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MARINE MAMMALS AS ECOSYSTEM SENTINELS

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The earth's climate is changing, possibly at an unprecedented rate. Overall, the planet is warming, sea ice and glaciers are in retreat, sea level is rising, and pollutants are accumulating in the environment and within organisms. These clear physical changes undoubtedly affect marine ecosystems. Species dependent on sea ice, such as the polar bear (*Ursus maritimus*) and the ringed seal (*Phoca hispida*), provide the clearest examples of sensitivity to climate change. Responses of cetaceans to climate change are more difficult to discern, but in the eastern North Pacific evidence is emerging that gray whales (*Eschrichtius robustus*) are delaying their southbound migration, expanding their feeding range along the migration route and northward to Arctic waters, and even remaining in polar waters over winter—all indications that North Pacific and Arctic ecosystems are in transition. To use marine mammals as sentinels of ecosystem change, we must expand our existing research strategies to encompass the decadal and ocean-basin temporal and spatial scales consistent with their natural histories.

Key words: climate change, marine ecosystems, marine mammals, seals, sentinels, whales

Evidence that the earth's climate is changing at an extraordinary rate is now ubiquitous (Intergovernmental Panel on Climate Change 2007; Walsh 2008). Glaciers and polar sea ice are in rapid retreat as sea levels rise (e.g., Overpeck et al. 2005, 2006; Serreze et al. 2007), tropical and temperate flora and fauna are advancing poleward (e.g., Overland et al. 2003), and reported variation in phenology of natural history phenomena in reptilian, avian, and mammalian fauna is consistent with climate change (Durant et al. 2007; Hare and Mantua 2000; Root et al. 2003). Although evaluation of climate cycles over more than 100 years is constrained by a lack of suitable data (Lindsay and Zhang 2005) and by regional variability (Laidre and Heide-Jorgensen 2005), the weight of evidence suggests the overall change is unidirectional toward a warmer earth. Whether directional or cyclic, the rapid rate of change will challenge the capability of marine mammal to adapt.

The millennium precipitated various ''state of the earth'' reviews, one of which focused on marine mammals and their environment in the 21st century. Harwood (2001) predicted moderate to extreme selection pressure on marine mammals based on anticipated alteration of their ''critical habitats,'' which he defined as ''functioning ecological units required for successful breeding and foraging'' (Harwood 2001:630). As part of a worldwide, threat-based review of conservation challenges for marine mammals (Reynolds et al. 2005), Moore (2005) evaluated the effects of long-term climate change on marine mammals based on the temporal (years to decades) and spatial (tens to thousands of kilometers) scales of their natural histories. Because marine mammals integrate and reflect ecological variation across large spatial and long temporal scales, they are prime sentinels of marine ecosystem change.

A number of marine mammals have been described as sentinels of coastal ecosystems (Aguirre and Tabor 2004), including southern sea otters (*Enhydra lutris nereis*—Jessup et al. 2004), bottlenose dolphins (*Tursiops truncates*—Wells et al. 2004), and manatees (*Trichechus*—Bonde et al. 2004). Efforts to quantify and model the sensitivity of Arctic marine mammals to habitat alteration associated with climate change (Laidre et al. 2008; Moore and Huntington 2008) provide a basis for assessment of marine mammals as ecosystem sentinels. Not surprisingly, species dependent on sea ice for feeding and breeding, such as the polar bear (*Ursus maritimus*) and the ringed seal (*Phoca hispida*), provide the clearest examples of sensitivity to environmental change (Derocher et al. 2004; Stirling 2002).

The utility of marine mammals as ecosystem sentinels is a function of their ecological diversity and the variability inherent in marine ecosystems. Here, I use the behavioral ecology of gray whales (*Eschrichtius robustus*) in the eastern North Pacific and Arctic to illustrate the importance of ecological scale. I then discuss the use of marine mammals as sentinels of hotspots in ocean production, changes to food

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Table 1.—List of families, common names, and number of marine mammal species in 3 mammalian orders.

Order	Family	Common name	No. species
Sirenia	Trichechidae	Manatees	3
	Dugongidae	Dugong or sea cow	2 (1 extinct)
Carnivora	Ursidae	Polar bear	1
	Mustelidae	Sea and marine otters	2
Suborder			
Pinnipedia	Odobenidae	Walrus	1
	Otariidae	Fur seals	9
		Sea lions	5
	Phocidae	True seals	19
Cetacea			
Suborder			
Mysticeti	Eschrichtiidae	Gray whale	1
	Balaenidae	Right whales	4
	Balaenopteridae	Rorqual whales	6
Suborder			
Odontoceti	Physeteridae	Sperm whales	3
	Monodontidae	Beluga and narwhal	2
	Ziphiidae	Beaked whales	18
	Delphinidae	Dolphins	31
	Phocoenidae	Porpoises	6
	Platanistidae	River dolphins	5

webs, contaminant levels, and disease pathways. I conclude with specific recommendations for including marine mammal research in future local- to- large-scale ocean studies.

Marine Mammal Diversity

Roughly 118 extant marine mammal species comprise 3 diverse mammalian orders: Sirenia, Carnivora, and Cetacea (Table 1). Evolution of species in these orders converged from land-adapted, elephant-like (Sirenia), bear- or weasel-like (Carnivora), and cow- or pig-like (Cetacea) mammalian ancestors (Reynolds et al. 1999). Detailed natural histories of extant marine mammal species are fully described in textbooks and field guides (e.g., Shirihai and Jarrett 2006) and are beyond the scope of this article.

Although they do not share phylogeny, all marine mammals are adapted anatomically and physiologically to aquatic (mostly marine) ecosystems and are dependent on those ecosystems for survival. It is this dependency that makes them natural sentinels of ecosystem variability and degradation.

Ocean Domains and Variability

Oceanographers often divide the marine environment into domains based upon latitude (polar, temperate, and tropical), bathymetry (coastal, shelf, slope, and basin), or proximity to shore (estuarine, neritic, and pelagic) because regions so defined can be associated with broad patterns of ocean circulation and productivity (Pickard and Emery 1990). In general, central-basin ocean circulation gyres are cyclonic (Northern Hemisphere) or anticyclonic (Southern Hemisphere), creating zones of upwelling and enhanced primary and secondary production along continental shelf margins and to a lesser degree at equatorial and temperate convergence zones. Conversely, the central ocean basins are comparatively unproductive areas.

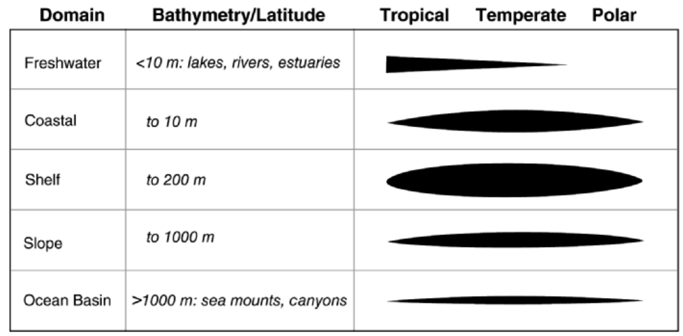

Fig. 1.—Marine mammal biogeography extends from freshwater to ocean basin habitats, but the distribution of species is not uniform (Moore 2005:figure 9.2, reproduced with permission).

Marine mammal species are not uniformly distributed among the oceanographic domains, nor are they typically confined to only 1 (Fig. 1). For example, a few species of seals (2), dolphins (4), and manatees (3) are nearly completely confined to lakes, rivers, and estuaries, whereas others are most commonly found over the comparatively shallow and productive continental shelves (Reynolds et al. 1999). Of the oceanic species, 19 are endemic to polar waters. Among the far more numerous temperate and tropical species, migratory movements between adjacent latitudinal domains are common.

Variability within and across ocean habitats is ubiquitous, and over the past few decades oceanographers have described several basinwide oscillatory patterns throughout the world ocean (e.g., Vimont 2005). Perhaps the best tracked are the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) in the North Pacific (Fig. 2; Bond and Harrison 2000). The ENSO has an oscillatory period of roughly 2–7 years, and has demonstrated effects on the body condition and survivorship of pinnipeds (Trillmich and Ono 1991) and on the distribution of cetaceans (Tershy et al. 1991; Urban et al. 2003) in the northeastern Pacific. As the name implies, the PDO has a roughly decadal cycle and has been linked to "a major reorganization of biota in the northeast Pacific," subsequently called a "regime shift" (Francis et al. 1998:1; Hare and Mantua 2000) that occurred in the late 1970s (Fig. 2: arrow).

Typically, correlative descriptions of physical ocean conditions and biota ends at chlorophyll *a*, which is the standard descriptor of ocean productivity available from satellite images. Some studies investigate linkages among chlorophyll *a* and zooplankton or fish, but often stop short of inclusion of predators at higher trophic levels. Yet seabirds and marine mammals are conspicuous animals that integrate changes in the ecosystem and reflect the existing state of the environment (Aguirre and Tabor 2004; Boersma 2008; Thiele et al. 2004). For well over a decade, rising levels of contaminants in the bodies of seabirds and marine mammals have demonstrated the degree to which marine ecosystems are affected by anthropogenic pollutants (e.g., Burger and Gochfeld 2004; Reijnders et al. 1999). Although such reports are instructive as to pollutant

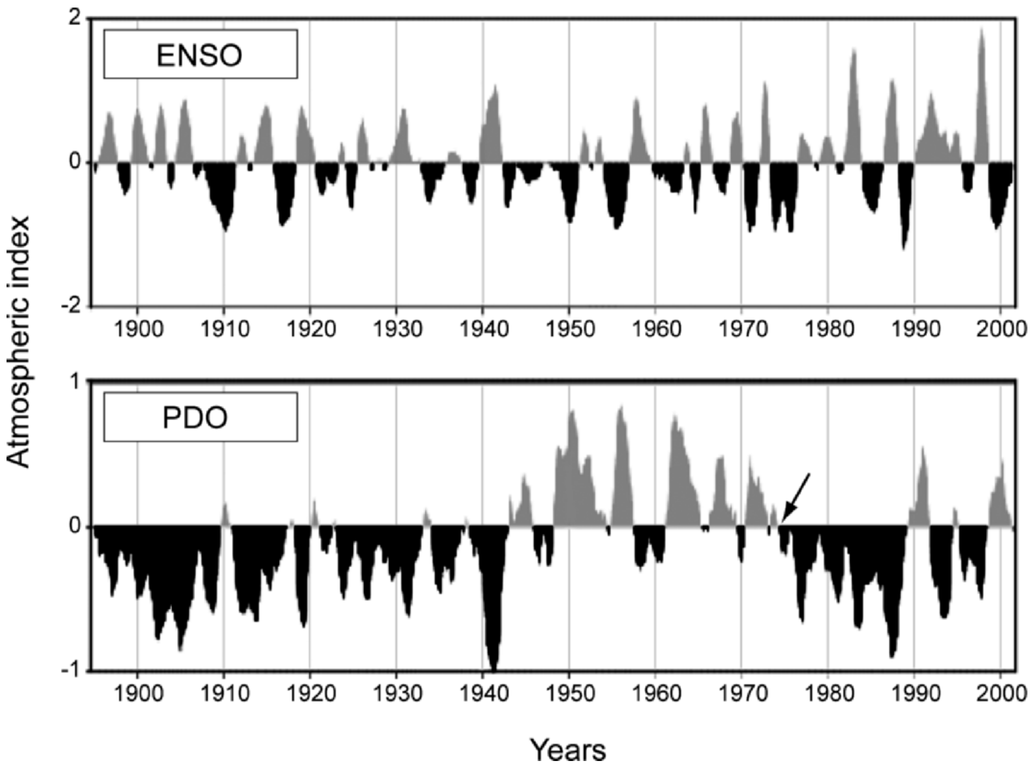

FIG. 2.—Two examples of broadscale cyclic variability in ocean climate of the eastern North Pacific: the El Niño Southern Oscillation (ENSO) and the North Pacific Decadal Oscillation (PDO). The arrow points to the occurrence of the ''regime shift,'' 1st described by Francis et al. (1998:1).

pathways, much more can be achieved by selecting specific marine mammal species as vectors to investigations of full ecosystems.

Selecting the appropriate marine mammal species to use as a sentinel of change depends on the ecological alteration of concern. Migratory mysticete whales may be used if broadscale shifts in ecosystems are to be investigated, whereas polar cetaceans are more useful for assessing the effects of rapid changes in sea ice conditions on food webs in these strongly seasonal ecosystems, and coastal dolphins for examination of pollutant or disease vectors in nearshore habitats. Below, I use the gray whale to illustrate the value of marine mammals as sentinels of broadscale ecosystem change.

ECOLOGICAL SCALE AND EASTERN NORTH PACIFIC GRAY WHALES

Two populations of gray whales occur in the North Pacific, nominally called eastern and western stocks (Swartz et al. 2006). The eastern North Pacific population numbers roughly 18,000 animals (Rugh et al. 2005) and migrates annually between summering areas extending from the Pacific Northwest to Alaska, and wintering areas extending from southern California to Mexico (Fig. 3). This population was removed from the list of endangered and threatened species in 1994 after 3 decades of research supported the conclusion that it had recovered from commercial whaling (Rugh et al. 2005). In 1999 and 2000, the number of stranded gray whales on beaches from Mexico (the majority of dead whales) all along the migration corridor to Alaska increased 7- to 9-fold (Gulland et al. 2005). The emaciated condition of many of the whales generated speculation that starvation linked to a decline in benthic productivity in the northern Bering Sea's Chirikov Basin was the primary cause of the mortalities (LeBoeuf et al. 2000). However, because gray whales feed over an extensive range and consume a variety of prey, other factors such as disease or toxins could not be ruled out (Moore et al. 2001).

The mortality event indicated that alterations in the northern Bering Sea ecosystem could have direct and dire effects on the eastern North Pacific gray whale population. Subsequent surveys found a 3- to 17-fold decline in the relative abundance of gray whales in the Chirikov Basin, suggesting that region was no longer the prime forage area it had once been (Moore et al. 2003). As described below, this discovery together with observations reported by other researchers suggest that this population is clearly responding to ecosystem alterations and is thereby acting as a sentinel to change at an ecological scale that spans decades and thousands of kilometers.

Gray Whales as Sentinels to Ecosystem Shifts

Six correlations between changes in the distribution and behavior of gray whales and changes in their environment suggest that they are effective sentinels of change in North Pacific and western Arctic ecosystems (Table 2). The 1st involves the timing of migration. Rugh et al. (2001) reconstructed whale passages between 1967 and 1999 at 2 census stations located along the California coast (Fig. 3: Granite

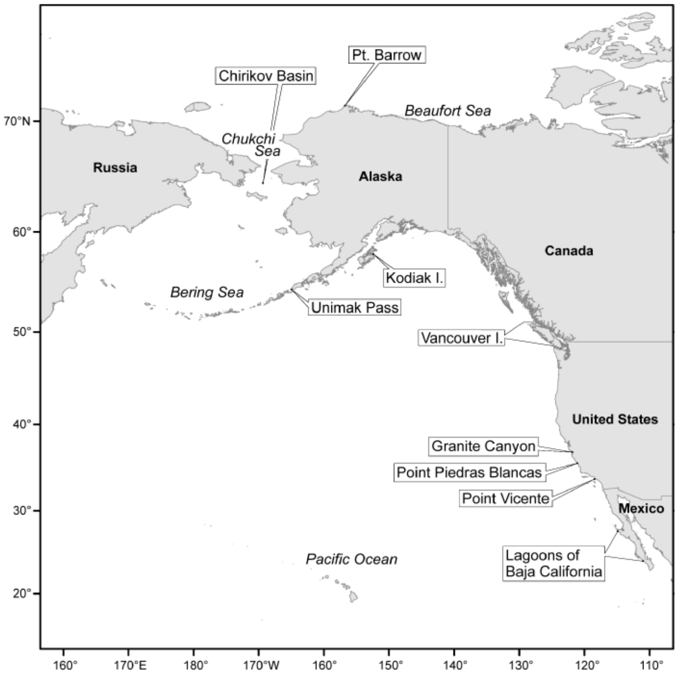

Fig. 3.—Range of eastern North Pacific gray whales, depicting coastal study sites from wintering areas offshore of southern California and Mexico, to summering areas extending from the Pacific Northwest to Alaska (after Rugh et al. 2001:figure 1).

Canyon and Point Vicente) and found a 6.8-day (confidence interval [CI] = 2.0) delay in the southbound migration evident after 1980. Specifically, the overall median sighting date shifted from 8 January ($CI = 1.3$) before 1980 to 15 January ($CI = 1.7$) after 1980. This shift in migration timing is coincident with the aforementioned North Pacific ''regime shift'' that occurred the late 1970s.

The 2nd line of evidence involves counts of calves at Point Piedras Blancas, California, during the northbound migration (Perryman et al. 2002). Although the timing of the northbound migration of females and calves seemed unaffected, the number of calves counted from 1994 to 2000 varied significantly among years. Highest calf counts were associated with the length of time the Chirikov Basin was ice-free the previous year, as determined from weekly ice charts produced by the National Snow and Ice Data Center (http://nsidc.org/data/easytouse.html, accessed 7 December 2007) for the Bering and Chukchi seas. The length of time pregnant females had access to that historically prime feeding area was suggested as the basis for the apparent relationship between survivorship of gray whale calves and the early departure of sea ice in spring. Subsequent analyses of sea ice trends found an increase in area of open water in March and June for the Chirikov Basin, with even stronger trends reported for the southern Chukchi Sea over the 1979–2002 period (Moore and Laidre 2006).

A 3rd line of evidence stems from responses of gray whales to the extremes of variability associated with warm El Niño and cold La Niña conditions in their southern range (Urban et al. 2003). Mother–calf pairs provided the strongest signal, with their presence declining by half and their peak occupancy delayed in Laguna San Ignacio, Mexico, after the strong 1997–1998 El Niño.

The 4th and 5th lines of evidence involve the spike in strandings of gray whales after the 1997–1998 El Niño (Gulland et al. 2005). The strandings in 1999 and 2000 appear to have resulted at least in part from poor foraging conditions in the Chirikov Basin. This conclusion is supported by the subsequent finding that abundance of gray whales dropped at the time of a decline in benthic prey in that region (Moore et al. 2003). Comparatively large numbers of gray whales were observed feeding southeast of Kodiak Island in 1999 and 2000 and these observations also were initially thought to indicate a response to the 1997–1998 El Niño. However, year-round sightings of feeding gray whales, tallied during the course of aerial surveys for pinnipeds from 1999 to 2005, suggested that whales might be responding to a comparatively reliable prey source there (Moore et al. 2007). Investigation of available prey near shore found that whales were feeding on unprecedented densities of cumaceans (Diastylidae: Crustacea), an atypical prey for gray whales. The regularity of sightings during this period suggested that whales were commonly feeding in waters formerly thought to be only a part of the annual migration route.

Table 2.—Gray whales as sentinels of ecosystem shifts in the North Pacific and western Arctic oceans: summary of evidence from published papers. Names of locations are given in Fig. 3.

Reference	Evidence	Interpretation
Rugh et al. 2001	One-week delay in southbound migration	Response to late 1970s regime shift in the North Pacific (see text)
Perryman et al. 2002	Increase in calf production coincident with ice-free Chirikov Basin in early spring	Response to early access to prime feeding areas by pregnant females
Urban et al. 2003	Reduction in calf numbers and changes in timing of occupation of breeding lagoons by gray whales	Response to 1997–1998 El Niño perturbation of the North Pacific ecosystem
Moore et al. 2003	Lack of gray whales feeding during July in the Chirikov Basin	Response to benthic prey decline in the Chirikov Basin and possible enhancement of prey base in southern Chukchi
Moore et al. 2007	Gray whales feeding year-round offshore Kodiak Island, Alaska	Response to localized prey availability along the migration route
Stafford et al. 2007	Gray whale calls detected in the western Beaufort Sea over the winter of 2003–2004	Response to reduction in sea ice, providing access to Arctic areas over winter

The last, and most surprising, evidence that gray whales have shifted their habits in response to environmental change was the detection of their calls on autonomous recorders in the western Beaufort Sea throughout the winter of 2003–2004 (Stafford et al. 2007). An appraisal of sea ice conditions from satellite images found that open-water cracks sufficient for gray whales to breathe occurred near the recorder deployment sites throughout that winter. So, in dramatic contrast to conditions in 1988, when 3 gray whales became entrapped in sea ice near Barrow, Alaska, passive acoustic detection provided evidence that this temperate species of mysticete could overwinter in Arctic waters.

Sentinel Potential

Grebmeier et al. (2006) presented evidence for a major ecosystem shift in the northern Bering Sea, including data on gray whales and walruses (*Odobenus rosmarus*). This paper elaborated on the correlation between the distribution of gray whales and benthic productivity (Moore et al. 2003), and integrated a suite of physical and biological measures to describe an ecosystem in transition from arctic to subarctic conditions. The geographic displacement of whales and walruses over the past decade has coincided with a reduction of sea ice and benthic prey populations as well as an increase both in air and ocean temperatures and in the occurrence of pelagic fishes. The changes observed on the shallow shelf of the northern Bering Sea could affect a broad portion of the western Arctic, which is strongly influenced by inflow of water through the Bering Strait.

The potential use of marine mammals as ecosystem sentinels goes beyond tracking changes in their distribution. As long-lived animals carrying a layer of blubber for insulation, marine mammals are great storehouses of lipophilic pollutants (O'Hara and O'Shea 2005; Reijnders et al. 1999). Although actual levels of pollutants in tissues of marine mammals are mediated by a number of biological and ecological processes (Ross et al. 2000), an increasing number of studies illustrate the utility of marine mammals to indicate the prevalence and persistence of pollutants in marine ecosystems (e.g., Hoekstra et al. 2003). Furthermore, profiles of stable carbon isotopes (Dehn et al. 2006) and fatty acids (Budge et al. 2006; Iverson et al. 2004) in blubber can be used to infer the diet of marine mammals, thereby providing evidence of changes to food webs within marine ecosystems. In essence, the overall health of marine mammals ultimately reflects the health of the ecosystems upon which they depend (Burek et al. 2008). Changes in individual body condition can demonstrate shifts in the prey base and food web structure as well as alterations in pathogen transmission. Indeed, to explore variability of ecosystem productivity and health, it seems essential to incorporate the biology and ecology of marine mammals and other top predators in multidisciplined programs of research.

Conclusions and Recommendations

Marine mammals rely on healthy ecosystems for their survival and, being fully adapted to aquatic environments, they are uniquely suited to reflect ecosystem variability and degradation. Until recently, most studies of marine mammals were species-focused and included little or no coincident measures of the ocean environment or individual animal health. Toward the end of the 20th century, increasing concern for ocean health, and for the condition of certain populations of marine mammals such as coastal bottlenose dolphins, Steller sea lions (*Eumetopias jubatus*), and sea otters underscored the need to investigate linkages between these top oceanic predators and their environment. From investigations reported to date it is clear that marine mammals offer a view that gives us insight into ocean ecosystems both from the top-down via signals carried in their tissues and from the bottom-up by patterns of their distribution and movements.

Subsequent to the reviews of ocean health and research provided by the Pew Oceans Commission (POC 2003) and the United States Commission on Ocean Policy (USCOP 2004), a document, *Ocean Research Priorities Plan and Implementation Strategy*, was prepared (http://noppo@coreocean.org, accessed 7 December 2007). The goal of this new plan is to address the ''most compelling issues and areas of interaction between society and the ocean'' in a holistic manner. Twenty-one research priorities are subsumed under 6 themes: Increasing Resilience to Natural Hazards; Enabling Marine Operations; Stewardship of Natural and Cultural Ocean Resources; The Ocean's Role in Climate; Improving Ecosystem Health; and Enhancing Human Health. Research that includes marine mammals as sentinels is germane to all but the first 2 of these themes. Specifically, as sentinels to the ecosystems upon which they depend, marine mammals can guide human stewardship activities, reflect the ocean's role in climate interactions across regions, demonstrate ecosystem vulnerabilities and health, and thereby lead to ways to enhance human health. Moreover, as charismatic megafauna, marine mammals capture the attention and concern of the public. This capability provides clear opportunities for education and outreach on oceanic and environmental themes. Given the pace of climate change experienced in the past 30 years and the need for comprehensive research to reveal the consequences, we must act now to both broaden and integrate our research approach, and one important way to do so is to use marine mammals as sentinels to ecosystems in transition.

Resumen

El clima del planeta esta cambiando, posiblemente a un ritmo sin precedentes. En conjunto, el planeta se está calentando, los glaciares y el hielo polar están en retroceso, el nivel del mar aumenta y los contaminantes se están acumulando en el ambiente y en los organismos. Estos cambios físicos evidentes indudablemente afectan a los ecosistemas marinos. Las especies dependientes del hielo marino, como los osos polares (*Ursus maritimus*) y la foca anillada (*Phoca hispida*) proveen de claros ejemplos de sensitividad al cambio climático. La respuesta de los cetáceos es mas difícil de discernir pero en el Pacífico Nororiental la evidencia sugiere que la ballena gris (*Eschrichtius robustus*) está retrasando su migración hacia el sur, esta expandiendo su zona de alimentación a lo largo de la ruta migratoria también hacia el norte, y hasta permaneciendo en aguas polares durante todo el invierno. Todo esto son indicadores de que tanto los ecosistemas del Pacífico Norte como el Ártico están en transición. Si deseamos utilizar a los mamíferos marinos como centinelas del cambio en los ecosistemas debemos expandir las estrategias de investigación existentes para abarcar las escalas espacio-temporales oceánicas consistentes con la historia de vida de estos animales.

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