

Stalking the Southern Oscillation: environmental uncertainty, climate change, and North Pacific seabirds

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Abstract

The oceans and atmosphere vary across many space and time scales that affect populations of North Pacific seabirds. The most important of these variations, or at least the most readily detected by current research, is the El Niño-Southern Oscillation, a shift in tropical atmospheric circulation and oceanic currents that has major effects in the North Pacific. At time scales longer than decades, the North Pacific and adjacent lands have exhibited warm and cool periods. At still longer intervals, glacial cycles affect sea and air temperatures, atmospheric circulation, rainfall, and sea level at centennial and millennial scales. Seabirds have thus evolved in environments that have varied greatly over time, so that inferences from the present must be made with caution.

Although scenarios of future climate change are necessarily speculative, we can use insights from research under existing conditions to predict the potential effects on seabird distribution and ecology of rising sea level, increased ambient temperatures, and changes in oceanic and atmospheric circulation and productivity. Detecting such effects will require us to work at the appropriate scales, with long-term, regionally extensive, cooperative projects that are now uncommon in seabird research.

Résumé

Les conditions atmosphériques et océanographiques varient beaucoup dans le temps et l'espace, influant ainsi sur les populations d'oiseaux marins du Pacifique Nord. L'épisode El Niño-oscillation australe est le plus important (du moins, celui que la recherche actuelle détecte le plus facilement). Il s'agit d'un décalage de la circulation de l'air tropical et des courants océaniques, dont les effets sont considérables dans le Pacifique Nord. Dans des échelles de temps supérieures à des décennies, le Pacifique Nord et les terres limitrophes de cette région du globe ont présenté des périodes successives de réchauffement et de refroidissement. Dans des intervalles encore plus longs, à l'échelle séculaire ou millénaire, les cycles glaciaires ont modelé les températures de l'eau et de l'air, la circulation atmosphérique, les précipitations et le niveau de la mer. Les oiseaux marins évoluent dans des milieux qui ont subi de fortes variations. Par conséquent, les conclusions tirées des conditions actuelles doivent être empreintes de prudence.

Bien que les scénarios de modification du climat soient nécessairement conjecturaux, nous pouvons utiliser les aperçus des chercheurs, issus des conditions actuelles, pour prévoir les effets possibles de l'élévation du niveau de la mer, de la hausse

des températures ambiantes et de l'évolution de la circulation et de la productivité des courants océaniques et atmosphériques sur la distribution et l'écologie des oiseaux marins. Pour préciser ces effets, il faudra réaliser des travaux de recherche concertée, approfondis à l'échelle régionale, de longue haleine et de portée adéquate. Ce genre de recherche n'est pas courante en ce qui a trait aux oiseaux marins.

1. Introduction

In the last several decades, oceanographers have come to see the ocean as varying at a variety of scales, from fine scale turbulence to global glacial cycles (e.g., Stommel 1963; Walsh 1978; Steele 1989). Biologically, such variability exists only within the context of an organism's life cycle and ecology (MacArthur and Levins 1964; Southwood 1978; Hunt and Schneider 1987; Wiens 1989). The universe of a planktonic organism represents but a single swallow for a baleen whale or a second's soaring for an albatross. The 24-hour life span of a plankton may be 10^4 times shorter than that of a whale or albatross. Studying seabirds, whales, or plankton is thus as much a matter of getting the scale right as of asking the right questions or using the right techniques (Wiens 1989).

Unfortunately, although a biologist has a professional life span similar to the life span of a whale or albatross, research projects usually last only a fraction of that time. In the past, marine bird research was usually confined spatially to a few nests in a single colony, closer in scale to plankton than to albatrosses. We study species with tens or hundreds of thousands of birds and with ranges that span entire oceans by watching a few pairs for a few years in a few places. We could well end up like the blind people with the elephant, each touching a different part and arguing his or her data indicate the beast is a snake, a tree trunk, or a wall.

In studying the effects of climate change on seabirds, the situation may appear especially unpromising. Like the blind people, we may have the right data, but we have yet to put it together. Worse yet, we may not even be collecting the right data.

This paper explores what we do know about North Pacific seabirds and climate change, ranging from annual variations such as the El Niño-Southern Oscillation and the Kuroshio Current Meander to long-term changes of the past. These scales are those most likely to affect seabird populations. The paper goes on to explore some of the possible effects of future climate change on seabirds, and it concludes with a discussion of the research needed to stalk and capture the effects of climate change on seabirds.

2. Variability between years

The best-known form of interannual variability in the Pacific is the El Niño–Southern Oscillation (ENSO) (e.g., Wooster and Fluharty 1985; Glynn 1990; Philander 1990). El Niño is essentially a temporary collapse of the normal oceanic and atmospheric circulation patterns of the Pacific Ocean. Normally, strong surface trade winds, blowing around atmospheric highs counterclockwise in the southern hemisphere and clockwise in the northern hemisphere, combine in the equatorial Pacific to push surface water westwards toward Indonesia. The water accumulates and heats up, evaporates, and causes local air masses to rise. These drop their moisture as they rise, resulting in heavy rainfall, then cool and move eastwards along the equator. Reaching the west coast of South America, they descend, warming and absorbing water, to produce the dry conditions of the Peruvian and Chilean coasts. These winds and those revolving around the high-pressure zones become the westward-flowing trade winds of the eastern Pacific, producing upwelling, the transport of surface water offshore to be replaced by subsurface waters. These subsurface waters rise from depths without photosynthetic activity, so they have high levels of nutrients available for phytoplankton, when the waters reach the photic zone (Cushing 1975). The plankton achieve high rates of primary productivity that support short, very productive food chains, generating some of the world's largest single-species fisheries (Cushing 1975).

During ENSO, for reasons still not understood, the trade winds in the western Pacific stop and the warm mass of water in the west moves eastwards. This causes evaporation far to the east of its normal Indonesian location, and heavy rains begin in normally dry areas such as the central Pacific islands and the desert coast of Peru. The trade winds of the eastern Pacific may continue, but they upwell warm water, devoid of nutrients, from above the thermocline. The productive communities of the upwellings collapse, with reproductive failure and death of fish (Arntz et al. 1985) and birds (Jordan and Fuentes 1966).

There is a two-year periodicity related to the Southern Oscillation in tropical wind and rainfall (e.g., Doberitz 1968; Rasmussen et al. 1990), but strong and very strong ENSO events, most likely to affect the North Pacific, occurred about 9.9 years apart during the period 1525–1982, with intervals up to 20 years between events (Quinn et al. 1987). In addition, based on Peruvian records, there have been periods when clusters of ENSO events occurred, and these may also have affected the North Pacific during the following years: 1607–1624, 1701–1728, 1812–1832, 1864–1891, and 1925–1932 (Quinn et al. 1987).

When an ENSO event affects the North Pacific, it may have two origins; warm-water Kelvin waves moving out of the tropics and teleconnections or atmospheric transfers of heat (Norton et al. 1985). The Kelvin waves and their effects are much like those described for Peru; warm water moves north with a strengthened California countercurrent (e.g., Radovich 1961), local upwelling fails, and sea level rises with the collapse of upwelling (Lynn 1983; Mysak 1986). The atmospheric teleconnections, strongest in winter (Hamilton and Emery 1985), are much more complex. The heating of the eastern tropical Pacific sets up changes in atmospheric circulation that intensify the North Pacific High, the Aleutian Low, and the North American Continental High (Horel and Wallace 1981). The strengthening of the Aleutian Low leads to cooler water 1000–3000 km off the west coast of North America and to the warming of the Bering Sea (Niebauer 1985).

Unfortunately, biological data on North Pacific ENSOs are relatively recent. ENSO events were studied in 1940–41, 1957–58, 1972, and 1983 in the North Pacific, although the amount of information about the earlier events is limited (Sette and Isaacs 1960; Radovich 1961; McLain and Thomas 1983; Wooster and Fluharty 1985; Schoener and Fluharty 1985).

In the eastern Pacific, strong year-classes of the Pacific mackerel *Scomber japonicus* and sardine *Sardinops caerulea* coincide with ENSO events (MacCall 1979; Sinclair et al. 1984), but northern anchovy *Engraulis mordax* recruitment is negatively affected (Lasker 1978). Effects of ENSO on fish reproduction in the northeast Pacific include shortened spawning seasons, fewer adults with mature gonads, weight loss, altered spawning locations, and reduced survival of eggs and larvae (Bailey and Incze 1985). Hollowed et al. (1987) concluded that El Niño leads to good recruitment in California (pelagic) stocks and poor recruitment in groundfish.

Ainley et al. (1988), Ainley and Boekelheide (1990), and Duffy (1990) have reviewed the effects of ENSO on seabirds in the North Pacific. Warm-water seabirds move into northern California waters, normally too cold for them, and may abandon nest sites farther south (Radovich 1961; Ainley et al. 1988). Species may shift foraging areas, with warm-water species moving inshore (Ainley and Boekelheide 1990). Some species responded opportunistically to the oceanic changes. Western Gulls *Larus occidentalis* encountered increased food in southern California from an influx of pelagic crabs *Pleuroncodes planipes* (Stewart et al. 1984).

Adult mortality, either observed directly or inferred from post-ENSO populations, has ranged from 19% in Pigeon Guillemots *Cephus columba* (Hodder and Graybill 1985) to 50% in Tufted Puffin *Fratercula cirrhata* during the severe 1983 ENSO (Ainley et al. 1988; Ainley and Boekelheide 1990). Other species may not have exhibited reduced populations after the 1983 ENSO only because nonbreeding birds were recruited into colonies (Ainley et al. 1988).

Nesting failure and reduced nesting success are frequent during ENSO, but the extent varies with the severity of each event, with species, and perhaps with foraging type (e.g., Boekelheide et al. 1990a, 1990b; Ainley et al. 1990a, 1990b; Ulrich 1991). For example, Common Murres *Uria aadg* suffered a major reproductive failure on the Farallon Islands in 1983 (Boekelheide et al. 1990b). In contrast, surface-feeding Ashy Storm-Petrels *Oceanodroma homochroa* were very successful that year, although this may have been the result of reduced competition for nesting holes with the Cassin's Auklet *Ptychoramphus aleuticus* because of lack of nesting by the auklets (Ainley et al. 1990c). Brandt's *Phalacrocorax penicillatus* and Pelagic *P. pelagicus* cormorants also suffered reproductive failure (Ainley et al. 1990a; Boekelheide et al. 1990a). In Oregon, Pigeon Guillemots, which feed on benthic detritivores, and surface-feeding Western Gulls and Leach's Storm-Petrels *Oceanodroma leucorhoa* suffered little from the 1983 ENSO, whereas diving birds, such as Common Murres and Brandt's and Pelagic cormorants, were affected, as they had been in the Farallons (Graybill and Hodder 1985; Hodder and Graybill 1985; Bayer 1986). In Alaska, Hatch (1987) concluded, in contrast, that diving birds such as Common Murres were less affected by ENSO than were surface-feeders such as Black-legged Kittiwakes *Rissa tridactyla*.

In the western North Pacific, variations in the warm Kuroshio Current follow a strengthening of the Ogasawara High which in turn follows the onset of ENSO (Uda 1962; Kawabe 1985). Nakai (1962), Tanaka (1983), and Hayasi

(1983) found significant relationships between shifts in the Kuroshio Current and the distribution and population dynamics of Japanese sardine *Sardinops melanosticta*, Pacific saury *Cololabis saira*, and Pacific mackerel *Scomber japonicus*, suggesting that food abundance for seabirds around the Japanese islands is linked at least partially to ENSO events. During the 1983 ENSO, mortality of Short-tailed Shearwaters *Puffinus tenuirostris* occurred in Japan and may have been linked in the short term to shifts in the Kuroshio Current (Oka 1986; Oka and Maruyama 1986), although the ultimate cause of mortality was attributed to shortages of krill in the southern hemisphere (Oka et al. 1987).

At the global level, 33% of the variance in sea surface temperature at scales of less than 10 years is assignable to ENSO (Wigley and Raper 1990), but other sources of variability exist and need to be considered in seabird studies. For example, in the northeast Pacific, not all warm events in the North Pacific are caused by ENSO (Chelton et al. 1982; Mysak 1986), nor are all breeding failures (Hatch 1987; Murphy et al. 1991). Atmospheric teleconnections from the tropics to mid-latitudes in the North Pacific have occurred in 1958-59, 1960-61, 1962-63, 1967-68, 1979-80, and 1980-81 without concurrent ENSO events (Norton et al. 1985). Large numbers of Manx Shearwaters *Puffinus puffinus* were present during anomalously warm water conditions in 1979, unassociated with ENSO (Helbig 1983), and die-offs of seabirds in the Bering Sea during 1979 (DeGange and Rosapepe 1984) may also have been caused by the same event.

Michaelson (1977) has suggested a cycle of five or six years as warm-water masses rotate around the North Pacific gyre. McCreary (1983) suggested that mid-latitude internal Rossby Waves, set off by ENSO events, take two to nine years (depending on latitude) to circle the North Pacific and return westward, where they might trigger further ENSO events. If the two phenomena are related, then even some events outside ENSO years may indeed be part of a general ENSO cycle.

3. Variability between decades

Within the upwelling zone of the California Current, there have been several demonstrations of shifts in environment over decades or longer periods. The first, an analysis by Soutar and Isaacs (1973) of fish scales in bottom sediments from 1810 to 1970, shows apparent population peaks of Pacific sardine during 1855-1865, 1890-1900, and 1915-1925, with intervening troughs, especially from 1865 to 1890. Similarly, northern anchovy and Pacific hake *Merluccius productus* showed long-term fluctuations in population levels. Anchovy were relatively abundant in the sediment record from 1815 to 1925, then rare from 1925 until 1965. Hake scales were numerous from 1885 to 1925, with low levels thereafter.

The second line of evidence of variability between decades comes from the work of Hubbs (1948), who compared fish species lists from 1853-1857, 1880, and the 1940s, showing the presence of southern, warm-water species in the central California area during 1841-1859, a period of elevated water temperatures (Douglas et al. 1982). Effects of this period are also reflected in the bird fauna of the Farallon Islands: Cassin's Auklets were rare and Rhinoceros Auklets *Cerorhinca monocerata* ceased breeding (Ainley and Lewis 1974).

Most recently, commercial fishery landings and estimates of fish populations have shown major shifts, some of which may have been caused by overfishing while others are caused by periodic strong year-classes (MacCall 1983, 1986).

In the northern Gulf of Alaska, Royer (1985) showed that a cool period ran from 1940 to 1970, followed by a 1.5°C increase in sea temperature during 1970-1984. He suggested that elevated sea temperatures would increase evaporation and cloudiness, leading to increased precipitation and strength of the Alaska Coastal Current, or alternatively to growth of local glaciers. Increased temperatures would also influence the strength and location of the Aleutian Low (see also Pan and Oort 1983), leading to changes in storm tracks and rainfall for the rest of North America.

Farther south, McGuirk (1982) reported that the period 1905-1945 was anomalously dry along the northern segment of the western United States coastline and much wetter along the southern segment compared to periods before or after, but the causative mechanism remains unclear.

4. Variability between centuries

At the scale of 10² years or more, climate and glacial cycles have been variable. The Medieval Optimum from approximately AD 900 to 1200 brought arctic warming and the Greenland settlements of the Norse (Lamb 1965). The Little Ice Age from approximately AD 1550 to 1850 saw a resurgence of glaciers and of global cooling (Lamb 1979; Grove 1988). The present century has brought a return of warmer conditions (Cushing 1982). We have little idea of the effects of such changes on seabirds, although they are likely to have generated major shifts in range.

5. Variability between millennia and between longer periods

Over time spans of 10³ years or more, the climate has been equally variable. The last Ice Age peaked during 21 000-17 000 B.P., followed by the warm Holocene Climatic Optimum, approximately 8000-4000 B.P., and then by another cold period, before the Medieval Optimum described above. We know relatively little of changes in seabirds caused by climate at this scale. The arrival of Amerinds in North America and their subsequent hunting of seabirds may have led to changes in seabird nesting sites and to local extirpations, as well as the extinction of a flightless sea duck *Chendytes lawi* (Morejohn 1976).

At longer time scales, the North Pacific has also varied, both oceanographically and atmospherically. Sea level, relatively stable over the last 6000 years or so, has risen 60 m since the height of the last period of glaciation, beginning 10 000 years B.P. (Mörner 1969). Miocene and Pliocene California coastlines had numerous islands which have been lost in the Recent Epoch (Vedder and Howell 1980).

Wind speed has also varied over the past 75 000 years, with major variability at the 10³-year scale, exhibiting three alternating periods of wind speed during 75 000-50 000 B.P., 50 000-28 000 B.P., and 28 000-0 B.P. (Molina-Cruz 1977). Finally, overall, there appear to be climatic cycles of 20 000, 40 000, and 100 000 years (Kerr 1991).

At the scale of millions of years, sea level has varied greatly (Vail and Hardenbol 1979), and the California marine environment has shifted from subtropical in the Miocene, about 15 million years ago, to the present cool, eastern boundary current with seasonal, local upwelling (Mullineaux and Westberg-Smith 1986).

Such climatic variability has probably generated corresponding changes in avifauna, although biological factors

may also have been important. The flightless *Plotopteridae* disappeared in the Miocene, possibly as a result of the radiation of marine mammals (Olson and Hasegawa 1979). Boobies *Sula* disappeared in the Pliocene. The flightless auks *Mancalla* spp. and gannets *Morus* disappeared in the Pleistocene (Lindberg and Kellogg 1982). Flightless seabird diversity has been inversely correlated with sea levels, perhaps in part because of competition with pinnipeds for terrestrial landing sites (Warheit and Lindberg 1988).

6. Climate change and seabirds

Climate change across a wide range of scales has been the rule rather than the exception. Extant seabird species have had to cope with glaciation events, changes in sea level, fluctuations in global temperature, and major shifts in ocean circulation (e.g., Olson 1985; Warheit and Lindberg 1988). North Pacific seabirds may well have evolved for cooler oceanographic conditions and lower sea levels than we encounter during our studies today, and for interactions with extinct groups such as sulids. All these factors mandate caution when making inferences concerning evolution and ecology from short-term, present-day studies (Warheit and Lindberg 1988).

Looking toward the future, concern about anthropogenic causes of rapid climate change has fuelled a great deal of public interest and concern, with scenarios of global warming, predicting the melting of glaciers, massive rises in sea level, and major shifts in vegetation zones (e.g., DeFries and Malone 1989; Houghton and Woodwell 1989; Houghton et al. 1990).

For seabirds, there are perhaps three main effects that might be expected from global warming: 1) rising sea level (Broadus 1989; Algeron 1991); 2) increases in ambient temperatures during nesting (Mahlman 1989); and 3) changes in ocean temperature and circulation (Bakun 1990).

Sea level is likely to rise somewhere between 0.0 and 0.7 m, with the current best guess of 0.3 m by A.D. 2050 (Meier 1990). Few colonies are likely to be lost directly to rising sea level, except perhaps in marshes or on sandbars. On the other hand, storm surges and erosion (Bruun 1962) will cause damage even to colonies safely above normal water lines.

Increases in ambient temperature may cause heat stress during nesting for temperate and arctic seabird species and may allow tropical species to move northwards, possibly bringing them into competition with northern species for nesting sites. If the snow-free period and potential nesting season lengthen, this might allow younger birds to breed earlier. Increased temperatures may allow southern pathogens, predators, or parasites to expand northwards, coming into contact with boreal species unadapted to their presence. Human activity may also be facilitated by global warming, leading to settlements farther north than at present and to the possibility of increased exploitation of seabirds.

Seabird species may respond differently to increased ambient temperatures. High-latitude species that nest in holes and burrows should be least vulnerable to temperature change because of the thermal buffering of their nest sites, whereas surface-nesting species, especially those of relatively windless areas, may find their present colony sites too warm. Conversely, burrow-nesting species may be more vulnerable than surface-nesters to increased precipitation, because of flooding.

Changes in atmospheric and oceanic circulation may lead to increased upwelling in coastal ecosystems, and to more frequent cyclonic activity and ENSO events (Bakun 1990;

Brown 1991). This may accelerate the tendency toward boom/bust dynamics for certain seabird populations in upwellings (Duffy 1990) and increase the importance of mass mortality events for seabirds in ecosystems affected by cyclonic activity (e.g., Kohno et al. 1986).

Seabird biologists seem to have taken relatively little interest in the possible effects of climate change, Burger (1990) and Brown (1991) being the exceptions. Climate change models are obviously speculative, with wide variances; perhaps seabird biologists have been loath to pile speculation on speculation. On the other hand, many of the data we need to predict seabird response to future climate scenarios are already at hand. We have some idea of the distribution of birds in relation to different air (Root 1988) and sea surface (e.g., Wahl et al. 1989) temperatures; we have abundant information on the effects of heavy rains and vegetation on nest distribution and reproductive success (e.g., Becker et al. 1985; Erwin and Smith 1985; Storey et al. 1988; Clark et al. 1990), and we have numerous data on physiological response to temperature (Whittow and Rahn 1984). From studies of El Niño (e.g., Duffy 1983; Ainley et al. 1990a), we have some idea of how seabirds respond to changes of prey and oceanography at the ecosystem level.

Putting these together, we could ask, for example: what would happen in a warmer, wetter Alaska with increased flow of the Alaska Coastal Current and a longer snow-free season? Which seabird species might move north to join the community?; which species might decrease because of flooding, competition, or loss of foraging habitat? The resulting hypotheses may be fully testable only by our great-grand-children, but the present exercise may be quite useful in identifying data that they will need for any eventual answers.

7. Suggestions for cooperative research

Climate change presents an exciting theme around which to organize seabird research. Studies such as those reported from the Farallon Islands by Ainley and Boekelheide (1990) are what we need, but they represent a sustained investment in time, money, and professional skills to which few research institutions have the resources or the vision to commit themselves for any length of time.

The Farallon studies sponsored by Point Reyes Bird Observatory are excellent examples of the intensive research needed if we are to understand the effects of short- and long-term climate change on seabirds, but there is also a need for extensive studies, covering larger areas and more colonies, to put the intensive studies into context. Such extensive studies represent a little-exploited opportunity for research on seabirds and climate change.

What sort of research is needed? First, we need data replicated in time so that we can detect changes triggered by climate. We need methods that remain the same, or at least comparable, at the same sites over decades. Second, we need to select a few species that have wide ranges, are unlikely to be affected by human activity, and have well-studied ecologies. This would eliminate hunted species, those that feed on offal or at dumps, and those that nest on mainland sites. Third, we need data that can be collected over wide areas, at a variety of sites. Climate change might be expected to occur first at the extremes of a species' range. Fourth, we need low-energy research activities, requiring perhaps only a single morning's work, that can be conducted year after year, even when funds are limited. Fifth, we need some idea of seabird movement between colonies. Changes at a single colony are almost impossible to

interpret. They could be caused by changes in reproductive success at the colony itself, or by migration to or from the colony. A stable colony could be maintained because of immigration from elsewhere or it could be exporting excess birds. Sixth, we need some institutional or organizational base to provide the necessary homeostasis for the project, filling gaps in coverage when these occur and collecting and curating the data. Government organizations are unlikely to be able to serve this function, because of fluctuating budgets and limited planning horizons. Seabird groups or institutions such as museums may be the best possibilities, perhaps working cooperatively, with the seabird group collecting the data and the museum archiving it. Finally, we perhaps need to change our attitude toward archiving data. Much as oceanographers pool data, we should collect long-term data and make them freely available, while rewarding those who have the foresight and persistence to collect the information. We should also archive the data of individual researchers, at the end of their careers, so that their data remain available to future researchers. At present, such data are scattered or lost and we, as seabird biologists, have no long-term memory.

8. Conclusions

Whatever else may prove true, this is unlikely to be the last word about climate change and North Pacific seabirds. If this paper is successful in depicting the types of climatic variability that may affect seabirds and in setting an agenda for research on ways to catch such variability "in the act," future workers will likely find our present efforts simplistic and superficial, and indeed may look back with jealousy to the time when papers such as this could get published. Future research may well show that seabird species and colonies do not respond uniformly to climate change or that the effects of interactions of short-term and long-term change on seabirds are far more complex than we can speculate about now.

We do know that unless we begin collecting the sort of data that are needed, future workers really won't be much farther ahead than us; so, whatever their opinion, their work will be built on ours, if it is to be built at all.

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