C

CLIMATE CHANGE

Sue E. Moore

Global climate change is shifting the state of the world's oceans toward a future of increased acidity, warmer seas and higher sea levels, reduced sea ice, and regionally variable shifts in productiv-ity and marine biodiversity. Projections of ocean productivity sug-gest increases in subpolar and polar seas, as solar insolation initiates phytoplankton blooms earlier and over greater areas of open water, concomitant with sea ice thinning and loss. Decreases in ocean pro-ductivity are projected for temperate and tropical waters, driven chiefly by warming and stratification, which blocks nutrients nec-essary for phytoplankton growth. The impacts of these changes on marine mammals will be mainly indirect, mediated through alteration of physical habitat and predator–prey dynamics. As top predators, marine mammals function as sentinels of ecosystem var-iability due to climate change (Fig. 1), through changes in habitat use (extrinsic responses) and body condition (intrinsic responses). The concept of ecological scale, described as the interface between population biology and ecosystem science (Levin, 1992), is used here to interpret how climate change may affect various marine mammal species. Because many species of marine mammals migrate

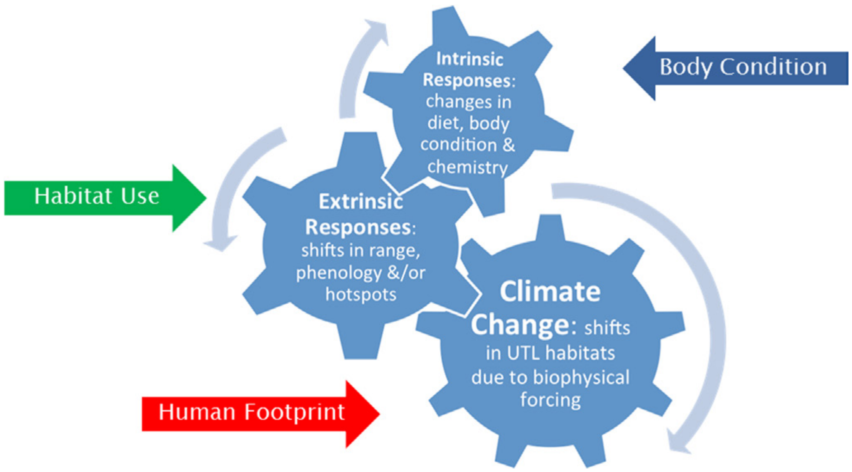

Figure 1 *As upper-trophic level (UTL) predators, marine mammals can act as sentinels to ecosystem alterations caused by climate change through shifts in habitat use (extrinsic responses) and body condition (intrinsic responses). Modified from Moore et al. (2014).*

between feeding and breeding areas, the concept of phenology, defined as the relationship between climate and periodic biological phenomena, is also invoked (Root et al., 2003). Finally, potential synergies between climate change and physiology are considered, including the rate and extent of marine mammal exposure to disease and toxins (Gulland and Hall, 2007).

I. Ecological Scale

The effects of climate change on a given species will vary with its ecological scale. Ecological scale is determined by intrinsic life-history characteristics and, for marine mammals, can extend from years to centuries in time and from tens to thousands of kilometers in space (Fig. 2). While individuals of some species roam across ocean basins for decades to centuries, others live within small freshwater, estuarine, or coastal home ranges. This breadth of scale can confound attempts to describe and predict the effects of climate change on marine mammals as a group. A basic tenet of ecology is that community structure is influenced by (1) disturbance events that physically alter habitats and (2) competition among species for resources in those altered habitats. On the temporal scale, it is likely that marine mammals can adapt to disturbance introduced by climate change, given that most extant species have evolved over roughly the past 10 million years. However, species that rely on resources available in specific regional habitats may not be able to adapt as rapidly as those environments are being altered. While description of the actual evolutionary steps that led to existing marine mammal fauna is outside the bounds of scientific measurement, impacts on marine mammals of anticipated warming over the next 50–100 years can be addressed with an eye toward the effects of disturbance anticipated across latitudinal zones.

A. Marine Mammals in Polar Regions

In Polar Regions, sea ice losses and glacial disintegration are the clearest signals of disturbance to the marine environment attributable to climate change. In the Arctic, areal extent of sea ice has been reduced by 50%, concomitant with a 75% loss of multiyear ice (Wood et al., 2015). If sea ice losses continue, or increase due to the absorption of heat by larger expanses of dark seawater (the albedo effect), the Arctic Ocean will be ice-free in September by about 2040. Of note, the rate of seasonal sea ice loss measured to date varies among Arctic subregions and most models predict retention of sea ice during winter. The effects of the loss of seasonal sea ice on marine mammals will depend on the degree to which a species uses ice for basic life functions (Moore and Huntington, 2008). The loss of sea ice will be most detrimental to those species that rely on ice as a platform for hunting and birthing, such as the polar bear (*Ursus maritimus*), the walrus (*Odobenus rosmarus*), and several seal species (Fig. 3). Sea ice losses will precipitate complex and cascading interactions among the trophic components of Arctic marine ecosystems (Post et al., 2013). In some cases, less sea ice may be beneficial if it enhances productivity or prey availability (e.g., George et al., 2015). In other cases, the decline of sea ice may result in the loss of preferred prey, and the predators that cannot switch to alternative food will decline in numbers and perhaps range (Harwood et al., 2015). Conversely, the loss of sea ice may be advantageous to seasonally migrant species (Fig. 3), as it will give them opportunities to forage in Arctic waters earlier and stay later in the feeding season.

Changes in marine mammal distribution and movements may also signal ecosystem shifts accompanying the loss of Antarctic sea ice. The dynamic relationship between sea ice and krill, the primary prey of migratory baleen whales and many Antarctic seals, will mediate the impact of climate warming on these species in the Southern Ocean. Off the Western Antarctic Peninsula (WAP), years of extreme ice extent have been associated with high krill biomass while reduced sea ice has been associated with high salp biomass, few krill, and poor survivorship for young seals (and penguins). Although the production–prey–predator dynamics among ice, krill, and marine mammals remain poorly understood in many regions of the Antarctic, reports of superaggregations of krill and humpback whales in nearshore waters of the WAP, where warming has been extreme, underscores the need for research at the "foraging scale" of various marine mammal species.

B. Marine Mammals in Temperate and Tropical Regions

In temperate and tropical regions, sea level rise, ocean acidification, and coral bleaching are the clearest signals of disturbance to the marine environment from climate change. Although these signs of environmental perturbation are alarming in their own right, the ultimate effects of these changes on marine mammals are not immediately evident. Rising sea levels can mean a loss of habitat for seals and sea lions that rely on low-lying coastal areas for rest, molting, pup birth and rearing, and courtship/mating. In the case of endangered and endemic fauna, such as Hawaiian monk seals (*Monachus schauinslandi*), an evaluation of potential effects of sea level rise by

C

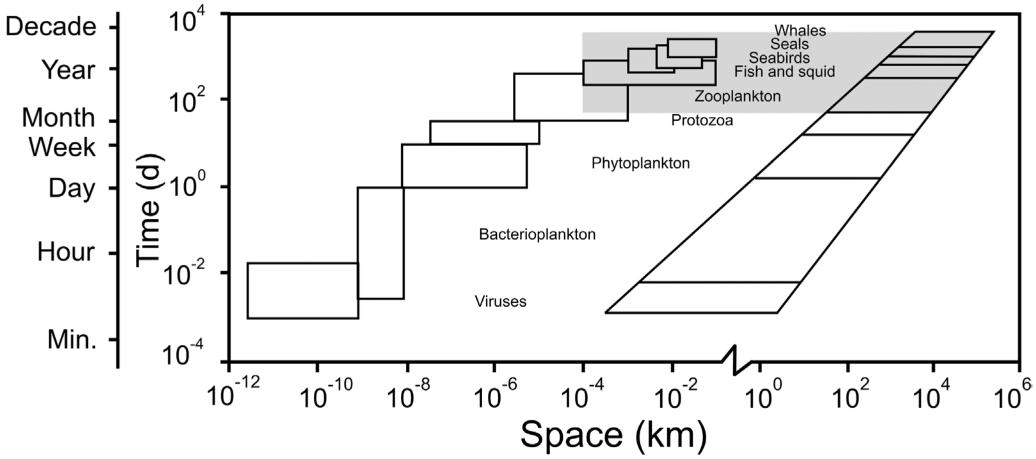

Figure 2 *Marine mammal ecological scale (shaded area) is determined by a species' life-history characteristics and, for marine mammals, can extend from years to centuries in time and from tens to thousands of kilometers in space.*

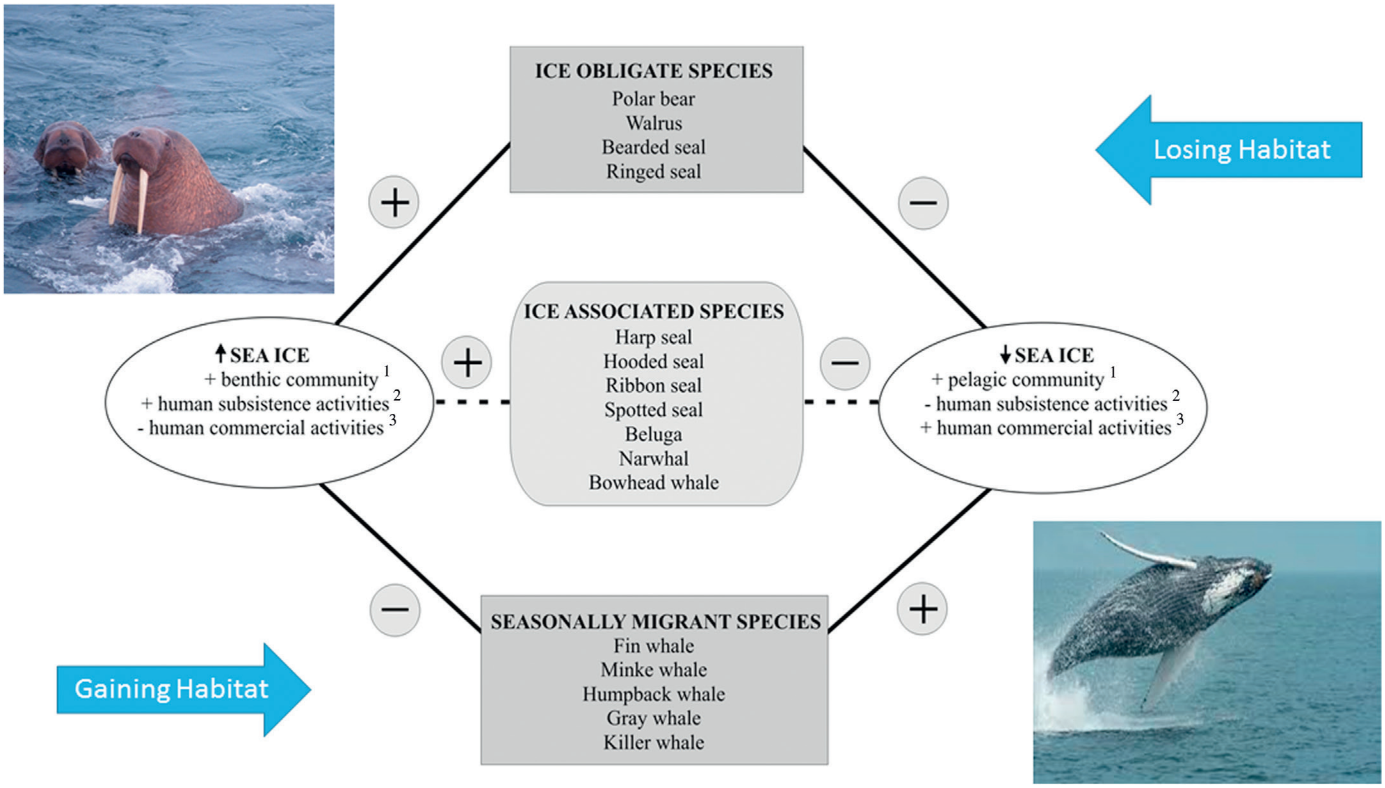

Figure 3 *A conceptual model of sea ice impacts on ice obligate, ice associated, and seasonally migrant marine mammal species: positive impacts are indicated by circled plus signs; negative impacts by circled minus signs. Dashed lines indicate uncertainty regarding potential impact of sea ice gain or loss for ice-associated species. Marine mammals will be affected differentially (positively + or negatively −) by anticipated changes in productivity[1] in both benthic and pelagic prey communities, and by changes in human subsistence[2] and commercial activities[3] in the Arctic. From Moore and Huntington (2008), with permission.*

2100 found that maximum projected habitat loss ranged from 65% to 75% under median and maximum scenarios of sea level rise, respectively. Perhaps more important than sea level rise is the question of how biophysical forcing will alter marine food webs in temperate and tropical waters. For example, it appears that over the past five decades the dynamics of Hawaiian monk seal populations may have been influenced more by climate—ocean variability than by direct human activity (Baker et al., 2012).

II. Phenology

Although marine mammal species have responded to climatic changes throughout their evolutionary history, the rates of those changes have been far slower than that measured during the past 100 years. Responses to recent global warming across a range of species from grasses and trees to mollusks and mammals have included pole-ward shifts in distribution and changes in the timing (phenology) of life-history events such as migration, flowering, or reproduction (Root et al., 2003). The broad-scale annual migrations by marine mammals between feeding and breeding areas have evolved to maximize foraging, reproductive success, and offspring survival. Although the environmental cues that initiate migration are not well understood, there is evidence to suggest that climate change is altering the timing of migrations in some marine mammal species. Such alteration in timing, or shifts in seasonal changes, to physical habitat, can lead to a mismatch between predator requirements and prey availability on the feeding grounds.

A. Migration Timing

Long-term data on migratory timing are available for only a few marine mammal species. One of the best records is that for the migration of Eastern North Pacific gray whales (*Eschrichtius robustus*) between feeding areas offshore Alaska and Siberia and breeding areas in the lagoons and coastal waters of Baja California, Mexico. The southbound migration for this population has been documented from a census site in central California since the mid-1960s, providing a rare opportunity to examine migratory timing. In doing so, researchers were able to define a week delay in migration that coincided with, and appeared to be a step response to the strong El Niño (periodic ocean warming) event that occurred in the North Pacific during 1998/1999. Prior to 1998/1999, the overall median date for gray whales passing southbound was 8 January, but since then the overall median date has shifted to 15 January. This shift in migration timing was accompanied by reports of more calves seen offshore California, well north of the Mexican calving areas. Collectively, these observations suggest that gray whales have modified their migration timing, and possibly their breeding range, in response to a climate event in the ocean (Moore, 2008). In another less-well-documented case, belugas (*Delphinapterus leucas*) that migrate along the northeast Alaskan coast in summer now arrive near the village of Point Lay roughly 2 weeks earlier than they did in the 1980s, and they have extended their foraging season in Arctic waters by at least 2 weeks (Hauser et al., 2016).

B. Feeding

There is no doubt that the temporal aspects of feeding are important for marine mammals, especially in Polar Regions where the productive season is short. The effects of climate warming on polar bears is a clear case where access to prey such as ringed seals (*Pusa hispida*) has been disrupted by earlier breakup and later formation of sea ice in some areas of the eastern Canadian Arctic. Long-term records show declines in population size and body condition for bears in Western Hudson Bay and Baffin Bay due to the extended fasting imposed on the bears by longer ice-free periods (Stirling and Derocher, 2012). There are no other species of marine mammals for which such a long-term record exists to investigate the potential effects of climate change on feeding opportunities. However, recent observations suggest that rapid loss of seasonal sea ice may be affecting feeding opportunities and recruitment in Pacific walruses. In summer, female walruses and their calves ride the retreating sea ice north from the Bering Sea to the northern Chukchi Sea. In the recent past, at maximum recession, the sea ice edge roughly corresponded to the edge of the Chukchi Sea continental shelf and adult female walruses could make easy forays there to feed, and then to return to suckle calves while hauled out on the ice. However, since the early 2000s, sea ice has retreated rapidly, far into the deep water of the Canadian Basin. The earlier and more extensive sea ice retreat and delayed freeze-up of sea ice has caused walruses to arrive earlier and stay later in the Chukchi Sea than in the past and to forage in nearshore instead of offshore areas (Jay et al., 2012).

III. Disease and Toxins

Infectious diseases can cause rapid declines in wildlife populations (Harvell et al., 2002). Rates of pathogen development, disease transmission, and host susceptibility are all influenced by climate, with a greater incidence of disease anticipated with warming (Moore and Gulland, 2014). Marine mammal health and reproductive success are also adversely affected by toxins associated with harmful algal blooms (HABs). Marine mammal deaths associated with HABs appear to have increased over the past three decades, as have the frequency and geographic distribution of the events. Although coincident with climate warming, these apparent increases may also reflect improvements in the ability to detect HABs and in the capability to identify algal toxins in marine mammal tissues. While marine mammals may face greater risk of mortality due to disease outbreak or exposure to toxins in a warming ocean, the magnitude of these threats and their relationships to climate are difficult to judge (Gulland and Hall, 2007). Fortunately, diagnostic tools to monitor and measure the effects of disease and HABs on marine mammal populations are in rapid development, coincident with improved access to satellite imagery of the oceans.

References

Baker, J.D., Howell, E.A., and Polovina, J.J. (2012). Relative influence of climate variability and direct anthropogenic impact on a sub-tropical Pacific top predator, the Hawaiian monk seal. *Mar. Ecol. Prog. Ser.* **469**, 175–189.

George, J.C., Druckenmiller, M.L., Laidre, K.L., Suydam, R., and Person, B. (2015). Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. *Prog. Oceanogr.* **136**, 250–262.

Gulland, F.M.D., and Hall, A.J. (2007). Is marine mammal health deteriorating? *EcoHealth* **4**, 135–150.

Hauser, D.W., Laidre, K.L., Suydam, R.S., and Richard, P.R. (2016). Decadal shifts in migration timing by Pacific Arctic beluga whales (*Delphinapterus leucas*) is related to delayed annual sea ice. *Global Change Biol.* doi:10.1111/gcb.13564.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S., and Samuel, M.D. (2002). Climate warming and disease risks for terrestrial and marine biota. *Science* **296**, 2158–2162.

Harwood, L.A., Smith, T.G., George, J.C., Sandstrom, S.J., Walkusz, W., and Divoky, G.J. (2015). Change in the Beaufort Sea ecosystem: diverging trends in body condition and/or production in five marine vertebrate species. *Prog. Oceanogr.* **136**, 263–273.

Jay, C.V., Fischbach, A.S., and Kochnev, A.A. (2012). Walrus area of use in the Chukchi Sea during sparse sea ice cover. *Mar. Ecol. Progr. Ser.* **468**, 1–13.

Levin, S.A. (1992). The problem of pattern and scale in ecology. *Ecology* **73**, 1943–1967.

Moore, S.E. (2008). Marine mammals as ecosystem sentinels. *J. Mamm.* **89**, 534–540.

Moore, S.E., and Gulland, F.M.D. (2014). Linking marine mammal and ocean health in the "New Normal" arctic. *Ocean Coastal Manage.* **102**, 55–57.

Moore, S.E., and Huntington, H.P. (2008). Article marine mammals and climate change: impacts and resilience. *Ecol. Appl.* **18**, S157–S165.

Moore, S.E., Logerwell, E., Eisner, L., Farley, E., Harwood, L., Kuletz, K., Lovvorn, J., Murphy, J., and Quakenbush, L. (2014). Marine fishes, birds and mammals as sentinels of ecosystem variability and reorganization in the Pacific Arctic region. In "The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment", (J. Grebmeier, and W. Maslowski, Eds), pp. 337–392. Springer, Dordrecht.

Post, E., Bhatt, U.S., Bitz, C.M., Brodie, J.F., Fulton, T.L., Hebblewhite, M., Kerby, J., Kutz, S.J., Stirling, I., and Walker, D.A. (2013). Ecological consequences of sea-ice decline. *Science* **341**, 519–524.

Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C., and Pounds, J.A. (2003). Fingerprints of global warming on wild animals and plants. *Nature* **421**, 57–60.

Stirling, I., and Derocher, A.E. (2012). Effects of climate warming on polar bears: a review of the evidence. *Global Change Biol.* doi:10.1111/j.1365-2486.2012.02753.x.

Wood, K.R., Bond, N.A., Danielson, S.L., Overland, J.E., Salo, S.A., Stabeno, P., and Whitefield, J. (2015). A decade of environmental change in the Pacific Arctic region. *Prog. Oceanogr.* **136**, 12–31.

C