Implications of Climate Change for Alaska's Seabirds

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Introduction

Seabirds are prominent and highly visible components of marine ecosystems that will be affected by global climate change. The Bering Sea region is particularly important to seabirds; populations there are larger and more diverse than in any similar region in North America—over 90% of seabirds breeding in the continental United States are found in this region. Seabirds, so named because they spend at least 80% of their lives at sea, are dependent upon marine resources for food. As prey availability changes in response to climatically driven factors such as surface sea temperature and extent of sea ice, so will populations of seabirds be affected.

Seabirds are valued as indicators of healthy marine ecosystems and provide a "vicarious use value" or existence value—people appreciate and value seabirds simply because they are there and enjoy them through venues such as pictures, nature programs, and written accounts without ever directly observing seabirds in their native environment. A direct measure of this value is demonstrated by Federal legislation that established specific national wildlife refuges to protect seabirds and international treaty obligations that provide additional protection for seabirds. Seabirds are also an important subsistence resource for many who live within the Bering Sea region. Furthermore, the rich knowledge base about seabirds makes them a valuable resource as indicator species for measurement of change in the marine environment. Understanding this latter relationship is particularly important for seabirds as they can be dramatically affected by development-related activities (e.g., oil spills, fishing); understanding the population effects due to climatic change is critical to interpreting the actual effects of specific human activities or events.

Why Seabirds?

Overview of Alaskan Seabirds

Populations of seabirds in Alaska are larger and more diverse than any similar region in the Northern Hemisphere. The extensive coastal estuaries and offshore waters of Alaska provide breeding, feeding and migrating habitats for 66 species of seabirds. At least 38 species of seabirds, over 50 million individuals, breed in Alaska. Eight Alaskan species breed only here and in adjacent Siberia. Five additional species range through the North Pacific, but their populations are concentrated in Alaska. In addition to breeding grounds, Alaskan waters also provide important wintering habitat for birds that breed in Canada and Eurasia. Shearwaters, which breed in the southern hemisphere, are the most numerous species in Alaskan waters during the summer (U.S. Fish and Wildlife Service 1992).

The most abundant breeding species in Alaska are northern fulmars, storm-petrels, kittiwakes, murres, auklets and puffins. These species also form the largest colonies. Fulmars, storm-petrels and kittiwakes are surface feeders, picking their prey from the surface or just below the surface; murres, auklets, and puffins dive for their food. Fulmars nest primarily on island groups in and around the

Bering Sea. They take a wide variety of prey (e.g., fish, squid, zooplankton, jellyfish) from the surface or just below the surface. Storm-petrels are strictly nocturnal and nest below ground in either burrows or crevices between rocks. They forage on zooplankton and squid; in some areas they are dependent upon small fish such as capelin and sand lance caught at the surface. Black-legged kittiwakes are widespread throughout Alaska, Canada and Eurasia while red-legged kittiwakes are found only in the Bering Sea region. Both are surface feeders although black-legged kittiwakes feed primarily on small fish and forage over the continental shelf and shelf break; redlegged kittiwakes feed primarily on myctophids and will forage beyond the shelf break. Murres nest on cliffs around the coast of Alaska, forming large colonies. They forage over the continental shelf and will dive up to 300 feet for prey (primarily fish during the breeding season and zooplankton during the winter). Six species of auklets nest in Alaska, four of which (Least, Crested, Whiskered and Parakeet) nest only in the Bering Sea region. Least auklets are the most abundant breeding seabird in Alaska; approximately one-fifth of the State's total breeding seabirds.

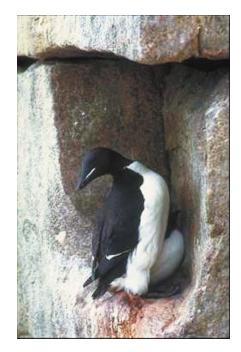


Figure 1. Nesting murre.

Auklets forage across the continental shelf; however, they are attracted to "fronts" between water masses where food is concentrated. They feed on zooplankton, usually diving to moderate depths but can dive up to 250 feet. Puffins breed throughout Alaska, where their populations are concentrated. Puffins generally forage near their breeding colonies and while their diet is broad over the course of the year, puffins depend upon fish to feed their young.

Habitat changes associated with projected shifts in climate will clearly affect seabirds through changes to their habitat—some species will be favored, others will not. Distributions will shift and relative abundances will change. For seabirds, their fate depends upon available, high quality prey and adequate nest sites. Direct mortality due to predation and storms are primary factors in shaping populations. For seabirds, habitat at sea is characterized by physical characteristics of water (e.g., temperature, salinity, turbidity, currents, nutrients and depth). Many marine organisms have fairly narrow temperature ranges that favor them, and directly or indirectly, temperature and salinity are the main physical indicators of different communities.

Intrinsic Value of Wildlife

Seabirds are an integral and quite visible part of the Bering Sea area and therefore valued simply for their existence. The Bering Sea region is generally an extreme environment and receives minimal recreational or tourism use in comparison to other coastal and marine environments. The existence of the region, however, is important and valued. Existence value relates to the appreciation and therefore value ascribed to wildlife and wilderness areas by individuals even though most would not visit the areas or directly view the wildlife (Krutilla 1967). Appreciation is gained instead through vicarious enjoyment of nature programs, books, art, and programs about unique areas (Randall 1992). The audiences to be considered in recognizing this type of value include Alaskan residents from outside the region and non-Alaskan residents (both national and international) (Thomas et al. 1992; McCollum and Bergstrom 1992).

Legal Framework

The intrinsic values of seabirds are demonstrated by specific legislation and land designations for the protection of seabirds. Early in the century, several national wildlife refuges were established primarily to protect seabird nesting habitats. These were ultimately combined into the Alaska Maritime National Wildlife Refuge, which was established as part of the Alaska National Interests Lands Conservation Act (ANILCA). The purposes of the refuge are, as outlined in Title III - National Wildlife Refuge System, Section 303 (B):

- "(i) to conserve fish and wildlife populations and habitats in their natural diversity including, but not limited to marine mammals, marine birds and other migratory birds, the marine resources upon which they rely, bears, caribou and other mammals;
- (ii) to fulfill the international treaty obligations of the United States with respect to fish and wildlife and their habitats;
- (iii) to provide, in a manner consistent with the purposes set forth in subparagraphs (i) and (ii), the opportunity for continued subsistence uses by local residents;
- (iv) to provide, in a manner consistent with subparagraphs (i) and (ii), a program of national and international scientific research on marine resources; . . ."

The intrinsic value associated with wildlife is further recognized and acknowledged in the International Treaty obligations contained in the Migratory Bird Treaty Act. The treaties speak to the protection of migratory bird populations and their habitats. A further consideration relates to the Endangered Species Act—it is easier and cheaper to manage a species to prevent it from being listed under the Act than to manage it as an Endangered Species. A recent example is the potential for closure of the long-line fishery due to mortality of the endangered short-tailed albatross.

Monitoring

Seabirds are a valuable indicator of the function and integrity of marine ecosystems (integrity being equivalent to "completeness" or "wholeness"). As marine systems shift in response to climate change, so will the numbers and composition of seabirds. Due to their dependence on different portions of the marine environment, seabirds are also a useful group of species to monitor how climate change affects marine ecosystems. Proceedings of earlier workshops on global change in Alaska sponsored by the International Arctic Science Committee have listed a number of implications of climate change on marine ecosystems (e.g., Weller and Anderson 1998). Seabirds, because they feed primarily on marine organisms, are good indicators of change in different parts of the marine food web (Montevecchi 1993) because their prey is directly affected by changes in sea temperatures, extent of sea ice, primary productivity in the ocean, and other physical and biological characteristics (e.g., Divoky 1978, Iverson et al. 1979, Cairns 1987, Murphy et al. 1991, Hamer et al. 1991, Springer 1991, Decker et al. 1995, Ohtani and Azumaya 1995, Springer et al. 1996). Furthermore, changes in sea level or increases in the frequency and intensity of storms could directly impact birds at nesting sites (Byrd and Tobish 1978) or contribute to die-offs in winter (Bailey and Davenport 1972). By monitoring parameters like reproductive success, timing of nesting events, and prey preferences of species indicative of various foraging guilds (e.g., surface feeding planktivores, diving planktivores, surface feeding piscivores, etc.), it is possible to see responses to annual changes in the marine environment. Parameters like survival rates and population trends reflect decadal-scale responses.

In addition to their utility as indicator species, it is important to understand the relationships between climate change and seabird distribution and abundance. Seabirds can be dramatically affected by other anthropogenic changes related to fishing or industrial development. Oil spills can result in dramatic impacts; over 36,000 dead birds were collected as a result of the *Exxon Valdez* spill in the

Gulf of Alaska in 1989. The effects of climate change need to be understood in order to clearly understand the effects of these other activities.

Subsistence

Subsistence, living off the land, is an important way of life for many residents in rural Alaska. The value transcends the economics associated with putting food on the table. As an elder from Fairbanks put it: "Subsistence tells us who we are and what we are worth, and without it, we would be lost." Subsistence harvest of seabirds is conducted by residents of coastal villages throughout the Bering Sea region. These villages are remote and have limited employment opportunities; consequently, many residents rely on subsistence resources. The relative use of seabirds depends in part on proximity to the resource; a study of bird hunting in Savoonga and Gambell over the course of a year found that nearly all households used birds (Wohl et al. 1995) (Table 1)

Households using seabirds

Total number of birds

Primary species

Gambell

92.8%

16,174 (estimated)

Crested Auklet, Common Murre, Pelagic Cormorant

Savoonga

100%

5,730 (estimated)

Common Murre, Pelagic Cormorant, Crested Auklet

Table 1. Subsistence Use of Birds, Savoonga and Gambell

Seabirds and their eggs, while a small portion of the overall subsistence diet, provide variety, particularly in the spring. Seabirds may also provide an important food resource in years when other resources are limited. Seabird hunting and egg gathering are activities generally done in family groups. These activities help to maintain family ties and provide cultural identity. Furthermore, the gathering activities are viewed both as food gathering and essentially as social and recreational activities (Wohl et al. 1995). The use of seabird resources extends beyond the region, as trade and barter are integral parts of the subsistence lifestyle; consequently, resources specific to certain regions or areas are used to trade for other resources that are not available locally.

Economic Values

While tourism activities directly related to seabirds may be minimal in the region, they can be important locally. Annually, many groups visit the Pribilof Islands to enjoy the spectacle of large and diverse seabird populations. This tourism is important to the local economy. In addition, the local Native corporation, in cooperation with the Fish and Wildlife Service, supports a science camp for young people to learn from their elders and others about the local environment. The camp, while being of great educational value, also provides income to the local area and important diversity to the local economy.

The Bering Sea region is a unique environment, particularly for seabirds as measured by their diversity and populations within the region. This uniqueness contributes to science and educational products and outputs—one of the last "wilderness" laboratories (McCollum and Bergstrom 1992). Use by scientists and resource managers provides distinct economic values related to the employment of people who study and manage seabirds and all the related goods and services they need. Factors that need to be considered in evaluating the economic value of this aspect include the logistics required by

scientists to pursue onsite studies, and then support for data analyses and report preparations back at their respective home bases. Resource managers are supported for a variety of activities from scientific studies to public education and outreach (Hoehn 1992).

Available Information

Distribution and Relative Abundance at Breeding Colonies

Two programs largely were responsible for initial inventories of seabird breeding colonies in Alaska: 1) the Outer Continental Shelf Environmental Assessment Program (OCSEAP), which was associated with offshore oil leasing in Alaska beginning in the mid-1970s, and 2) surveys associated with Wilderness Area designation in the Aleutian Islands National Wildlife Refuge in the early 1970s (Sekora et al. 1979). Results of these descriptive surveys were used to publish "Catalog of Alaskan Seabird Colonies" (Sowls et al. 1978), which mapped the distribution of seabird breeding colonies, provided a list of breeding species, and included approximate counts of individuals present. Since the objective for these surveys was to delineate important seabird concentrations, initial inventories were crude for most colonies, providing data useful for determining relative abundance of species but adequate for measuring only very large population changes in the future. The U.S. Fish and Wildlife Service's Division of Migratory Bird Management in Anchorage developed, and has maintained, a computer data base on seabird breeding colonies which is updated as new information is received. An updated version of the 1978 catalog was produced in 1996 (Mendenhall and Stephensen 1996), and the database has been expanded to include colony surveys on the Russian side of the Bering Sea.

Breeding Ecology

Also as part of the OCSEAP program, studies of breeding ecology of common species of seabirds at selected colonies were undertaken. Study sites were scattered along most of Alaska's coastline to cover all the potential oil leasing areas. Some of these studies continued for several years and information was gathered on timing of nesting events, reproductive success, and prey preferences. Furthermore, research was conducted on sources of variability involved in monitoring population trends. The data gathered during these and subsequent studies provided the basis for a seabird monitoring program designed to document patterns of change.

Distribution at Sea

Opportunistic and directed transect surveys of potential marine oil lease sites and other areas were conducted using standard methods during the OCSEAP studies, and these data were entered into a "Pelagic Seabird Database" maintained by the U.S. Fish and Wildlife Service. Over the past two decades, additional survey information has accumulated, but the database has not been completely updated. Currently there is a need for funding to enter data and to make the database more user-friendly.

Monitoring

As indicated above, baseline data on breeding seabirds began to accumulate in the mid-1970s due to OCSEAP studies and continuing work sponsored primarily by the Minerals Management Service and the U.S. Fish and Wildlife Service. After the Alaska National Interests Lands Conservation Act of 1980 established the Alaska Maritime National Wildlife Refuge, with a purpose of conserving marine bird populations, a more formal monitoring program began.

The stated objectives of the existing monitoring program are to provide long-term, time-series data from which: 1) biologically significant changes may be detected, and 2) hypotheses about cause of

changes may be tested. Since it was impractical to monitor every breeding parameter for every species at every site annually, choices had to be made about the most appropriate approach. The idea was to detect signals of change in the marine ecosystem using seabirds as indicators. From the standpoint of conservation of seabirds, changes in population levels are of paramount interest, but populations of these long-lived birds would more likely respond to changes of a decadal rather than annual time scale. Reproductive success, timing of nesting events, prey preferences, and adult survival rates were deemed to be more sensitive to annual changes in the environment.

Different species of seabirds use different portions of the marine food web, so the group of species selected for monitoring included both piscivores and planktivores. Within these groups, species were included that are able to forage in the water column (down to 100 m) along with species that are restricted to feeding on the surface of the sea. In addition, both inshore and offshore feeders were included. This mixture of species provides a basis for evaluating the extent of impacts of perturbations in the marine ecosystem.

The geographic coverage of the monitoring system is statewide, but the density of sites is low. A total of 12 sites have been designated for annual monitoring by the U.S. Fish and Wildlife Service (Alaska Seabird Inventory and Monitoring Plan, U.S. Fish and Wildlife Service, Anchorage). Besides the annual sites, data are being gathered opportunistically at other sites visited less frequently. Supplementary information is also provided through research projects like those funded by the *Exxon Valdez* Oil Spill Trustee Council and monitoring sponsored by the Minerals Management Service.

Most of the data being gathered annually are being entered into the "Pacific Seabird Monitoring Database," a project coordinated by the Pacific Seabird Group and initially funded by the U.S. Geological Survey, Biological Resources Division. Furthermore, annual reports of monitoring results are being distributed by the U.S. Fish and Wildlife Service (e.g., Byrd and Dragoo 1997, Byrd et al. 1998).

Relationship to Environment

Colony Locations/Breeding Habitat

Collectively seabirds use a wide range of coastal habitats for nesting, but common characteristics of all nesting habitats are safety from mammalian predators and availability of marine prey near nesting colonies. Colonies are distributed along the entire coastline of Alaska. Most seabirds nest on offshore islands or mainland coastal cliffs, with some species nesting on the ground, some nesting in earthen burrows, others nesting in rock crevices, and some species using cliff ledges. The availability of habitat in spring following snow melt is a factor that can affect timing of nesting events and ultimately reproductive success at more northerly colonies (Sealy 1975). Abnormally high rainfall can affect survival of chicks in earthen burrows, and incidence of big storms with high winds during the chick-rearing period can cause mortality for chicks of species nesting on cliff-ledges (Byrd and Tobish 1978).

At-sea Distribution in Summer

Most species of seabirds nesting in Alaska feed within 50 km of breeding colonies. The practical distance for foraging is limited by the time it takes to capture and transport food to chicks frequently enough for adequate growth. The relative abundance and distribution (in time and space) of prey is affected by ocean dynamics including climate and physical factors (e.g., Piatt and Anderson 1996). Changes in the availability of prey can cause reproductive failures (Ainley et al. 1996).

Feeding Guilds

Ashmole (1971) described foraging strategies used by different groups of seabirds. Since species exploit identifiable parts of the food web, seabirds as a group offer opportunities to compare responses of different portions of the marine ecosystem to perturbations like climate change. For example, species that feed on organisms at the surface of the sea may be more sensitive to changes in distribution of prey than those that are able to pursue prey deep into the water column. Furthermore, species that feed on plankton may respond differently than forage-fish feeders to change in the marine environment.

Wintering Habitat

Relatively little is known about the winter ecology of seabirds nesting in Alaska. Few surveys have been made at sea during the winter, and it is virtually unknown where seabirds from any particular breeding colony winter. Nevertheless, it is known that some species (e.g., murres) remain as far north as there is open water in winter, and concentrations of several species of seabirds are associated with the sea ice edge. Clearly, the extent and duration of ice cover has a major impact on the amount of winter habitat available in the Arctic Ocean and Bering Sea.

Potential Effects of Climate Change—Case Studies

Long-term Changes in the Gulf of Alaska Marine Ecosystem on Marine Birds and Mammals

Abrupt changes in marine fish communities in the northern Gulf of Alaska are reflected in the diets and population biology of many marine birds and mammals. Capelin were the dominant prey of seabirds in the late 1970s, but were absent or much reduced in seabird diets in the late 1980s and early 1990s. Capelin were replaced by sandlance (*Ammodytes hexapterus*) and pollock. Likewise, diets of northern fur seals (*Callorhinus ursinus*), Steller sea lions (*Eumetopias jubatus*) and harbor seals (*Phoca vitulina*) collected in the 1970s were rich in fatty forage fish such as capelin and herring (Pitcher 1980, 1981; Castellini 1993). These prey were rare in stomachs of fur seals and Steller sea lions collected in the 1980s (Alverson 1992; Castellini 1993; R. Merrick, pers. comm.).

Coupled with these changes in diet, and probably because of them (Castellini 1993, Springer 1993), there have been marked changes in the population ecology of several marine bird and mammal species in the Gulf of Alaska. For example, breeding success of black-legged kittiwakes (*Rissa tridactyla*) at colonies in the Gulf of Alaska declined dramatically through the 1980s (Hatch and Piatt *in press*). Kittiwake populations have declined (ca. 50%) at Middleton Island since about 1980. Common murre populations have declined by up to 90% at many colonies both inside and outside the *Exxon Valdez* oil spill zone and were declining at some affected colonies before the spill occurred. Prince William Sound boat surveys conducted in 1989–1991 suggest that there have been major declines (50–95%) in populations of 15 different coastal and marine bird species since surveys conducted in 1972–1973 (Klosiewski and Laing 1994). Species that have declined significantly include cormorants (-95%), Larus gulls (-69%), kittiwakes (-57%), pigeon guillemots (*Cepphus columba*, -75%), marbled and Kittlitz's murrelets (*Brachyramphus* spp., -68%), and horned puffins (*Fratercula corniculata*, -65%). Similarly, analysis of Christmas Bird Count data suggests that marbled murrelet populations throughout the Gulf of Alaska have declined by over 50% since the early 1970s (Piatt and Naslund 1995).

As another indication that food has been limiting in recent years, several large-scale die-offs of seabirds, mostly surface-feeding species, have been observed in the Gulf of Alaska during the last decade, most notably in 1983, 1989, and 1993 (Nysewander and Trapp 1984; Hatch 1987; Piatt 1990; USFWS unpubl. data). In March of 1993, an estimated 100,000 common murres died throughout an

area spanning southeast Alaska to the Alaska Peninsula. Starvation was determined to be the proximate cause of death. In contrast, there were no reported die-offs in the 1970s since Bailey and Davenport's (1972) report of a massive murre die-off along the Bering Sea side of the Alaska Peninsula in 1970.

Marine mammals have exhibited similar signs of food stress in recent years. Harbor seals at Tugidak Island in the Gulf of Alaska declined by about 85% between 1976 and 1988 (Pitcher 1990). Steller sea lion populations declined by 36% in the Gulf of Alaska between 1977 and 1985 (Merrick et al. 1987), and by another 59% between 1985 and 1990 (Castellini 1993). Northern fur seals declined about 35% by 1986 from their average numbers in the 1970s, although numbers had rebounded somewhat (20%) by 1990 (Castellini 1993). Associated with the declines in Steller sea lions are declines in birth rate, fewer breeding females, fewer pups, decreased adult body condition, decreased juvenile survival, and a change in population age structure (Merrick et al. 1987; Loughlin et al. 1992). Declines in marine mammal populations may be due in part to harvest, incidental catch in fishing gear, and disease, but the consensus among researchers is that changing food availability (lower quality or biomass) is the most likely cause of recent declines (Castellini 1993).

Conclusions. A variety of independent data point to an abrupt shift in the marine ecosystem of the Gulf of Alaska during the past 20 years. This shift has been manifested by marked changes in the composition of marine fish communities, reduced forage fish biomass, and dramatic changes in the population ecology of higher vertebrates that depend on those fish populations. Unlike short-term phenomena such as the El Niño, which may disrupt marine food-webs and diminish seabird productivity for 1- to 2-year periods (Ainley and Boekelheide 1990), this shift represents a more pervasive and persistent change in the ecosystem.

It appears that a "change of state" was initiated in 1976, when atmospheric circulation in the North Pacific shifted, and remained that way until the late 1980s (Trenberth 1990; Kerr 1992). Effects of this climate shift were evident in a host of environmental variables measured throughout the eastern North Pacific between 1968 and 1984 (Kerr 1992). It may have taken 3–5 years for this change of state to be manifested by changes in water temperatures, fish populations and seabird demography in Alaska. Atmospheric and ocean climate conditions may now be returning to those observed prior to 1976 (Royer 1993; Trenberth 1990).

Although they do not appear to be synchronized with events in the Gulf of Alaska, similar temporal relationships between water temperatures, fish stocks, seabirds and marine mammals have been observed in the Bering Sea (Alverson 1992; Springer 1992; Decker et al. 1995). Productivity of seabirds nesting on the Pribilof Islands started declining in about 1978, as water temperatures rose above average and an unusually large year-class of pollock appeared. Seabird productivity remained low through the 1980s, while pollock stocks increased dramatically. Diet composition of murres and kittiwakes changed significantly, and indicator species such as capelin and hyperiid amphipods largely disappeared from diets in the 1980s (Decker et al. 1994). By the late 1980s, seabird productivity was increasing again as pollock stocks declined. As in the Gulf of Alaska (above), a strong negative relationship between pollock biomass and kittiwake production may be an indication that predators compete for forage fish and that food-webs are regulated by "top-down" interactions (Springer 1992). Alternatively, forage fish, pollock, kittiwakes and other predators may all be responding in their own fashion to changing oceanographic conditions and primary production ("bottom-up" control; Springer 1992).

Whatever the mechanism, natural long-term cycles in marine productivity may account for much of the variation observed in seabird population parameters. For example, Aebischer et al. (1990) demonstrated a remarkable similarity between long-term (33-year) trends in wind patterns, the abundance of phytoplankton, zooplankton, and herring (*Clupea harengus*), and kittiwake clutch size, phenology,

and chick production in the North Sea. All these measures of biological production declined from about 1955 to the late 1970s, and have been increasing since that time.

Black Guillemots in Arctic Alaska

The anticipated changes in air temperature associated with global climate change will have the most immediate effects on the distribution and biology of arctic seabirds. The response of snow and ice cover to elevated temperatures from global change will be immediate and pronounced. While snow and ice influence the life histories of most subarctic and many temperate birds, their influence on arctic species is most pronounced. Arctic seabirds have evolved a range of life history characteristics in response to the temporal and spatial patterns of snow and ice cover in the region. Seabird species most dependent on, or constrained by, the presence or amount of ice and snow would be expected to be among the first affected by warming.

There is increasing evidence of ongoing climate warming in the Arctic in general (Overpeck et al. 1997; Cavalieri et al. 1997) and northern Alaska in particular (e.g., Foster 1989; Foster et al. 1991; Sharratt 1992). While the consequences of the predicted warming on arctic species have been the subject of much speculation (Brown 1991; Peters and Lovejoy 1992), little has been done to monitor or document recent or ongoing effects (Jarvinen 1995). One of the few examples of contemporary climate change on Alaskan arctic seabirds is demonstrated by the distribution and abundance of the black guillemot (*Cepphus grylle*) in northern Alaska. The black guillemot is a circumpolar arctic seabird typically associated with snow and sea ice habitats for the entire year. In the western Arctic this species breeds north of the Bering Strait in coastal locations (Sowls et al. 1978), which are typically snow-covered for approximately nine months each year (Brower et al. 1977). They nest in cavities and require a minimum of 80 days from first occupation of the cavity to chick fledging, an atypically long period for an arctic nesting species. Successful reproduction in the Arctic is dependent on early occupation of a nest site shortly after cavities become snow-free, and on fledging chicks before snow again accumulates in late summer or early autumn.

Studies at a northern Alaska black guillemot colony over the last two decades (Divoky 1998) show that black guillemot breeding chronology and success are sensitive to snow melt and accumulation. Ovulation by females occurs only after they can occupy a nesting cavity. Initial occupation of the colony in the spring and breeding initiation are dependent on the timing of snowmelt. During the study period, black guillemot breeding chronology, as measured by dates of colony occupation and clutch initiation, was correlated with snowmelt at the colony and advanced 4.5 days per decade in response to climate amelioration. Snow accumulation in late summer and early fall had the potential of decreasing breeding success. In 1988, when the period between spring snowmelt and fall snow accumulation was <80 days, chicks were trapped in nesting cavities, reducing fledging success and post-fledging survival.

While black guillemots were commonly recorded at Point Barrow since the late 1800s (Bailey 1948), the first breeding record was obtained in 1966 (Maclean and Verbeek 1968). Prior to that time, snow conditions may have prevented successful breeding. Examination of historic weather records dating back to the 1940s indicates that the snow-free period in arctic Alaska has regularly exceeded 80 days only since the mid-1960s. The observed warming temperatures at Barrow are part of a long-term warming trend that began in the region early this century after approximately three centuries of cooler summer temperatures (Overpeck et al. 1997). The recent establishment and growth of black guillemot colonies in northern Alaska may be the result of the century-long warming trend in the region.

Other bird species may be responding to the increased snow-free summer period in arctic Alaska. Horned puffins (*Fratercula corniculata*), a subarctic species whose breeding range extends as far north as the central Chukchi Sea, have prospected potential breeding sites in the Barrow area since at

least 1972 (Divoky 1982 and unpubl.), and the first breeding record occurred in 1986 when a pair bred successfully in a nest box on Cooper Island (Divoky unpubl.). Horned puffins have a longer nesting period than the black guillemot, requiring about 90 days from the onset of egg formation to chick fledging. Snow-free periods <90 days occurred regularly until the 1980s, and like that of the black guillemot, the first record of a horned puffin nesting in arctic Alaska may have been related to the increasing snow-free period.

Warming temperatures have allowed guillemots to breed in the Barrow area, but continued warming may be creating conditions unfavorable for the persistence of a regional population. The reliance on the pack ice as a foraging habitat through most of the year makes black guillemots sensitive to changes in the extent and nature of pack ice. In northern Alaska annual variation in guillemot breeding success is inversely correlated with the distance of the pack ice from the shore in August due to the abundance of arctic cod (*Boreogadus saida*) at the ice edge and a lack of alternative prey in ice-free nearshore waters (Divoky unpubl.). In the eastern Canadian Arctic, changes in breeding distributions and abundance of black guillemots are associated with annual variation in distribution of sea ice (Prach and Smith 1992). If temperature increases in the arctic are as high as predicted, the Beaufort Sea pack ice may regularly retreat >100 km from mainland Alaska (McGillivray et al. 1993), far greater than the foraging range of guillemots (typically <15 km).

While anticipated changes in the Beaufort Sea would affect the productivity of the Cooper Island colony, recent reductions in sea ice extent may already be contributing to the colony's decline. From 1989 to 1997 the colony decreased from 225 to 110 pairs, primarily due to decreases in immigration and annual survival of adults. Both decreases may be due to alterations in sea ice cover resulting in decreased prey abundance or availability. Winter sea ice has been decreasing throughout the Arctic over the past 20 years (Johannessen et al. 1995), and summer sea ice extent decreased 9% in 1990–1995 compared with the previous ten years. Some of the greatest reductions in summer ice extent have been in the eastern Siberian Sea (Maslanik et al. 1996). Guillemot colonies from that location may be in the same metapopulation as the northern Alaskan colonies (Divoky 1998).

Future Research

Besides identifying trends, time series data on seabirds can be used to test hypotheses about effects of climate change. The wildlife group at the workshop developed, as examples, some predictions that could be tested given various responses of the marine environment to climate change, particularly warming. The group decided that less emphasis needs to be placed on economics; while there are modeling techniques available to determine estimated dollar values of seabirds, the importance of seabirds relates to their utility for monitoring. The following topics describe how seabirds may be affected by changes in climatically driven variables. From these relationships, specific hypotheses for testing can be developed.

Extent of Sea Ice. If warming continues, the extent of sea ice will continue to decline. Some species of seabirds may benefit (increased productivity, range extensions) by being able to feed in open water near nesting areas earlier in spring and fledge young before fall freeze-up. Nevertheless, reduced sea ice may adversely affect species dependent on feeding at the ice edge. More open water could increase severity of rough seas, potentially causing increased winter mortality of birds at sea.

Surface Sea Temperature. If sea temperatures change substantially, the distribution of seabird prey will shift. For some species and sites, the shift may be beneficial (e.g., species that feed on prey that local conditions now favor), but for others it could be detrimental (e.g., surface feeders whose prey has been driven too deep for them to access). Initially, productivity of seabirds would be affected and ultimately population change would occur.

Spring Snow Melt. If warming continues, snow melt in spring will make nesting sites available earlier. This could be beneficial for some species at locations where productivity, particularly survival of young, has been reduced due to the shortness of the available nesting period. In contrast, it is possible that enhanced vegetation growth during extended growing seasons could cover crevices used by auklets.

Air Temperature. If average spring air temperatures continue to increase, coastal permafrost could thaw, potentially making new areas available to burrow-nesting seabirds.

Storm Intensity. If warming causes increased storminess (duration and/or frequency), mortality of seabird chicks at nest sites could occur and adult mortality in winter might also result due to rough seas interfering with feeding and dispersing prey.

Precipitation. If warming causes increased precipitation in summer, burrow nesting seabirds may experience increased chick mortality from flooding.

Sea Level. If warming causes significant increases in sea level, low-lying nest sites on barrier islands and nearshore scree nesters might be lost.

Literature Cited

- Aebischer, N.J., J.C. Coulson, and J.M. Colebrook. 1990. Parallel long-term trends across four marine trophic levels and weather. *Nature* 347:753–755.
- Ainley, D.G., and R.J. Boekelheide, editors. 1990. *Seabirds of the Farallon Islands, Ecology and Dynamics of an Upwelling-system Community*. Stanford Univ. Press, Stanford, California.
- Ainley, D.G., W.J. Sydeman, and J. Norton. 1996. Apex predators indicate interannual negative and positive anomalies in the California Current food web. *Marine Ecology Progress Series* 137:1–10.
- Alverson, D.L. 1992. A review of commercial fisheries and the Steller sea lion (*Eumetopias jubatus*): The conflict arena. *Reviews in Aquatic Sciences* 6:203–256.
- Ashmole, N.P. 1971. Sea bird ecology and the marine environment. Chapter 6. In *Avian Biology Vol. 1*. D.S. Farner and J.R. King, eds. Academic Press Inc., New York.
- Bailey, A.M. 1948. *Birds of Arctic Alaska*. Popular Series 8, Colorado Museum of Natural History, Denver, Colorado.
- Bailey, E.P., and G.H. Davenport. 1972. Die-off of common murres on the Alaska Peninsula and Unimak Island. *Condor* 74:215–219.
- Brower, W.A.J., H.W. Searby, J.L. Wise, H.F. Diaz, and A.S. Prechtel. 1977. *Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska*. National Oceanic and Atmospheric Administration, Asheville, North Carolina.
- Brown, R.G.B. 1991. Marine birds and climatic warming in the northwest Atlantic. In *Studies of High-Latitude Seabirds*. *1. Behavioural, Energetic and Oceanographic Aspects of Seabird Feeding Ecology*. Occasional Paper No. 68 Edition. Canadian Wildlife Service, Ottawa, pp. 49–54.
- Byrd, G.V., and D.E. Dragoo. 1997. *Breeding Success and Population Trends of Selected Seabirds in Alaska in 1996*. U.S. Fish and Wildlife Service Report AMNWR 97/11. 44 pp.
- Byrd, G.V., and T.G. Tobish. 1978. Wind-caused mortality in a kittiwake colony at Buldir Island, Alaska. *Murrelet* 59:37.
- Byrd, G.V., D.E. Dragoo, and D.B. Irons. 1998. *Breeding Status and Population Trends of Seabirds in Alaska in 1997*. U.S. Fish and Wildlife Service Report AMNWR 98/02. 59 pp.

- Cairns, D.K. 1987. Seabirds as indicators of marine food supplies. *Biological Oceanography* 5:261–271.
- Castellini, M. 1993. Report of the marine mammal working group. In *Is it Food?: Addressing Marine Mammal and Seabird Declines: Workshop Summary*. Alaska Sea Grant Report 93-01, University of Alaska Fairbanks, pp. 4–13.
- Cavalieri, D.J., P. Gloersen, C.L. Parkinson, J.C. Comiso, and H.J. Zwally. 1997. Observed hemispheric asymmetry in global sea ice changes. *Science* 278:1104–1106.
- Decker, M.B., G.L. Hunt Jr., and G.V. Byrd Jr. 1995. The relationships among sea-surface temperature, the abundance of juvenile walleye pollock (*Theragra chalcogramma*) and the reproductive performance and diets of seabirds at the Pribilof Islands, southeastern Bering Sea. In *Climate Change and Northern Fish Populations*. R.J. Beamish, ed. Canadian Spec. Publ. of Fish. and Aquatic Sci. 121:425–437.
- Divoky, G.J. 1978. The distribution, abundance, and feeding ecology of birds associated with the pack ice. In *Environmental Assessment of the Alaskan Continental Shelf*. Final Report of Princ. Invest. 2. BLM/NOAA/OCSEAP, NOAA, Anchorage, Alaska, pp. 167–509.
- Divoky, G.J. 1982. The occurrence and behavior of non-breeding Horned Puffins at Black Guillemot colonies in northern Alaska. *Wilson Bulletin* 94:356–358.
- Divoky, G.J. 1998. Factors Affecting the Breeding of the Black Guillemot in Arctic Alaska. Ph.D. dissertation. University of Alaska Fairbanks. 144 pp.
- Foster, J.L. 1989. The significance of the date of snow disappearance on the Arctic tundra as a possible indicator of climate change. *Arctic and Alpine Research* 21:60–70.
- Foster, J.L., J.W. Winchester, and E.G. Dutton. 1991. The date of snow disappearance on the arctic tundra as determined from satellite, meteorological station and radiometric in-situ observations. IEEE 1955–1958.
- Hamer, K.C., R.W. Furness, and R.W.G. Caldow. 1991. The effects of changes in food availability on the breeding ecology of great skuas, *Catharacta skua*, in Shetland. *Journal of Zoology* 223:175–188
- Hatch, S.A., and J.F. Piatt. In press. *Status and Trends of Seabirds in Alaska*. National Biological Survey, Report on Status and Trends of the Nation's Wildlife, Washington, D.C.
- Hoehn, J.P. 1992. The production of natural resource services: an analysis of supply side economic benefits and costs. In *Valuing Wildlife Resources in Alaska*. G. Peterson, C.S. Swanson, D.W. McCollum, and M.H. Thomas, eds. Westview Press, Boulder, Colorado. 357 pp.
- Iverson, R.L., L.K. Coachman, R.T. Cooney, R.S. English, J.J. Goering, G.L. Hunt, Jr., M.C. Macauley, C.P. McRoy, W.S. Reeburgh, and T.E. Whitledge. 1979. Ecological significance of fronts in the southeastern Bering Sea. In *Ecological Processes in Coastal and Marine Systems*, R.J. Livingston, ed. Plenum Press, New York, pp. 437–466.
- Jarvinen, A. 1995. Global warming and egg size of birds. *Ecography* 17:108–110.
- Johannessen, O.M., M.W. Miles, and E. Bjorgo. 1995. The Arctic's shrinking sea ice. *Nature* 376:126–127.
- Kerr, R.A. 1992. Unmasking a shifty climate system. Science 255:1508–1510.
- Klosiewski, S.P., and K.K. Laing. 1994. *Marine Bird Populations of Prince William Sound, Alaska, Before and After the Exxon Valdez Oil Spill*. Natural Resource Damage Assessment Bird Study No. 2., Final Report, U.S. Fish and Wildlife Service, Anchorage, Alaska.
- Krutilla, J.V. 1967. Conservation reconsidered. American Economic Review 57:777–786.
- MacLean, S.F., Jr., and N.A.M. Verbeek. 1968. Nesting of the Black Guillemot at Point Barrow. *Auk* 85:139–140.

- Maslanik, J.A., M.C. Serreze, and R.G. Barry. 1996. Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. *Geophysical Research Letters* 23:1677–1680.
- McCollum, D.W., and J.C. Bergstrom. 1992. Measuring net economic value and regional economic impact. In *Valuing Wildlife Resources in Alaska*. G. Peterson, C.S. Swanson, D.W. McCollum and M.H. Thomas, eds. Westview Press, Boulder, Colorado. 357 pp.
- McGillivray, D.G., T.A. Agnew, G.A. McKay, G.R. Pilkington, and M.C. Hill. 1993. *Impacts of Climatic Change on the Beaufort Sea-Ice Regime*. Environment Canada CCD 93-01.
- Mendenhall, V., and S. Stephenson. 1996. *Catalog of Alaskan Seabird Colonies, Updated*. Unpublished report, Migratory Bird Management, U.S. Fish and Wildlife Service, Anchorage, Alaska.
- Merrick, R.L., T.R. Loughlin, and D.G. Calkins. 1987. Decline in abundance of the northern sea lion, *Eumetopias jubatus*, in Alaska, 1956–86. *Fishery Bulletin* 85:351–365.
- Montevecchi, W.A. 1993. Birds as indicators of change in marine prey stocks. In *Birds as Monitors of Environmental Change*. R.W. Furness and J.J.D. Greenwood, eds. Chapman and Hall, London, pp. 217–266.
- Murphy, E.C., A.M. Springer, and D.G. Roseneau. 1991. High annual variability in reproductive success of kittiwakes (*Rissa tridactyla* L.) at a colony in western Alaska. *Journal of Animal Ecology* 60:515–534.
- Nysewander, D.R., and J.L. Trapp. 1984. *Widespread Mortality of Adult Seabirds in Alaska, August–September 1983*. Unpublished Report, U.S. Fish and Wildlife Service, Anchorage, Alaska.
- Ohtani, K., and T. Azumaya. 1995. Influence of interannual changes in ocean conditions on the abundance of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea. In *Climate Change and Northern Fish Populations*. R.J. Beamish, ed. Canadian Spec. Publ. of Fish. and Aquatic Sci. 121:87–95.
- Overpeck, J., K. Hughen, D. Hardy, R. Bradley, R. Case, M. Douglas, B. Finney, K. Gajewski, G. Jacoby, A. Jennings, S. Lamoureux, A. Lasca, G. MacDonald, J. Moore, M. Retelle, S. Smith, A. Wolfe, and G. Zielinski. 1997. Arctic environmental change of the last four centuries. *Science* 278:1251–1256.
- Peters, R.L., and T.E. Lovejoy, editors. 1992. *Global Warming and Biological Diversity*. Yale University Press, New Haven, Connecticut.
- Piatt, J.F. 1990. Aggregative response of Common Murres and Atlantic Puffins to their prey. *Studies in Avian Biology* 14:36–51.
- Piatt, J.F., and P.J. Anderson. 1996. Response of common murres to the Exxon Valdez oil spill and long-term changes in the Gulf of Alaska marine ecosystem. In *Exxon Valdez Oil Spill Symposium Proceedings*. S.D. Rice, R.B. Spies, D.A. Wolfe, and B.A. Wright, eds. American Fisheries Society Symposium No. 18.
- Piatt, J.F., and N.L. Naslund. 1995. Abundance, distribution and population status of Marbled Murrelets in Alaska. In *Conservation Assessment for the Marbled Murrelet*. C.J. Ralph, G.L. Hunt, Jr., M.G. Raphael, and J.F. Piatt, eds. General Technical Report PSW-GTR-152. USDA, Forest Service, Pacific Northwest Forest and Range Experiment Station, Albany, California, pp. 285–294.
- Pitcher, K.W. 1980. Food of the harbor seal, *Phoca vitulina* richardsi, in the Gulf of Alaska. *Fishery Bulletin* 78:544–549.
- Pitcher, K.W. 1981. Prey of the Steller sea lion, *Eumetopias jubatus*, in the Gulf of Alaska. *Fishery Bulletin* 79:467–472.
- Pitcher, K.W. 1990. Major decline in number of harbor seals, *Phoca vitulina* richardsi, on Tugidak Island, Gulf of Alaska. *Marine Mammal Science* 6:121–134.

- Prach, R.W., and A.R. Smith. 1992. Breeding distribution and numbers of Black Guillemots in Jones Sound, N.W.T. *Arctic* 45:111–114.
- Randall, A. 1992. A total value framework for benefit estimation. In *Valuing Wildlife Resources in Alaska*. G. Peterson, C.S. Swanson, D.W. McCollum, and M.H. Thomas, eds. Westview Press, Boulder, Colorado. 357 pp.
- Royer, T.C. 1993. High-latitude oceanic variability associated with the 18.6-year nodal tide. *Journal of Geophysical Research* 98:4639–4644.
- Sealy, S.G. 1975. Influence of snow on egg-laying in auklets. *Auk* 92:528–538.
- Sekora, P.C., G.V. Byrd, and D.D. Gibson. 1979. Breeding distribution and status of marine birds in the Aleutian Islands, Alaska. In *Conservation of Marine Birds of Northern North America*. J.C. Bartonek and D.N. Nettleship, eds. U.S. Fish and Wildlife Service Wildl. Res. Rep. #11. Washington, D.C., pp. 33–46.
- Sharratt, B.S. 1992. Growing season trends in the Alaskan Climate Record. Arctic 45:124–127.
- Sowls, A.L., S.A. Hatch, and C.J. Lensink. 1978. *Catalog of Alaskan Seabird Colonies*. FWS/OBS-78/78. U.S. Fish and Wildlife Service, Biol. Serv. Program, Anchorage, Alaska. 32 pp. plus atlas.
- Springer, A.M. 1991. Seabird relationships to food webs and the environment: examples from the North Pacific Ocean. In *Studies in High-Latitude Seabirds*. 1. Behavior, Energetic, and Oceanographic Aspects of Seabird Feeding Ecology. W.A. Montevecchi and A.J. Gaston, eds. Canadian Wildlife Service, Ottawa, pp. 39–48.
- Springer, A.M. 1992. A review: Walleye pollock in the North Pacific—how much difference do they really make? *Fisheries Oceanography* 1:80–96.
- Springer, A.M. 1993. Report of the seabird working group. In *Is it Food?: Addressing Marine Mammal and Seabird Declines: Workshop Summary*. Alaska Sea Grant Report 93-01, University of Alaska Fairbanks, pp. 14–29.
- Springer, A.M., J.F. Piatt, and G. Van Vliet. 1996. Seabirds as proxies of marine habitats in the western Aleutian Arc. *Fisheries Oceanography* 5:45–55.
- Thomas, M.H., S.M. Miller, and W.L. Pamplin. 1992. An agency review and perspective on the importance of economic information in wildlife management. In *Valuing Wildlife Resources in Alaska*. G. Peterson, C.S. Swanson, D.W. McCollum, and M.H. Thomas, eds. Westview Press, Boulder, Colorado. 357 pp.
- Trenberth, K.E. 1990. Recent observed interdecadal climate changes in the northern hemisphere. *Bulletin of the American Meteorological Society* 71:988.
- U.S. Fish and Wildlife Service. 1992. *Alaska Seabird Management Plan*. Unpublished report, U.S. Fish and Wildlife Service, Anchorage, Alaska. 102 pp.
- Weller, G., and P.A. Anderson, editors. 1998. *Implications of Global Change in Alaska and the Bering Sea Region*. Proceedings of a workshop held at the University of Alaska Fairbanks, June 1997. Center for Global Change and Arctic System Research, University of Alaska Fairbanks, Fairbanks, Alaska. 157 pp.
- Wohl, K.D., T.L. Nelson, and C. Wentworth. 1995. *Subsistence Harvest of Seabirds in Alaska*. Unpublished report, U.S. Fish and Wildlife Service, Anchorage, Alaska. 21 pp.

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