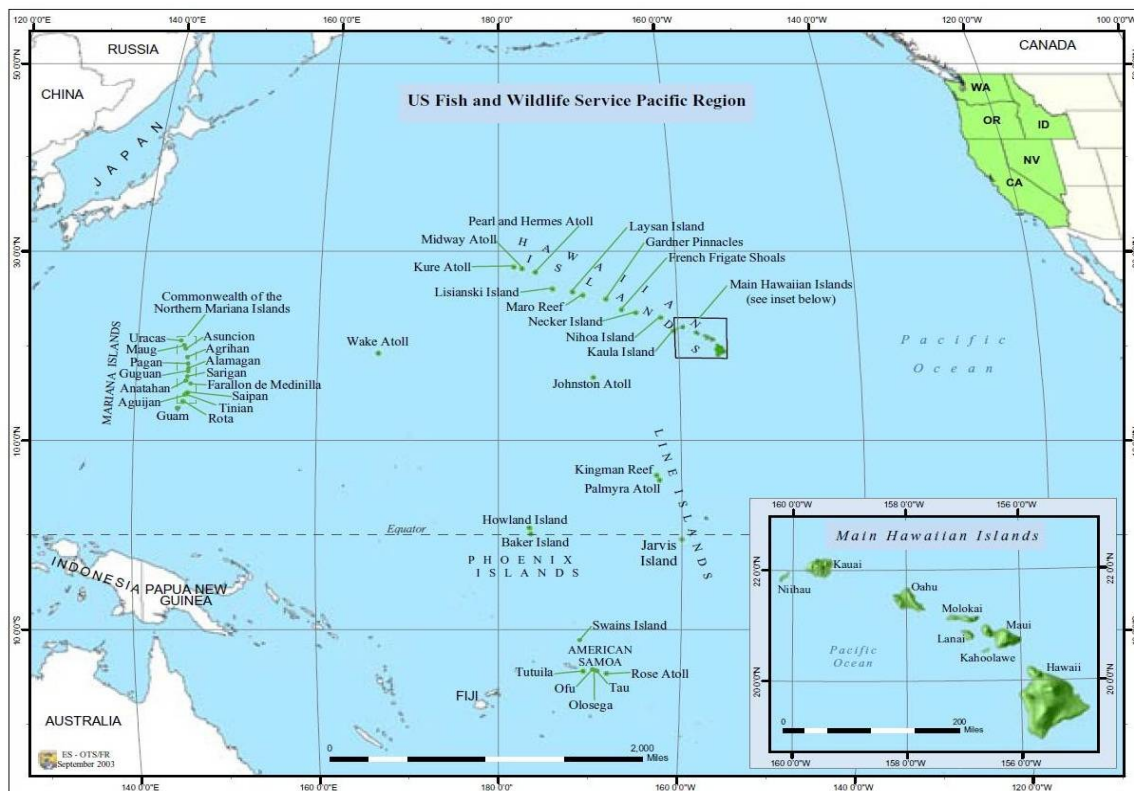


Figure 1. Map of the U.S. Fish and Wildlife Service Pacific Region.

Natural Climate Variability and North Pacific Ecosystems

The effect of climate variability on North Pacific ecosystems has been reviewed extensively (e.g., Francis et al. 1998). Natural climate variability and complexities of the marine environment make it difficult to predict how seabirds of the California Current System and Pacific Islands ecosystems will respond to climate change or attributed observed changes to anthropogenic global warming. Climate variability in the subtropical Pacific is dominated by the vertical Hadley and Walker Circulation (described in the Pacific Islands Ecosystem section below). Climate variability in the temperate Pacific is dominated by the Aleutian Low Pressure in the Gulf of Alaska and North Pacific High Pressure systems over western North America and the eastern Pacific. Ocean circulation in the North Pacific is dominated by a clockwise rotating series of currents that together form the North Pacific Gyre: these currents include the northward-flowing Kuroshio Current off of Asia, the eastward-flowing North Pacific Current, the southward-flowing California Current and the North Equatorial Current which flows west to the Kuroshio (Figure 2).

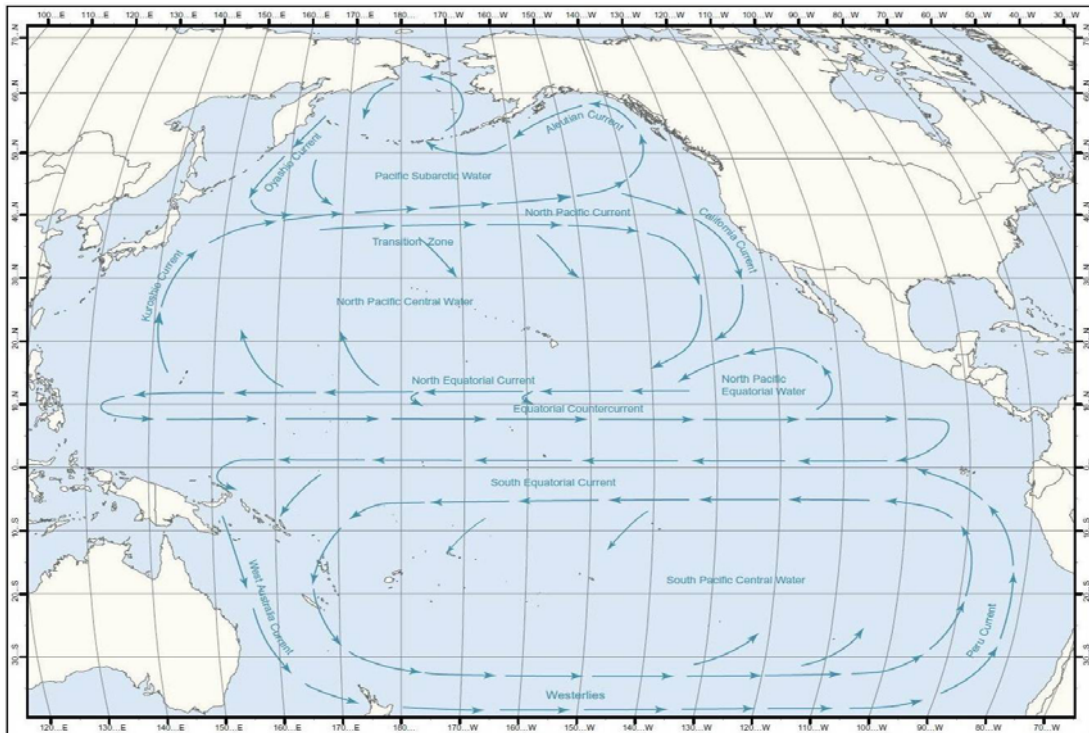


Figure 2. Diagram of major currents of the North Pacific Ocean.

The interaction of winds, currents, and land masses drives temperatures and vertical mixing of nutrients in the upper water column of the ocean. This mixing is a critically important variable promoting primary production, the foundation of the food-webs upon which seabirds depend. Water column mixing, however, can be inhibited by lack of wind or a strong water column temperature (thermocline) or salinity (halocline) gradient (stratification), providing greater resistance for the two water masses of different densities layered on top of one another to mix. Thus, surface heating is one mechanism by which climate warming might reduce upper ocean productivity in the absence of strong surface winds to break through the density gradient.

The depth and strength of the stratified water varies throughout the North Pacific. In the California Current, for example, the mixed layer depth, when present, is relatively shallow due to wind-driven upwelling along the coasts, and surface waters are cold and oxygen-rich, providing the basis for a very productive ecosystem. In contrast, the Pacific Islands region is dominated by warm, nutrient-limited, and relatively deeply stratified surface waters, providing the basis for lower production, oligotrophic ecosystems that are dominated by long-ranging seabirds such as albatrosses and shearwaters.

Interannual variation in ocean temperature and atmospheric winds greatly affects the physical attributes described above which in turn affect ocean productivity and prey availability for seabirds. The most familiar, and arguably a dominant, climate pattern that affects seabirds in the North Pacific involves *El Niño* and *La Niña* anomalies, which result from changes in atmospheric wind patterns. Intermittently, equatorial surface winds weaken for months or longer leading to the phenomenon known as *El Niño* (Cane and Zebiak 1985, Deser and Wallace 1987, Philander 1992). During *El Niño*, reduced westward-blowing equatorial winds allow deep-water waves of warm water to flow eastward toward the coast of South America and relaxation of the westward-tilting thermocline and sea surface height results in kelvin waves. Upon reaching Central America, these waves may move to the north and south, sending warm waters north into the California Current and south into the Humboldt Current, deepening the thermocline in these regions. Atmospheric processes during these periods also often cause a reduction or geographic shift of winds at higher latitudes, lessening coastal upwelling. Upwelling that does occur under these conditions may be ineffectual because thermocline depths are increased and nutrient-rich, cold waters are too deep to be upwelled. During *El Niño*, weakened ocean mixing and limited nutrient influx to the photic zone can result in a food web collapse, causing seabird reproductive failure and mass mortality. The 1982-83 *El Niño*, one of the strongest on record, resulted in the death of millions of seabirds in the equatorial Pacific Ocean due to starvation, and also affected reproductive success of some species globally (Schreiber and Schreiber 1989). In California and Oregon, the 1982-83 *El Niño* caused reduced seabird reproductive success and increased mortality (Hodder and Graybill 1985, Bayer 1986). In contrast, during *La Niña* events, equatorial surface winds intensify, eastern Pacific upwelling is intense, and the ocean is typically cooler than average. During *La Niña* years, marine systems can be spectacularly productive (Deser and Wallace 1987).

Whereas the *El Niño/La Niña* cycle has a duration of 6-18 months and periodicity of 3-7 years, decadal-scale climate variability also occurs in the North Pacific. The Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) have periodicities of 50-60 years and low frequency variation of 25-30 years (Mantua et al. 1997), affects seabirds and ocean ecosystem dynamics (Trenberth and Hurrell 1994, Anderson and Piatt 1999, Deser et al. 2004, Di Lorenzo et al. 2008). Projected long-term climate change will not likely affect North Pacific ecosystems in the same way as *El Niño/La Niña* events or shifts in the PDO/NPGO, however, some responses will likely be analogous. Therefore, determining how seabirds are affected by these well documented, but shorter-term, climate events (e.g., Ainley et al. 1995, Vandenbosch 2000, Sydeman et al. 2001, Wolf et al. 2009) is critical to understanding how seabirds might respond to longer-term climate change.

The California Current

In the U.S., arguably one of the best-studied marine ecosystems is the California Current (CC), an ocean domain including the coasts of southern British Columbia, Washington, Oregon, California, and northern Baja California (Hickey 1989, Checkley and Barth 2009). Because fisheries of the California Current such as Pacific sardine (*Sardinops sagax*) collapsed in the late 1930s (MacCall 1979), a wide range of observational programs and modeling efforts have been underway for many decades to evaluate

climatic impacts on this ecosystem. The longest running oceanographic sampling effort is the California Cooperative Oceanic Fisheries Investigations (CalCOFI) survey which started collecting physical, chemical and biological data in 1949 (Pena and Bograd 2007). This program, and others initiated more recently (Bjorkstedt et al. 2010), have produced an unparalleled body of information on how climate change has affected and will affect biological systems, including seabirds.

Climate Change factors

Atmospheric circulation

One key climate change projection for the CC concerns changes in the large-scale atmospheric pressure gradients that cause coastal upwelling. Because upwelling-favorable wind stress is generated by differences between the continental low and oceanic high pressure systems, and these systems may heat at different rates due to anthropogenic global warming, upwelling-favorable winds have been predicted to intensify (Bakun 1990, Bakun et al. 2010). Upwelling intensification could increase water column mixing, bringing more nutrients into the upper euphotic zone and enhancing phytoplankton production. However, global warming also will increase water column stratification, which could inhibit mixing (Bakun 1990, Auad et al. 2006). Therefore, a key question for future research is how these processes will interact to enhance or impede primary productivity. Moreover, even if upwelling intensifies and nutrient input increases, increasing winds may lead to greater turbulence and offshore advection, potentially causing decreases in planktonic zooplankton and larval fish populations (Cury and Roy 1989, Botsford et al. 2003). This could reduce food availability for seabirds. The upwelling intensification hypothesis is controversial, with records of increasing as well as decreasing winds in the CC and other eastern boundary upwelling systems globally (Chavez and Messie 2009). For example, based on an analysis of buoy data, winds have increased and SST decreased in central California, but these variables showed no systematic change off southern and northern California (Garcia-Reyes and Largier 2010). Thus, at this time we don't know if winds will increase or decrease or stay the same. It is clear, though, that changes in winds will be different in different regions of the CC. In addition, the timing of upwelling may change (Bograd et al. 2009). Changes in the timing of upwelling may have severe ecosystem consequences, with effects on seabirds, as was observed in 2005 when upwelling was delayed and seabird breeding success, primarily that of auklets, was reduced to near zero (Sydeman et al. 2006).

Ocean Warming and Stratification

Patterns of change in ocean temperature in the CC vary with length of the time series under consideration and size of the region over which data are summarized. Generally speaking, the longest temperature records (e.g., Scripps Pier in La Jolla) show an overall trend of increasing temperature (SST) over most of the past century as well as interannual to interdecadal variability (McGowan et al. 1998, Breaker 2006, Field et al. 2006, Hsieh et al. 2009). Observations and model experiments confirm that warming has increased stratification of the water column (Di Lorenzo et al. 2005). Records of SST off southern British Columbia, a region of weaker upwelling, show a warming trend of $\sim 1^{\circ}\text{C}$ over 50 years (Crawford and Irvine 2009). Regional variability, however, influences the extent to which these results can be broadly applied. One effect of ocean warming could be a decrease in the efficacy of wind stress on upwelling, which could lead to changes in food webs and prey availability for seabirds. Another potential effect of ocean warming could be an increase in harmful algal blooms. Seabirds may be impaired by toxins in phytoplankton, such as domoic acid (Shumway et al. 2003). In the worse case, mortality may result. For example, in recent 2007 and 2009 events, foam from the organic material of

red tides contained surfactant-like proteins that coated the bird's feathers and removed protective oils, causing hypothermia (Jessup et al. 2009).

Ocean Chemistry

De-oxygenation is a potential concern for the CC. The frequency of hypoxic (low O₂) waters off Oregon has apparently increased recently, but time series are too short for this effect to be attributed to climate change (Grantham et al. 2004, Chan et al. 2008). Similarly, off southern California, Bograd et al. (2008) reported shoaling of the hypoxic zone between 1984 and 2006. Upwelling intensification could decrease O₂ concentrations by bringing more oxygen-depleted waters to the surface. The effect of hypoxia on seabirds, however, is unknown. Effects could be either positive or negative, depending on the portion of the water column affected and the diets of seabirds involved. A positive response could result from mobile seabird prey being driven away from low-oxygen bottom waters and into greater concentrations in the upper water column where they might be more susceptible to seabird predation. A negative response could result from increased mortality of prey or movement of prey away from seabird foraging areas. Ocean acidification is another potential concern, though long-term records of pH in the CC are very rare. In Monterey Bay, pH has decreased from 1989 – present (Monterey Bay Aquarium Research Institute, unpublished). The potential effect of ocean acidification on seabirds is unknown. Off Oregon, shelf waters with low pH occur during upwelling periods (upwelling brings deep, low pH waters to the euphotic zone). Reduced pH could negatively affect the production and growth of some calcifying organisms (Hauri et al. 2009, OCCRI 2010, Barton et al. 2012). As the ocean continues to absorb carbon dioxide, there are potential food web consequences that could affect seabirds. For example, when marine organisms requiring calcium are sufficiently affected by ocean acidification, their reproduction, and availability to seabirds will be affected, especially if food webs shift toward communities with lower calcium requirements, such as gelatinous zooplankton (jellyfish). Seabird food supplies could be reduced through increased competition with jellyfish.

Prey Availability

Time series of phytoplankton biomass and community composition and estimates of primary productivity are surprisingly rare and generally of short duration. Given this, we don't know if phytoplankton biomass and primary productivity in the CC will increase or decrease. However, to date most studies suggest an increase in phytoplankton biomass and primary productivity. For example, data from southern California (based on the CalCOFI program) indicate increasing primary productivity corresponding to a shallowing of nutrient concentrations (Aksnes and Ohman 2009). Satellite data from 1997-2006 generally corroborate these findings of increasing chlorophyll concentrations (Henson and Thomas 2007, Kahru et al. 2009, Chavez et al. 2011). Menge et al. (2009) have shown a similar pattern of chlorophyll increase in the surf zone off Oregon. Finally, Kim et al. (2009) have demonstrated an advancement in the timing of the spring bloom. Thus, changes in phytoplankton may include a temporal component as well as effects on phytoplankton biomass. Seabirds of the CC forage primarily on mesozooplankton (krill [family Euphausiidae] and copepods), squids, and forage fish (anchovy (*Engraulis mordax*), Pacific sand lance (*Ammodytes hexapterus*), Pacific sardine (*Sardinops sagax*), myctophids (lanternfish, family Myctophidae), age-0 rockfish (*Sebastes* spp.), and Pacific hake (*Merluccius productus*)). Studies of these seabird food resources are rare. Off southern California, Hsieh et al. (2009) have shown changes (primarily increases) in abundance (25/34 species), and re-distributions (16/34 species) of larval fish, mostly myctophids, over the past 50 years. Off central California, Field et al. (2010) showed a general decline in the relative abundance of age-0 rockfish (*Sebastes* spp.) over 25 years. Moreover, potential seabird competitors may increase with climate change. For example, Zeidberg and Robison (2007) reported an extensive range expansion of Humboldt squid (*Dosidicus*

gigas) in the CC in the late 1990s and early 2000s; these large predatory squid consume many of the same prey that seabirds do, such as northern anchovies.

Potential Impacts on Seabirds

Seabirds in the CC have shown a variety of changes, some of which are consistent with expectations under climate change. However, given the length of time series to date, we cannot attribute these changes with certainty to anthropogenic global warming. The longest time series on seabird ecology in the CC are less than 50 years; therefore, natural climate-ecosystem variability could explain all observations. Trends in CC seabirds that are consistent with climate change expectations include changes in: phenology (earlier breeding of murre, *Uria aalge*, Sydeman et al. 2009), (ii) distribution and abundance at sea (Ainley and Hyrenbach 2010), and (iii) breeding biology, survival, and other demographic traits (e.g., Sydeman et al. 2001, Wolf et al. 2010). In terms of distribution and abundance of seabirds at sea, observations suggest a shift towards seabird assemblages characteristic of warmer, lower productivity waters (Hyrenbach and Veit 2003), as well as a trend toward generally decreasing biodiversity with increasing ocean temperature (Sydeman et al. 2009). Mechanistically, most of the climatic impacts appear to have affected CC seabirds indirectly, through variation in their food resources or variation in habitat characteristics that affect feeding ecology. Heat stress for birds on colonies, especially at the southern end of their range, may be a concern, however, this is not yet well documented. Given that most seabirds in the CC do not nest on low-lying islands, as do many Pacific Island species, sea level rise is less of a concern for seabirds in this ecosystem. Although estuarine and beach breeding species are less abundant overall, some populations and species (including endangered species) are at risk of sea level rise. As noted above, the impacts of changes in ocean chemistry (O_2 and pH) are unknown and unknowable at this time. Thus, given that observations point to changes in food resources as a primary mechanism of seabird change to date, we have organized the following section under that assumption that predator-prey relationships will continue to be an important mechanism affecting CC seabirds in the future.

Climate change may affect CC seabirds differently, depending upon foraging locations (nearshore vs. offshore habitat; concentrated vs. dispersed prey), foraging strategy (surface foraging vs. diving), and degree of prey specialization (Table 1). Four generalized foraging guilds describe the majority of breeding birds in the California Current. These groups are treated separately and include:

1. Surface feeding piscivores
2. Surface feeding planktivores
3. Diving piscivores
4. Diving planktivores

Surface feeding piscivores

This group includes brown pelican, ring-billed, California, western, and glaucous-winged gulls, gull-billed, caspian, royal, elegant, Forster's, and least terns, and black skimmer (for scientific names and ranking of climate change concerns for breeding species see Table 1). With the exception of some of the gulls, these species are the most restricted in terms of their foraging range and diet composition. Pelicans, terns, and skimmers feed primarily in estuaries or within a few kilometers of shore on the outer coast, and depend on the availability of patchy, near-surface schooling fishes such as anchovies. In contrast, gulls are habitat and dietary generalists (Annett and Pierotti 1989) and may be relatively unaffected by changes in food resources. Range shifts within this group have been documented. For

example, off Oregon, non-breeding brown pelicans have increased substantially (Wright et al. 2007; U.S. Fish and Wildlife Service unpubl. data). While undoubtedly this dramatic increase reflects the population recovery from DDT contamination, previous major northward expansions have been associated with warm ocean conditions, such as occurs during *El Niño* events.

Surface feeding planktivores

This group includes fork-tailed, Leach's, ashy, and black storm-petrels that nest in the CC (Table 1). Storm-petrels are the smallest seabirds in the CC, with large foraging ranges that often extend beyond the continental shelf (fork-tailed, Leach's, ashy, and black storm-petrels; red and red-necked phalaropes; Table 1). For the storm-petrels, long foraging bouts may cause egg neglect and long incubation periods. Chicks are infrequently (every several days due to extended foraging trips of adults) fed a lipid-rich oil. Diets include a diversity of crustaceans, fishes, squids, jellyfishes, and detritus from the ocean surface (neuston layer). While these species have foraging and life history adaptation to facilitate variation in prey availability, they also rely on fronts and eddies for efficient foraging (Yen et al. 2006).

Diving piscivores

Diving piscivores occur primarily on the CC continental shelf where the ocean is highly productive and include double-crested, Brandt's, and pelagic cormorants; common murre, pigeon guillemot, marbled and Xantus's murrelet, rhinoceros auklet, and tufted puffin (Table 1). As proficient divers, these species exhibit low flying efficiency due to high wing loading (i.e. high mass relative to low wing surface area). Therefore, while they efficiently forage in 3 dimensions, increased travel distances from their breeding colonies to prey may greatly increase their energetic demands. Cormorants and pigeon guillemots are opportunistic foragers, have diverse diets, and feed within estuaries or a few kilometers of shore and throughout the water column, including benthic habitats. Murres, murrelets, auklets, and puffins feed primarily on forage fishes (and at times krill (Euphausiids)) and have fairly diverse diets, however, the most successful reproductive years are often linked to the abundance of a few key prey species. Species such as murres and marbled murrelets that deliver one fish a time to the nestling have the potential to suffer the greatest reproductive loss from reduced forage fish availability (Becker et al. 2007). A decrease in alcids and an increase in some procellariid seabirds (Hyrenbach and Veit 2003) may suggest a hypothesis that climate change will adversely affect diving seabirds more so than surface feeding ones.

Diving planktivores

This group includes ancient murrelets and Cassin's auklets (Table 1). As with diving piscivores, diving planktivores occur mainly in highly productive regions of the CC. These species also exhibit high wing loading. These two species consume zooplankton (primarily euphausiids, copepods, larval fish and squid) and therefore are highly susceptible to climatic conditions and ocean features such as fronts that affect plankton. Changes in seasonal abundance, peak biomass date, and narrowing of the period of peak biomass have been observed (Mackas et al. 2007, Batten and Mackas 2009), and may make zooplankton less available to foraging seabirds, with demographic consequences. For example, Bertram et al. (2001) concluded that the changes in the dates of availability of the large copepod *Neocalanus* spp. caused a mismatch in the availability of the prey to auklets, resulting in reduced reproductive success. On Southeast Farallon Island over the past 40 years (1970-present), auklets have declined by ~90% (Lee et al. 2007), while at the same time, some piscivorous species have shown increases.

Wind Patterns and weather

Most breeding seabirds in the CC forage within 60-100 km of their colonies and do not rely on winds for efficient long-distant foraging flights, as exemplified by some Pacific Island procellariids (see below).

Changes in wind patterns, however, could affect seabird flight efficiency and access to prey by affecting ocean surface turbulence.

Winds and air temperature may also affect localized habitat characteristics on colonies. For example, surface-nesting species may be affected by excessive heating, thereby causing mortality to nestlings (Oswald et al. 2008). Changes in regional wind patterns in the CC, however, probably will have greater effects on seabirds through changes in coastal upwelling and food productivity rather than changes in flight efficiency, surface foraging, or heating on colonies. Heating (and cooling) could also be affected by cloud cover and air temperature.

Increased winter storm intensity (Ruggiero et al. 2010) can also affect seabird populations, with some species (and age classes) being more susceptible to storm-associated mortality than others, as has been demonstrated for cormorants in the North Sea (Frederiksen et al. 2008). There is, however, no direct evidence yet of increased seabird mortality with storm events for the California Current.

Sea level rise

Sea level rise should have little direct effect on most breeding seabirds of the CC because colonies tend to be well above the current high tide levels. Species nesting adjacent to rocky intertidal zones (e.g., black oystercatcher, *Haematopus bachmani*), or on beaches or on low-lying sandy islands in estuaries (e.g., terns), however, could experience habitat loss due to sea level rise (Daniels et al. 1993) and increased storm-driven surges and waves (Ruggiero et al. 2010). Of all the CC seabirds, the surface-feeding piscivores (see above) may be most affected by sea level rise. Many terns and skimmers nest on low elevation islands and sand bars, and therefore would be susceptible to erosion and inundation due to storm surges and sea level rise.

Pacific Islands Ecosystem

Compared to the highly productive waters of the California Current, the warm, salty waters of the Pacific Islands ecosystem are relatively unproductive (Longhurst et al. 1995). The region encompasses three distinct tropical and sub-tropical oceanographic regions: (1) the North Pacific which includes the Transition Zone Chlorophyll Front (TZCF), North Pacific Central Water, and North Equatorial Current; (2) the Central Pacific which includes the Equatorial Countercurrent and Equatorial Front; and (3) the South Pacific which includes the South Equatorial Current and South Pacific Central Water (outlined in Figure 2). Climate in the North and South Pacific regions have similar, parallel oceanographic characteristics that are tied to the currents and trade winds that produce oligotrophic gyres. Climate in the subtropical Pacific is dominated by latitudinally circulating Hadley Cells and longitudinally circulating Walker Cells. Air heated by intense tropical solar radiation rises in an area of light winds and very warm sea surface temperatures (SST) along the Equator known as the Inter-tropical Convergence Zone (ITCZ). In the Northern Hemisphere the air moves north and east, and then gradually descends at about 30-35° N as it cools and loses moisture (Webster 2004). The descending air mass then turns back toward the Equator near the surface, forming what are known as the trade winds, which turn southwest and converge with similar trades from the Southern Hemisphere in the ITCZ and repeating the cycle (Webster 2004). The ITCZ shifts seasonally, moving northward during the boreal summer, when solar radiation is most intense north of the equator, and south during the austral summer.

Climate Change Factors

Atmospheric circulation

The ITCZ is sensitive to the position of Hadley Cells; if Hadley Cells shift northward in response to global warming (Lu et al. 2007), the ITCZ may experience decreased upwelling in its northern portions. However, its southern sections may experience increased upwelling where southern hemisphere trades cross the Equator. In the past 27 years, satellite data indicate that Hadley Cells are indeed beginning to expand poleward (Lu et al. 2007, Gastineau et al. 2009, Hu et al. 2011) and decelerate with global warming. Decreasing intensity of the Hadley cell leads to a slowdown of the entire overturning circulation pattern in the Pacific which leads to a poleward expansion of the subtropical and tropical warm, oligotrophic waters (Brierley et al. 2009) and thus affects productivity throughout the tropical Pacific.

Ocean warming, stratification, and primary production

As discussed above for the California Current, it is hypothesized that the sub-tropical Pacific Islands ecosystem may experience a decrease in vertical mixing inhibiting primary productivity (Behrenfeld et al. 2006, Polovina et al. 2008). The Hawaiian Ocean Time (HOT) program's station ALOHA (A Long-Term Oligotrophic Habitat Assessment), located 115 km north of Oahu, has been collecting oceanographic data over the past two decades. At this site, Dave and Lozier (2010) found increases in primary productivity, but also found that stratification and productivity were not strongly coupled. Bidigare et al. (2009) also showed that primary productivity has increased over the same period. Increases in primary productivity with increasing temperature and stratification (Corno et al. 2007), as observed for both the Pacific Islands and California Current ecosystems, presents a conundrum as primary productivity should decrease with ocean warming. However, this could be explained by decoupling new and recycled primary production which can have different responses to increased surface temperatures.

Much of the primary production, particularly in oligotrophic waters, is the result of recycling of organic matter and nutrients within microbial loop: small phytoplankton grow, then they are grazed by microzooplankton which re-mineralize the organic matter into inorganic nutrients, and the small phytoplankton grow again (Fenchel 2008). The magnitude of this recycled production does not depend on the input of new nutrients from below the euphotic zone, but only on the metabolic rate at which microzooplankton and picoplankton recycle nutrients. At higher temperatures, these rates are faster, but no new biomass is produced. So many ecosystem models do, in fact, project increased primary production with increasing temperatures, but it is the new (or exported) production that is often focused on when food web changes are discussed (Finkel et al. 2010). This is the primary production by larger phytoplankton which feeds the larger zooplankton, fish, and seabirds, and it is often assumed that this type of primary production depends on the supply of “new” nutrients to the system (either by mixing across the nutricline or nitrogen fixation) and thus will be more dependent on changes in stratification (Finkel et al. 2010).

Ocean chemistry

Changes in ocean chemistry, particularly in pH, have the potential to have large impacts on the marine environment. Ocean acidification has far-ranging consequences for the maintenance of coral reefs which are composed primarily of calcium carbonate which are sensitive to changes in pH. As CaCO_3 can begin to dissolve at the lower pH levels projected for some environments later in this century (Silverman et al. 2009), reef habitat may decrease. These reefs are in turn critical for atoll-building which form the basis for much of the low-lying seabird breeding habitat in the region. Impacts may be exacerbated by corals rejecting their symbiotic algae at lower pH and higher temperatures, resulting in coral bleaching.

Measurements of seawater pH at station ALOHA north of Hawaii show a significant decreasing trend from 8.13 to 8.08 pH units from 1988-2007 (Dore et al. 2009). This translates into a 30% increase in acidity due to the logarithmic scale of pH unity. The same pattern has been documented in the South Pacific where pH has decreased by over 0.1 units in the upper 200 m of the water column (Goyet et al. 2009). Changes in pH may indirectly affect the developmental stages of seabird prey (larval and juvenile fishes discussed below) by degrading the coral reef habitats on which they rely on during their larval phases. Little is known of the direct vulnerability of marine fish species to increased CO_2 levels, but the most vulnerable life stages appear to be the youngest (Ishimatsu et al. 2008), some of which are important seabird prey. Forster's lizardfish (*Trachinocephalus myops*), delicate round herring (*Spratelloides delicatulus*), thornback cowfish (*Lactoria fornasini*), and juvenile goatfish (Mullidae) are important seabird prey (Harrison et al. 1983) that may be affected by changes in coral reefs. Many common tropical seabirds, such as brown booby, white and gray-backed tern, and black noddies, feed on these fish and could likely be affected, indirectly, by declining quantity and quality of coral reef habitat. While these effects may be detrimental, the opportunistic foraging of tropical seabirds could also result in prey-switching with no change in demography (e.g. breeding success). In short, the full implications of acidification in the Pacific Islands ecosystem remain to be understood.

Prey availability

For some seabird species, the Transition Zone Chlorophyll Front (TZCF), at the northern edge of the North Pacific Subtropical Gyre, is an important foraging area (Ogi 1984, Hyrenbach et al. 2002). The TZCF marks a transition from the subtropical to the sub polar gyre with higher chlorophyll-a values (Laurs et al. 1984). Productive subarctic water sinks beneath the warmer, less productive subtropical waters, creating a convergence front that is replete with eddies that concentrate prey at the surface (Favorite et al. 1976). The location of the transition varies between 30-35° N in winter and 40-45° N in

summer, with significant variation between years (particularly as a result of *El Niño* events), but is approximated by the 18° C SST isotherm (Bograd et al. 2004). However, a consistent prediction under climate change scenarios is a northward shift in the TZCF (Polovina et al. 2008, Sydeman et al. 2011), which could result in longer commutes for Hawaiian seabirds that forage within this region. For other seabird species, the southern boundary of North Pacific Subtropical Gyre along the northern edge of the Equatorial Counter Current is an important foraging area, particularly at the localized and irregular upwelling areas found there (e.g., Spear et al. 1995).

Skipjack tuna (*Euthynnus pelamis*) are the most common species found in association with seabirds that forage in association with predatory fish (Hebshi et al. 2008). Skipjack expand northward during warmer conditions that associated with the boreal summer and *El Niño* events (Lehodey et al. 2003). Models suggest that skipjack habitat will increase in the Eastern Pacific under conditions of global warming (Loukos et al. 2003), so the Subtropical Gyre may actually improve as a foraging environment for seabird species that associate with skipjack. However, species dependent on the upwelling areas of the ITCZ, such as Newell's shearwater (King 1970, Spear et al. 1995), may have to travel farther north to reach the remaining upwelling areas, and may experience reduced reproductive success as a result.

Potential Impacts on Seabirds

Most piscivorous seabirds of the Pacific Islands ecosystem forage in association with sub-surface predatory fish (particularly skipjack tuna), which drive forage fish to the surface (Harrison 1990). Laysan and black-footed albatrosses forage substantially on squids and are often found north of the TZCF (Hyrenbach et al. 2002, Kappes et al. 2010). The Central Pacific is a more dynamic oceanographic system than that surrounding the Hawaiian Islands with pronounced upwelling and a convergence zone (Equatorial Front) where surface waters between the South Equatorial Current and North Equatorial Countercurrent diverge. Planktivorous seabirds, such as storm-petrels, concentrate in the Equatorial Front, but piscivorous seabirds do not (Spear et al. 2001).

The ultimate impacts of changes in oceanographic conditions on the region's seabirds will depend to a large extent on the foraging locations and strategies of the species (Table 1). Five generalized foraging guilds describe the majority of tropical species discussed here:

1. Albatrosses
2. Species associated with subsurface predators (predatory fishes and mammals)
3. Solitary-foraging Pelecaniformes
4. Nocturnal Procellariiformes
5. Neuston-feeding terns

Albatrosses

Laysan, black-footed and short-tailed albatrosses have functionally similar but geographically distinct foraging strategies. In general, all three species feed relatively near their breeding islands (Laysan and black-footed albatrosses principally in Hawaii; short-tailed albatross principally in Japan) when their young are small, but later in the nesting cycle black-footed albatrosses extend their foraging trips to the West Coast of North America and Laysan Albatrosses extend their foraging to the Aleutian Islands, Northwest Pacific, and Gulf of Alaska (Fernández et al. 2001, Suryan et al. 2008). Short-tailed albatrosses typically stay within the Kuroshio Current system off Japan during the chick-rearing period (Suryan et al. 2008). Due to the long distances travelled by albatrosses from their nesting islands, their reliance on prevailing winds for locomotion, and the already northerly location of their foraging habitats relative to their southern breeding sites, these species will be greatly affected by changes in the

distribution of marine productivity. For example, during *La Niña* conditions, the TZCF generally shifts north and can offer reduced foraging opportunities for top predators (Polovina et al. 2008, Sydeman et al. 2011), sometimes resulting in increased foraging durations for adult albatrosses and decreased reproductive success at some colonies (USFWS unpubl. data). A climate-change induced, long-term, northward shift in the TZCF (Ashmole and Ashmole 1967, Au and Pitman 1986, Hebshi et al. 2008) could result in chronic reduction in breeding success at Hawaiian albatross colonies that are farthest from this important foraging habitat feature (Table 1).

Species associated with predatory fishes

This group is the largest foraging guild and includes wedge-tailed, Christmas, Newell's, and Audubon's shearwaters, Hawaiian, herald, and phoenix petrels, red-footed boobies, black and brown noddies, and sooty and white terns (Table 1). This group is sometimes referred to as 'tuna birds' for their tendency to forage on the same prey brought to the surface by predatory fish, especially tuna (Lehodey et al. 2003). As a result, aspects of climate change which change the abundance or distribution of tuna species, and other large predatory fish that drive seabird prey to the surface, will directly affect seabird foraging and prey availability. If skipjack tuna move northwards, as they do during the warmer conditions that occur during the northern summer and during *El Niño* events (Loukos et al. 2003), then habitat for these birds will potentially increase with global warming, as described above (King 1970).

Solitary Pelecaniformes

This group includes brown and masked boobies, tropicbirds, and frigatebirds. Brown boobies forage for near-surface prey and flying fish (Exocoetidae). Red- and white-tailed tropicbirds are solitary pursuit plungers that forage inshore and offshore, respectively (Harrison et al. 1983), on flying fish and squid (Harrison et al. 1983). Greater and lesser frigatebirds often feed alone on flying fish and other surface prey, being unable to enter the water because of their wettable plumage (Harrison et al. 1983, Au and Pitman 1986). They may, however, join foraging flocks to steal prey from other seabird species. Masked boobies are more social than the preceding species, and may feed alone or with seabirds associated with predatory fish; their prey consists of flying fish and other surface-dwelling fish (Harrison et al. 1983). The potential effects of climate change on solitary foragers are especially difficult to assess (Table 1), but they are likely to be similar to those expected for tuna birds because they do rely to a certain extent on predatory fishes to make prey available.

Nocturnal procellariiformes

This group includes bonin, Bulwer's and Tahiti petrels, and Tristram's, band-rumped and Polynesian storm-petrels which are primarily offshore, solitary, nocturnal species (Table 1). They prey on surface neuston species such as sea striders (*Halobates sericeus*), as well as lanternfishes (Myctophidae), hatchetfishes (Sternoptychinae) and other midwater species that migrate to the surface at night or when chased by tuna (Simons 1985). Hawaiian petrels take fish and squid (Adams and Flora 2010) and move farther north beyond the ITCZ and occasionally to the CCE (Harrison et al. 1983).

Neuston-feeding terns

Grey-backed terns and blue-gray noddies dip for sea striders, other invertebrates, and small fish, some of which, when larger, are eaten by other seabirds (Neelin et al. 2006, Christensen et al. 2007). The tern forages farther offshore than does the noddy. Little terns feed by plunge-diving in shallow water to pursue prey consisting of small fish, crustaceans, insects, annelids and mollusks. Predicting the effects of climate change on these species is difficult, but their generalized diet and foraging strategy may

provide some buffer against detrimental effects and allow them to switch prey species or proportions (Table 1).

Wind patterns and weather

Many Pacific Islands seabirds, procellariids in particular, use side winds to increase lift and reduce energy expenditure while flying (Spear and Ainley 1997, Weimerskirch et al. 2000, Suryan et al. 2008). Black-footed albatross (*Phoebastria nigripes*) appear to take advantage of counterclockwise airflow associated with the North Pacific Subtropical gyre to commute to the American west coast (Fernández et al. 2001, Kappes et al. 2010). A significant decrease in northeast trade winds with a slowing of the Hadley circulation may increase energy expenditures for various species to search for prey and commute to breeding locations. Models have shown that certain North Pacific albatross species may indeed have trouble expanding ranges based on current wing loading levels (Suryan et al. 2008).

Changes in precipitation, air temperature, and wind that might affect nesting of seabirds in the North and South Pacific appear likely to follow from the slowing of Hadley circulation. Ambient air temperatures in Hawaii are expected to increase by less than 2.5°C, which while modest, may be much higher on the mountains and at night (Chu and Chen 2005, Cao et al. 2007, Giambelluca et al. 2008) due to the changes in the inversion layer. The increase in montane air temperature may affect cloud height and development, thereby lowering the inversion layer. In this scenario, a lower inversion layer may reduce the landscape exposed to trade wind showers and mist, thus further reducing precipitation (Brandt et al. 1995, Ainley et al. 1997, Slotterback 2002). The montane-nesting petrels (Hawaiian petrel, Newell's shearwater, Audubon's shearwater, band-rumped storm-petrel, herald petrel, Tahiti petrel) can nest in both rainforest and in lava fields. The habitat plasticity of these burrow nesters suggests they will be little affected by temperature increases and associated changes in precipitation and vegetation.

For surface or tree nesters such as albatrosses, frigatebirds, boobies, terns, and noddies, the combination of increased temperature and decreased wind may raise substrate temperatures, reducing habitat that is suitable for nesting and increasing heat stress while nesting. Predicting how this will affect a particular site will be difficult, as the outcome will likely be the result of a complex interplay of terrain, substrate, and exposure with each species' thermal tolerance. For example, sooty terns do not appear to tolerate temperatures much above 35°C, while great frigatebirds have been reported to tolerate temperatures of up to 51.7°C (Mahoney et al. 1985). Dehydration is mentioned as a cause of death of Laysan albatross chicks at Midway Island during hot weather (Sileo et al. 1990). This could become more of a problem with increased temperatures and decreased winds, particularly for species nesting during the summer.

There is as yet no clear connection between hurricanes or storm intensity and global warming (Bender et al. 2010), although recent work suggests that the hurricanes that do occur may be more intense (Chu and Wang 1997, Chu et al. 2002, Chu and Chen 2005). Central Pacific hurricanes and Hawaiian droughts and fires tend to be more frequent at or after the peak of *El Niño* events (Bindoff et al. 2007). Whether or not *El Niño* events and hurricanes prove to be positively correlated with global warming, the overall effect could be the same: drier islands, with rare events of heavy rainfall and flooding and probably increased wildfires. However, increased storm intensity and frequency will likely inundate low-lying nesting sites and cause widespread failures during the breeding season. Indeed, these effects are already occurring. In February 2011, strong winds and large storm surges washed over portions of Midway Atoll and Laysan Island resulting in the deaths of tens of thousands of Laysan (Cazenave and Llovel 2010) and black-footed albatrosses and bonin petrels (USFWS unpub data). These extreme events coupled with changes in sea level rise could significantly reduce reproductive output.

Sea level rise

Satellite altimeter data reveal that the average global sea level is changing at a rate of 3.3 ± 0.4 mm/year (over the period 1993–2006), which is consistent with tidal gauge data (IPCC 2007), and is tracking the highest projections in the AR4 (Cazenave and Llovel 2010). Current estimates of future sea level rise by 2100 range from 0.5 to 1.2 m (Grossman and Fletcher 1998, Chowdhury et al. 2010). Hawaii and the rest of the Pacific have experienced sea level fluctuations of up to 200 m in the past (Olson and James 1982), but that was before human activity greatly reduced predator-free areas on the main Hawaiian islands (2006) and other high islands in American Samoa, Guam and CNMI that might be used as alternative nesting sites for seabirds responding to such fluctuations. Baker et al. (2006) examined the potential effect of sea-level rise on the Northwest Hawaiian Islands. Their work was based on a projected sea-level rise of 48-88 cm by the end of the century, on the higher end of other predictions of 18-76 cm (Firing et al. 2004). None of the studies included seasonal heating which may contribute 4 cm to the rise, as well as periodic eddies which can add up to 15 cm at their peak (Rice 1959), so potential sea-level rise could be 100 cm by 2100.

These higher levels combined with storm surges (and occasional seismic event such as large tsunamis) may place even more island areas at risk than projected by Baker et al. Midway, Kure, and Lisianski Islands are not more than 6 m above sea-level. Midway, Pearl and Hermes Islands and French Frigate Shoals, at less than 2 m above sea level, already suffer at least partial over-washes during storms, and are likely face the greatest risk from rising sea level. In a “3-foot” tsunami at Midway in 1957, “many young albatrosses were washed away or drowned”, and in 1958, “twelve-foot breakers” from Typhoon Ophelia caused an estimated destruction of 35% of black-footed albatross nests, “flooding large areas inland” (Rice 1959). At Pearl and Hermes Islands, the nest mortality for black-footed Albatrosses for the same event was estimated at 43% (Duffy 2010). In March of 2011, a 1.5-m tsunami was generated by a magnitude 9.0 earthquake off Japan that washed over up to 60% of Laysan and Midway Islands resulting in the deaths of an estimated 110,000 Laysan and black-footed albatross chicks and over 2,000 adults, or 22% of the year’s reproductive output for those species (USFWS unpub data). The impact to burrow-nesting bonin petrels during the same tsunami could not be estimated due to poor population estimates and their burrow-nesting habits, but it is likely that many thousands died. Kure Atoll also sustained substantial seabird losses during the tsunami, particularly in black-footed albatrosses which tend to nest on the perimeter of islands. Interestingly, Tern Island and most of the southern atolls, along with the main Hawaiian Islands were relatively unaffected by this tsunami.

With the exception of montane-nesting petrels, white-tailed tropicbirds, and several small, upslope or sea-stack colonies of Laysan albatrosses, wedge-tailed shearwaters, and boobies, the majority of species in the Pacific Islands nest at or near sea level, regardless of the maximum elevation of the island they nest on. As a result, species that currently nest on high islands may be better able to adapt to sea level rise since sea-level habitat will still be available as long as islands remain above water. In contrast, species nesting on low limestone or coralline islands will eventually be displaced. Unfortunately, the largest colonies of most species occur on mostly low limestone or coralline islands since they typically harbor no human populations and fewer alien predators than high islands. Because most or all high-island habitat in the U.S. Pacific is infested with non-native mammalian predators, providing safe, predator-free refugia on high islands is essential for colonies and species that will be displaced by rising sea level.

Conclusions

Given the differences in oceanography between the two focal regions in the Pacific, it is highly likely that climate change will affect these systems and their seabirds in different ways; though some potential impacts could be similar. For example, the abundance and availability of seabird food resources may diminish in both systems, leading to changes in vital rates such as breeding success, survival, and recruitment, which in turn affect population dynamics. Anticipated differences between the two systems include more severe impacts of sea level rise and ocean acidification on the Pacific Islands ecosystem and its low-lying terrestrial breeding sites for seabirds, which are more vulnerable than breeding sites in the California Current to coastal inundation and storm surges. The impacts of ocean acidification may be more severe in the Pacific Islands system as well owing to the importance of calcareous biogenic habitat (coral reefs and associated prey) in that system and the importance of barrier and fringing reefs in modulating accretion and erosion on island shores. Effects of climate change on ocean temperature, stratification, and upwelling, however, are predicted to be more severe in the California Current which is more 'sub-arctic' in character and may be more vulnerable to changes in atmospheric-oceanic interactions that drive productivity.

While there are clear indications that climate change is occurring, there is limited data available on how seabirds have responded to these changes despite the existence of multiple long-term seabird monitoring data sets. Compiling and analyzing existing data sets should be a high priority as this will provide a wealth of information to help prioritize conservation actions for little cost compared to the cost of implementing new management programs. For species for which very few data exist, particularly those thought to be most vulnerable to climate change (e.g., phoenix petrel and Polynesian storm-petrel), establishing research and monitoring programs should be a priority. Research and monitoring should focus on indicator species and determining the environmental factors that affect breeding phenology, reproductive success, diet, and population changes. Long-term monitoring of indicator species should occur at selected sites. At fewer selected sites, additional monitoring variables should include at-sea distributions, foraging trip duration and offspring provisioning statistics, demographic analysis, and diet sampling including stable isotope analysis. The combination of these variables would provide a valuable monitoring baseline from which changes through time could be observed and correlated with changes in the environment. Without such analyses, much of our understanding will remain speculative. Despite the uncertainty regarding some of the impacts climate change may have on seabirds, mitigation of population impacts caused by climate change could include many common and well-known management actions that are known to enhance seabird populations (USFWS 2005).

For species currently dependent on low-lying islands for nesting that are vulnerable to sea level rise, management efforts should shift to high islands in the main Hawaiian Islands, American Samoa, Guam, and the CNMI that can be made and kept predator-free with fencing and active management (see for example Gummer 2003, Miskelly et al. 2009). Unfortunately, high elevation islands are typically inhabited and have non-native mammalian predators and habitat-altering non-native plants – circumstances that present another set of challenges. Efforts should be made to create or restore suitable nesting habitat in such areas, to attract nesting seabirds using decoys or sound, or even to translocate nestlings (Pichegru et al. 2010).

From a marine perspective, two potential ways to mitigate population declines include reducing fishery bycatch of albatrosses and other species for which this is a documented problem, and to regulate fisheries to ensure that suitable prey are available for seabirds. The idea of using marine protected

areas (MPAs) to locally enhance marine productivity is showing promise for seabird conservation (USFWS 2005), and as such, important foraging areas that overlap with commercial fishing effort should be considered as candidates for protection.

Climate change itself, and consequent processes such as changing stratification and upwelling, ocean acidification, and increased storm intensity, are difficult to predict accurately and may prove impossible to manage. Based on our current understanding of these processes and how they may affect marine ecosystems and seabirds' breeding habitat in the California Current and Pacific Islands ecosystems, a suite of broad-scale, tangible management actions can prevent or slow population decline that could result from climate change. Table 1 summarizes the relative magnitude of the climate change effects by species and provides suggestions for management actions that could mitigate potential losses as a result of climate change.

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Table 1: Potential impact of climate change on breeding seabirds in the California Current and Pacific Islands region of the North Pacific. The overall perceived degree of threat of climate change and the specific aspects of climate change likely to pose the greatest risk to each species are listed in the first two columns. Overall impact is ranked from 0-2; 0 = no or little impact expected; 1 = some impact; 2 = serious impact. Specific aspects of climate change are listed for impact rankings of 1 or 2 and include i = increasing SST and stratification; ii= Poleward shift of the westerlies and other wind/current changes; iii= sea level rise; iv= increase in storm frequency or severity; and v= food web changes. The justification column describes the main reason(s) for the impact ranking, and the management actions column are those recommended for each species as a way to mitigate climate change by maximizing population numbers. Management actions are only listed for impact rankings of 1 or 2 and we attempted to specifically address climate change mitigation and not simply repeat recommendations for all conservation concerns detailed in the seabird conservation plan action list. Management actions: A= secure breeding sites on higher elevation or more northerly islands, B= conduct habitat restoration (predator control, vegetation stabilization, etc.), C= reduce bycatch, D= fisheries management to protect prey stocks, E= reduce light attraction to reduce collisions.

ECOSYSTEM/Species	Overall impact	Specific aspect of climate change	Justification of impact ranking	Management actions
CALIFORNIA CURRENT				
Fork-tailed Storm-Petrel (<i>Oceanodroma furcata</i>)	0		Nests well above sea level; Large, offshore foraging range	
Leach's Storm-Petrel (<i>Oceanodroma leucorhoa</i>)	0		Nests well above sea level; Large, offshore foraging range	
Ashy Storm-Petrel (<i>Oceanodroma homochroa</i>)	1		Declining productivity over time, but nests well above sea level; Large, offshore foraging range,	
Black Storm-Petrel (<i>Oceanodroma melania</i>)	0		Nests well above sea level; Large, offshore foraging range	
Brown Pelican (<i>Pelecanus occidentalis</i>)	1	iv, v	Documented effects of changing ocean conditions; Diet specialist; Storm impacts	D
Double-crested Cormorant (<i>Phalacrocorax auritus</i>)	0		Nests well above sea level; Diet generalist	
Brandt's Cormorant (<i>Phalacrocorax penicillatus</i>)	1	iv, v	Documented effects of changing ocean conditions; Storm impacts	D

Pelagic Cormorant (<i>Phalacrocorax pelagicus</i>)	1	iv, v	Documented effects of changing ocean conditions; Storm impacts; Limited foraging range	D
Ring-billed Gull (<i>Larus delawarensis</i>)	0		Few coastal nesting sites; Diet generalist	
California Gull (<i>Larus californicus</i>)	0		Few coastal nesting sites; Diet generalist	
Western Gull (<i>Larus occidentalis</i>)	0		Nests well above sea level; Diet generalist	
Glaucous-winged Gull (<i>Larus glaucescens</i>)	0		Nests well above sea level; Diet generalist	
Gull-billed Tern (<i>Gelochelidon nilotica</i>)	2	iii, v	Nests near sea level; Surface feeder; Diet specialist	A,B
Caspian Tern (<i>Hydroprogne caspia</i>)	2	iii, v	Nests near sea level; Foraging specialist	A,B
Royal Tern (<i>Thalasseus maximus</i>)	2	iii, v	Nests near sea level; Foraging specialist	A,B
Elegant Tern (<i>Thalasseus elegans</i>)	2	iii, v	Nests near sea level; Foraging specialist	A,B
Forster's Tern (<i>Sterna forsteri</i>)	2	iii, v	Nests near sea level; Foraging specialist	A,B
Least Tern (<i>Sterna antillarum</i>)	2	iii, v	Nests near sea level; Surface feeder; Diet specialist; Limited foraging range	A,B
Black Skimmer (<i>Rhynchops niger</i>)	2	iii, v	Nests near sea level; Surface feeder; Diet specialist; Limited foraging range	A,B
Common Murre (<i>Uria aalge</i>)	1	i, ii, v	Coastal upwelling dependent; Diet generalist; Large, 3 dimensional, foraging range	D
Pigeon Guillemot (<i>Cephus columba</i>)	2	iii, v	Nests near sea level; Limited nearshore foraging range; Declining productivity over time	A,B,D
Marbled Murrelet (<i>Brachyramphus marmoratus</i>)	2	i, ii, v	Inland nesting and single prey delivered to chick causing greater reproductive failure with increased foraging range	B,D
Xantus's Murrelet (<i>Synthliboramphus hypoleucus</i>)	2	i, ii, v	Documented effects of changing ocean conditions; Diet specialist; Limited foraging range	A,B,D

Ancient Murrelet (<i>Synthliboramphus antiquus</i>)	1	i, ii, v	Documented effects of changing ocean conditions; Plankton generalist; Widespread, northerly distribution	D
Cassin's Auklet (<i>Ptychoramphus aleuticus</i>)	2	i, ii, v	Increasing variability in productivity over time; Documented effects of changing ocean conditions; Euphausiid specialist	D
Rhinoceros Auklet (<i>Cerorhinca monocerata</i>)	1	i, ii, v	Documented effects of changing ocean conditions; Diet generalist	D
Tufted Puffin (<i>Fratercula cirrhata</i>)	1	i, ii, v	Documented effects of changing ocean conditions	D
HAWAII & US PACIFIC ISLANDS	Overall impact	Specific aspects of climate change	Justification of impact ranking	Management actions
Short-tailed Albatross (<i>Phoebastria albatrus</i>)	1	i, ii, iv	Documented effects of changing ocean and wind conditions affecting transport and food availability	B, C
Black-footed Albatross (<i>Phoebastria nigripes</i>)	2	i, ii, iii	Nests primarily at sea level; Surface feeder; Travels long distances to provision for chicks	A,B,C
Laysan Albatross (<i>Phoebastria immutabilis</i>)	2	i, ii, iii	Nests primarily at sea level; Surface feeder; Travels long distances to provision for chicks	A,B,C
Hawaiian Petrel (<i>Pterodroma sandwichensis</i>)	1	i, ii, v	High altitude nesting habitat may become unsuitable with increasing temperatures and vegetation changes; Large foraging range	A,B,E
Herald Petrel (<i>Pterodroma arminjoniana</i>)	0		Nests well above sea level; Presumed large foraging range	B

Tahiti Petrel (<i>Pterodroma rostrata</i>)	0		Nests well above sea level; Presumed large foraging range	B, E
Phoenix Petrel (<i>Pterodroma alba</i>)	2	i, iii, v	Small population; Restricted breeding range; Nests at sea level in low latitudes	A,B,D
Bonin Petrel (<i>Pterodroma hypoleuca</i>)	1	iii, v	Nests near sea level	A,B
Bulwer's Petrel (<i>Bulweria bulwerii</i>)	1	iii, v	Nests near sea level	B
Wedge-tailed Shearwater (<i>Puffinus pacificus</i>)	1	iii, v	Nests near sea level; Dependent on commercially valuable predatory fishes to make prey available	A,B
Christmas Shearwater (<i>Puffinus nativitatis</i>)	1	iii, v	Nests near sea level	A,B
Newell's Shearwater (<i>Puffinus auricularis newelli</i>)	1	i, ii	High altitude nesting habitat may become unsuitable with increasing temperatures and vegetation changes; Large foraging range	A,B, E
Audubon's Shearwater (<i>Puffinus lherminieri</i>)	1	iii, v	Nests near sea level; Dependent on commercially valuable predatory fishes to make prey available	A,B

Band-rumped Storm-Petrel (<i>Oceanodroma castro</i>)	1	ii, v	Mortality in severe storms; Surface feeder	B
Tristram's Storm-Petrel (<i>Oceanodroma tristrami</i>)	1	ii, iii, v	Mortality in severe storms; Surface feeder	A,B
Polynesian Storm-Petrel (<i>Nesofregetta fuliginosa</i>)	2	i,ii, iii	Small population; Restricted breeding range; Nests at sea level in low latitudes	A,B
Masked Booby (<i>Sula dactylatra</i>)	1	i,v	Nests near sea level in low latitudes; Dependent on commercially valuable predatory fishes to make prey available	A,B
Brown Booby (<i>Sula leucogaster</i>)	1	i,v	Nests near sea level in low latitudes; Dependent on commercially valuable predatory fishes to make prey available	A,B
Red-footed Booby (<i>Sula sula</i>)	1	i,v	Nests near sea level in low latitudes; Dependent on commercially valuable predatory fishes to make prey available	A,B
Great Frigatebird (<i>Fregatta minor</i>)	1	i, ii, v	Nests near sea level in low latitudes; Dependent on wind conditions and convectional heating for transport	A,B
Lesser Frigatebird (<i>Fregatta ariel</i>)	1	i, ii, v	Nests near sea level in low latitudes; Dependent on wind conditions and convectional heating for transport	A,B

Red-tailed Tropicbird (<i>Phaethon rubricauda</i>)	1	i,v	Nests near sea level in low latitudes	A,B
White-tailed Tropicbird (<i>Phaethon lepturus</i>)	0		Nests well above sea level; Diet generalist	
Sooty Tern (<i>Onychoprion fuscatus</i>)	1	i,iii, v	Nests near sea level in low latitudes; Dependent on commercially valuable predatory fishes to make prey available	A,B
Gray-backed Tern (<i>Onychoprion lunatus</i>)	1	i, iii	Nests near sea level in low latitudes; Dependent on commercially valuable predatory fishes to make prey available	A,B
Black Noddy (<i>Anous minutus</i>)	1	i, ii, iii	Nests near sea level in low latitudes	A,B
Brown Noddy (<i>Anous stolidus</i>)	1	i, ii, iii	Nests near sea level in low latitudes	A,B
Blue-gray Noddy (<i>Procelsterna cerulea</i>)	1	i, ii, iii	Nests near sea level in low latitudes; Small population size	A,B
White Tern (<i>Gygis alba</i>)	0		Widespread population; Can nest well above sea level	
Little Tern (<i>Sterna albifrons</i>)	0			

