

ARCTIC MARINE MAMMALS AND CLIMATE CHANGE: IMPACTS AND RESILIENCE

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Abstract. Evolutionary selection has refined the life histories of seven species (three cetacean [narwhal, beluga, and bowhead whales], three pinniped [walrus, ringed, and bearded seals], and the polar bear) to spatial and temporal domains influenced by the seasonal extremes and variability of sea ice, temperature, and day length that define the Arctic. Recent changes in Arctic climate may challenge the adaptive capability of these species. Nine other species (five cetacean [fin, humpback, minke, gray, and killer whales] and four pinniped [harp, hooded, ribbon, and spotted seals]) seasonally occupy Arctic and subarctic habitats and may be poised to encroach into more northern latitudes and to remain there longer, thereby competing with extant Arctic species. A synthesis of the impacts of climate change on all these species hinges on sea ice, in its role as: (1) platform, (2) marine ecosystem foundation, and (3) barrier to non-ice-adapted marine mammals and human commercial activities. Therefore, impacts are categorized for: (1) ice-obligate species that rely on sea ice platforms, (2) ice-associated species that are adapted to sea ice-dominated ecosystems, and (3) seasonally migrant species for which sea ice can act as a barrier. An assessment of resilience is far more speculative, as any number of scenarios can be envisioned, most of them involving potential trophic cascades and anticipated human perturbations. Here we provide resilience scenarios for the three ice-related species categories relative to four regions defined by projections of sea ice reductions by 2050 and extant shelf oceanography. These resilience scenarios suggest that: (1) some populations of ice-obligate marine mammals will survive in two regions with sea ice refugia, while other stocks may adapt to ice-free coastal habitats, (2) ice-associated species may find suitable feeding opportunities within the two regions with sea ice refugia and, if capable of shifting among available prey, may benefit from extended foraging periods in formerly ice-covered seas, but (3) they may face increasing competition from seasonally migrant species, which will likely infiltrate Arctic habitats. The means to track and assess Arctic ecosystem change using sentinel marine mammal species are suggested to offer a framework for scientific investigation and responsible resource management.

Key words: Arctic; climate change; impacts; marine mammals; resilience; sea ice.

INTRODUCTION

The earth is experiencing a rapid shift in environmental stability (Walsh 2008), which challenges the adaptive capacity of Arctic marine mammals. The polar bear (*Ursus maritimus*), walrus (*Odobenus rosmarus*), bearded seal (*Erignathus barbatus*), and ringed seal (*Phoca hispida*) may be especially vulnerable due to life histories reliant on sea ice, while the case for the narwhal (*Monodon monoceros*), beluga (*Delphinapterus leucas*), and bowhead whale (*Balaena mysticetus*) is less certain (Moore and Laidre 2006, Laidre et al. 2008). Temperate or seasonally migrant species have the capability to extend their geographic range into Arctic marine habitats. Since the mid-1990s, grizzly bears (*Ursus arctos*) have been reported in the Canadian High Arctic

(Taylor 1995), and the calls of gray whales were recorded throughout the winter of 2003–2004 in the western Beaufort Sea (Stafford et al. 2007). These species and others (e.g., fin, humpback, and minke whales and harp, hooded, ribbon, and spotted seals) are poised to disperse and become established further northward if the current overall trend toward a warmer Arctic climate continues.

Recognition that the biogeography of life on earth can change with climate is not new. Darwin (1859:459) described the movements of animals that must have accompanied the advance and retreat of glaciers as follows: “As the cold came on, and as each more southern zone became fitted for arctic beings and ill-fitted for their former more temperate inhabitants, the latter would be supplanted and arctic productions would take their place. . . . As the warmth returned, the arctic forms would retreat northward, closely followed up in their retreat by the productions of the more temperate regions.” Further, extant Arctic species have evolved

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over periods whereby adaptation to profoundly different climate regimes was required, such as ca. 12 000 years ago when the Bering land bridge closed the western Arctic to Pacific water intrusion (Walsh 2008) or during the retreat of the great ice sheets and the opening continental shelves at the onset of the Holocene (Harington 2008). What may distinguish current circumstances from those of the past several millennia, however, is the rate at which Arctic ecosystems are changing (Root et al. 2003, Overpeck et al. 2005, Walsh 2008). As highly derived long-lived (i.e., K-selected) species, Arctic marine mammals are ill equipped to respond quickly to rapid climate change.

The ecological scale of marine mammals, based on their natural histories, ranges from years to decades and from tens to thousands of kilometers (Fig. 1). These temporal and spatial scales are small compared with evolutionary and geologic scales, but vast compared with human research and resource management scales (Moore 2005). For example, local knowledge (also called traditional ecological knowledge or TEK) can provide clear observational records over relatively long temporal scales (Huntington et al. 1999, Huntington 2000, Metcalf and Robards 2008); these observations generally cover only a portion of the range of a marine mammal stock or species (Huntington et al. 2004a, b). Conversely, scientific research and monitoring can have greater spatial scope, but consistent long-term sampling is much harder to achieve (e.g., Murray 2008). This mismatch in scales complicates the task of predicting impact and assessing resilience for Arctic marine mammals in the face of climate change.

Here we draw upon contributions in this Special Issue to support a two-step approach to examining impacts and resilience of Arctic marine mammals to climate change. We first predict impacts based upon a conceptual model that accounts for species' ecological scale, then assess resilience relative to anticipated climate change in four Arctic regions. Impacts of climate change are defined as the potential challenges to species' survival associated with recent Arctic ecosystem perturbations, as summarized in Walsh (2008) and elsewhere (e.g., Overpeck et al. 2005, Comiso 2006, Serreze et al. 2007). We catalog impacts with regard to species' natural history as: (1) "ice-obligate" for species reliant on sea ice as a platform for resting, breeding, and/or hunting; (b) "ice-associated" for species associated with sea ice and adapted to the marine ecosystem of which ice is a key part; and (3) "seasonally migrant" species that by their movements encounter sea ice.

Subsequently, we evaluate resilience, defined as a species' ability to adjust or recover from impacts (e.g., Steiner et al. 2006), scaled to four Arctic regions demarcated by existing oceanographic features and projections of sea ice reductions in 2050. We conclude with suggestions for how these regional resilience scenarios might provide a framework for further study of marine mammals in an era of climate change. Other

papers in this Special Issue address the implications of impacts and resilience for human users of marine mammals (Hovelsrud et al. 2008, Metcalf and Robards 2008) and for conservation (Ragen et al. 2008). We therefore limit our discussion to the implications for research and monitoring.

POTENTIAL IMPACTS OF CLIMATE CHANGE

The evolutionary history of Arctic marine mammals demonstrates their ability to adapt to major climate shifts and ecosystem perturbations (Harington 2008, Murray 2008, O'Corry-Crowe 2008). Nevertheless, the projected course and rate of current climate change (Walsh 2008) may present new challenges to the well-being and survival of Arctic marine mammals. These challenges can be considered in four general categories: habitat modification (Laidre et al. 2008), ecosystem alteration (Bluhm and Gradinger 2008), stresses to body condition and health (Burek et al. 2008), and human interactions (Hovelsrud et al. 2008, Metcalf and Robards 2008). Change in sea ice is the common denominator to all these potential impacts, as direct loss of this habitat is the most prominent threat that Arctic species face. Alterations in prey, including potential reduction in overall marine production, may pose a major threat, although there is much more uncertainty about the trajectories of food webs than of sea ice. Decline of body condition or increases in the incidence of disease together with increases in human interactions may be considered secondary challenges in that they alone are unlikely to result in species extirpation.

Conceptual model

A conceptual model of the potential impacts of climate change to Arctic marine mammals can be constructed based on the gain or loss of sea ice (Fig. 2). Polar bear, walrus, bearded seal, and ringed seal are considered ice-obligate species because they rely on sea ice as a platform for hunting, breeding, and resting. As shown in the sensitivity index presented in Laidre et al. (2008), fitness for these species is positively correlated to sea ice; that is, increases in the seasonal and temporal extent and thickness of sea ice generally have a positive effect on populations. The situation for ice-associated species is much harder to predict. Overall, decreases in sea ice are anticipated to have a negative effect on these species, except perhaps through reduced risk of ice entrapment (Laidre and Heide-Jorgensen 2005), due to their adaptation to extant trophic regimes. Of note, we consider harp, hooded, ribbon, and spotted seals as ice-associated species for the purpose of the conceptual model due to their reliance on sea ice for whelping (Reeves et al. 1992, Johnston et al. 2005). Finally, the five seasonally migrant cetacean species are likely to benefit from net loss in sea ice, due to greater access to a pelagic-dominated ecosystem. In all cases, decreases in sea ice will provide less stable human hunting platforms

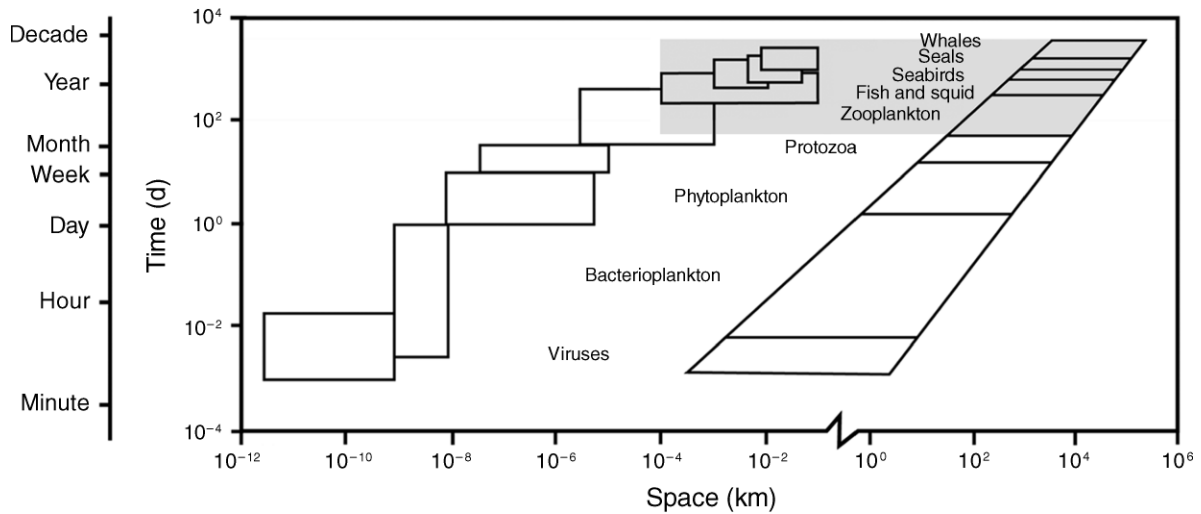


FIG. 1. Marine mammal ecological scale (shaded area) is based upon species' natural history and spans tens to thousands of kilometers and months to decades and, in the case of the bowhead whale, possibly centuries. The figure is modified from Moore (2005).

while generally increasing access to the Arctic for human commercial activities.

Although difficult to convey in conceptualized models, the fitness of Arctic marine mammals will be influenced by change to the dynamic balance among

sea ice's effects on ecosystem structure and prey availability, as well as its role as a barrier or platform. In the ice-obligate category, the polar bear provides the clearest example: reductions in sea ice remove their hunting and resting platforms and likely reduce survi-

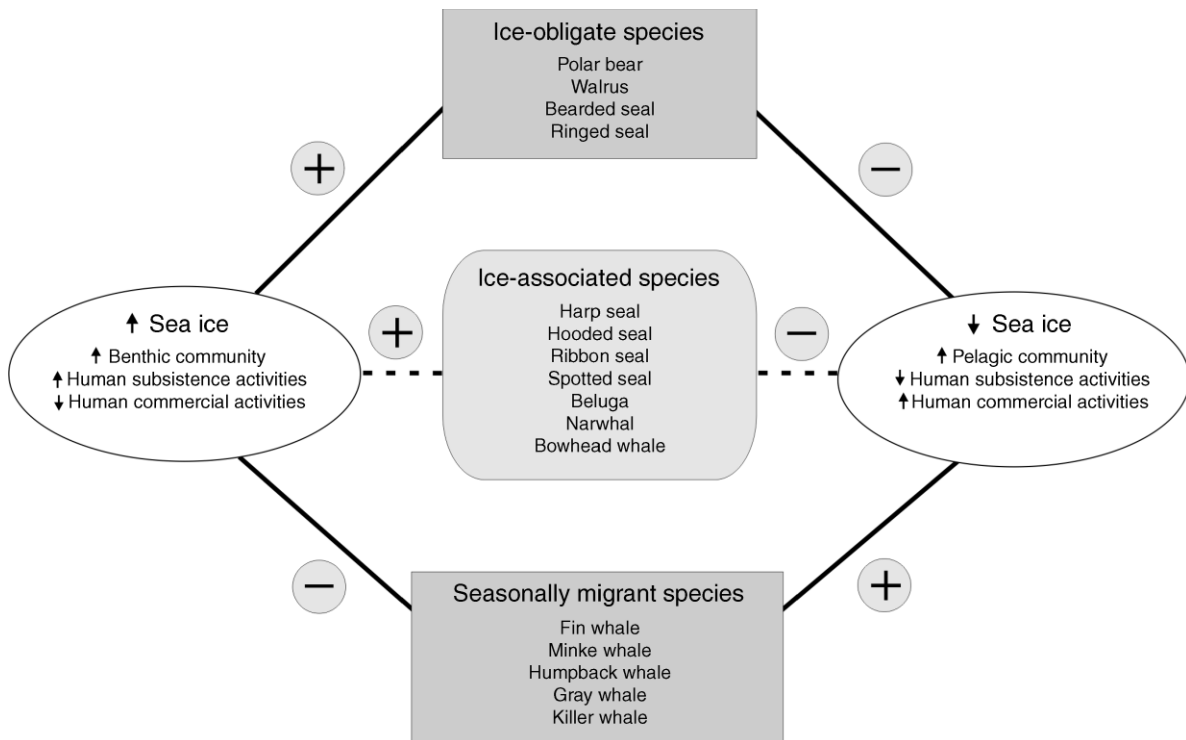


FIG. 2. A conceptual model of sea ice impacts on ice-obligate, ice-associated, and seasonally migrant marine mammal species: positive impacts are indicated by circled plus signs; negative impacts by circled minus signs. Dashed lines indicate uncertainty regarding potential impact of sea ice gain or loss for ice-associated species. Anticipated changes in benthic and pelagic community productivity are as presented in Bluhm and Gradinger (2008); anticipated change in human subsistence and commercial activities are as presented in Hovelsrud et al. (2008).

vorship of ringed seals, their primary prey (Derocher et al. 2004, Laidre et al. 2008). For the other ice-obligate species, such relationships are more dynamic and will be mediated by the effect of sea ice on ecosystem structure and productivity (Bluhm and Gradinger 2008). For example, walrus and bearded seals benefit from productive benthic bivalve prey communities, which are supported by tight pelagic–benthic coupling that transfers ice-associated production to the sea floor (e.g., Grebmeier et al. 1989). Conversely, these sea ice-mediated dynamics may not aid piscivorous ringed or other ice-associated seals, as reduced sea ice is hypothesized to favor pelagic over benthic production (Hunt et al. 2002).

As is the case for ice-obligate species, responses in populations of ice-associated species will depend on the dynamics of trophic cascades associated with annual cycles of production in sea ice-associated communities (e.g., Arrigo and van Dijken 2004, Bluhm and Gradinger 2008), and there will likely be surprises. While reductions in sea ice will likely have negative effects on seals that birth pups on ice (i.e., harp, hooded, ribbon, and spotted seals), the reliance of ice-associated whales (beluga, narwhal, and bowhead) on sea ice-mediated ecosystems is unclear (Laidre et al. 2008). Clearly these cetaceans are highly adapted to Arctic seas, but they are capable of survival at distances of tens to hundreds of kilometers from sea ice, and they sometimes select open-water habitats at least for part of the year (e.g., Moore et al. 2000a). For example, in the case of bowhead whales, reductions in sea ice may actually enhance feeding opportunities on prey both produced in and/or advected to their summer and autumn habitats (Moore and Laidre 2006). Specifically, the western Arctic population has increased steadily at 3.4% (George et al. 2004) during roughly two decades of sea ice loss in the Alaskan Beaufort Sea (Walsh 2008), a growth rate suggesting current trends in sea ice reduction are not hindering recruitment to this population as it rebounds from overhunting by commercial whaling. No similar comparisons can be made for narwhals or belugas, because trends in population size estimates are unavailable.

There is a very real likelihood that seasonally migrant cetaceans will range farther north and perhaps stay longer, if trends in sea ice reduction continue. Fin, humpback, minke, gray, and killer whales seem especially poised for such opportunity. These species now occur near or within seasonal ice in the Barents and Bering seas, the larger mysticetes feeding primarily upon forage fishes whose stocks may increase as a result of the boost to pelagic community production predicted to accompany reductions in sea ice (Hunt et al. 2002, Øien 2003, Bluhm and Gradinger 2008). It is noteworthy that fin whale calls have been recorded throughout winter on autonomous recorders in the southeastern Bering Sea (L. Munger, *personal communication*), where recent dramatic reductions in sea ice have been documented (Overland and Stabeno 2004), suggesting that at least

some of the hundreds to thousands of whales that occupy the Bering Sea during summer (Moore et al. 2000b, 2002, Tynan 2004) remain there over winter. Finally, at least some humpback whales remain in southeast Alaska and offshore Kodiak, Alaska, through winter, seemingly in response to the availability of herring (J. Straley, *personal communication*). Such plasticity of behavior is indicative of species that can adapt their migration habits based upon opportunity.

There is some evidence that gray whales may have already seized the opportunity to encroach into Arctic habitats. Gray whales are perhaps the most adaptable and versatile of the mysticete species. They are dynamic and opportunistic foragers (e.g., Nerini 1984, Darling et al. 1998, Dunham and Duffus 2001) and recently have been documented feeding year-round off Kodiak, Alaska (Moore et al. 2007). Most surprising, with regard to seasonal distribution, was the detection of their calls in the western Beaufort Sea throughout the winter of 2003–2004 (Moore et al. 2006). There was a marked wintertime reduction in calling rates (Stafford et al. 2007), but clearly a few gray whales remained in the Beaufort Sea over winter. It is unknown whether or not the (likely) few gray whales that remained in the Beaufort Sea found prey, but there could be a net metabolic advantage whereby the energetic costs of thermoregulation in cold water are offset by not undertaking the 10 000-km round-trip migration and remaining in northern seas to take advantage of spring forage.

Although killer whales routinely occur in the Greenland-Iceland-Norwegian (GIN) seas (Øien 1988) and are commonly seen near Barrow, Alaska, in summer (C. George, *personal communication*), they are generally considered to have only limited association with sea ice (Born 2000). As top predators, killer whales may simply follow either fish or mammalian prey that shift north into Arctic waters, with reductions in sea ice. The feeding ecology of killer whales in the North Pacific and Alaskan seas is an area of active investigation (e.g., Herman et al. 2005), due to debate regarding their role in structuring marine communities (e.g., Williams et al. 2004, DeMaster et al. 2006, Wade et al. 2007). The unfolding story in the North Pacific is one of a single recognized species that includes genetic differences at the “species” level, which correspond to three killer whale ecotypes that exhibit strong behavioral and dietary specialization (e.g., Ford et al. 2000). Although the impact of sea ice may differ with ecotype, speculation regarding advantages or disadvantages to any of the three is premature.

RESILIENCE AT REGIONAL SCALES

Recent warming in the Arctic has not been uniform, with many reports describing the regional nature of temperature trends and sea ice loss (Walsh 2008). To interpret the impacts suggested in the conceptual model (Fig. 2) at spatial scales relevant to marine mammal

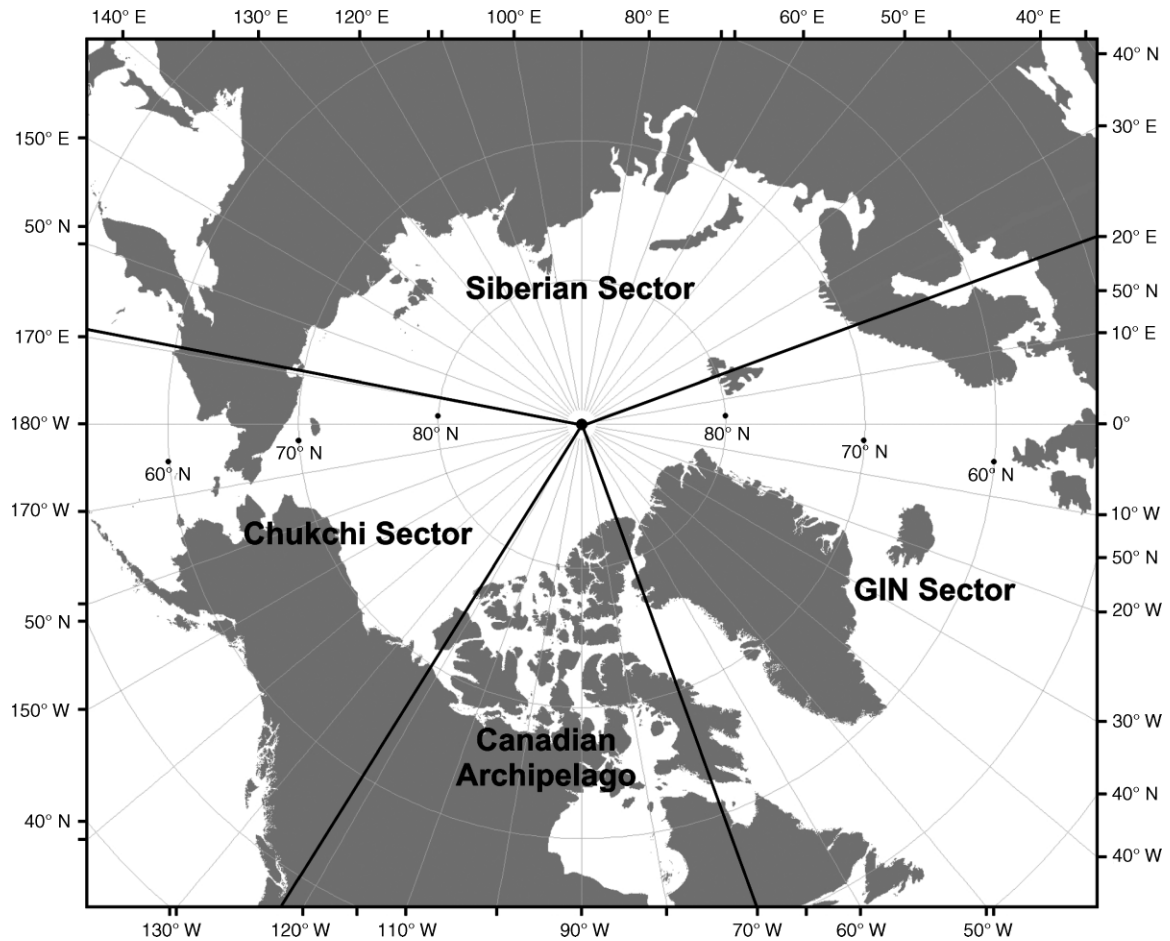


FIG. 3. Four regions of the Arctic for which resilience scenarios are provided for ice-obligate, ice-associated, and seasonally migrant species. Sector boundaries were based upon Figs. 14 and 15 in Walsh (2008) and with reference to continental shelf dynamics described in Carmack et al. (2006). The abbreviation GIN stands for Greenland-Iceland-Norwegian seas.

populations, we divide the basin into four regions (Fig. 3) based upon projections of sea ice loss by 2050 and extant variability in bio-oceanographic characteristics (Table 1). This exercise highlights some of the complexity of the Arctic marine ecosystem. For example, while the ice-free period is projected to increase by as much as 125 days in portions of the highly productive inflow systems represented by the Chukchi and Greenland-Iceland-Norwegian (GIN) sectors, only the latter is expected to retain a sea ice refugium in 2050. Conversely, the ice-free period is projected to increase by only

about 2.5 months (up to 75 days) on the lower productivity outflow and interior shelves, with a sea ice refugium likely in the Canadian Archipelago but not the Siberian sector.

The evolutionary history of marine mammals attests to the capability of many species to adjust to change (Harington 2008, O'Corry-Crowe 2008), but it lends little guidance as to how easily this was accomplished. With few exceptions, the population dynamics of extant Arctic marine mammal species are poorly quantified, precluding an assessment of demographic response to

TABLE 1. Summary of anticipated and extant environmental properties within four Arctic regions.

Region	Added days of open water	Existence of refugia	Shelf flow dynamics	Maximum APP ($\text{g C}/\text{m}^2$)
GIN sector	+125	yes	inflow and outflow	200
Canadian Archipelago	+75	yes	interior and outflow	70
Chukchi sector	+125	no	inflow	400
Siberian sector	+75	no	interior	50

Notes: Region boundaries are shown in Fig. 3. The abbreviation GIN stands for Greenland-Iceland-Norwegian seas. The anticipated increase in days of open water and existence of sea ice refugia in 2050 are from Walsh (2008: Figs. 14 and 15) and existing continental shelf flow dynamics and annual primary production (APP) measures are from Carmack et al. (2006: Figs. 2 and 13).

TABLE 2. Aggregate resilience scores for ice-obligate, ice-associated, and seasonally migrant marine mammals within four Arctic regions.

Species category	Canadian			
	GIN	Archipelago	Chukchi	Siberian
Ice-obligate				
Ice-free days	–	+	–	+
Sea ice refugia	+	+	–	–
Aggregate	uncertain	positive	negative	uncertain
Ice-associated				
Ice-free days	–	+	–	+
Sea ice refugia	+	+	–	–
Shelf flow	0	–	+	–
Production	+	–	+	–
Aggregate	positive	uncertain	uncertain	negative
Seasonally migrant				
Ice-free days	+	–	+	–
Sea ice refugia	–	–	+	+
Shelf flow	0	–	+	–
Production	+	–	+	–
Aggregate	positive	negative	positive	negative

Notes: Resilience capacity is scored as positive, negative, or uncertain based upon the anticipated combined effects on each species category of changes to the physical criteria that define the four regions. “Ice-free days” was scored as positive for increase in open water ≤ 75 days. “Sea ice refugia” was scored as positive only where refugia are anticipated to persist in 2050. “Shelf flow” was scored as positive when inflow predominates, negative when interior and outflow predominate, and zero for the GIN seas, where inflow and outflow are roughly in balance. “Production” was scored as positive for primary production ≥ 200 g C/m². The abbreviation GIN stands for Greenland-Iceland-Norwegian seas.

ecosystem variability (see Laidre et al. 2008). The resilience of Arctic marine mammals (meaning, in this case, their ability to adjust to the complexities of environmental alteration) will depend on individual animal’s adaptive capacity, which is beyond our capability to evaluate. Instead, we provide a gross evaluation of resilience for the three species groups presented in the conceptual model for each of the four regions.

Resilience scenarios

Resilience scenarios were constructed for ice-obligate, ice-associated, and seasonally migrant marine mammals by assigning either a positive (+) or negative (–) score to anticipated changes in sea ice and extant shelf oceanography in each of the four Arctic sectors (Table 2). Resultant scenarios for ice-obligate marine mammals were based solely on projected changes in sea ice due to their reliance upon it. Resilience for this species group was scored as strongly positive in the Canadian Archipelago and strongly negative in the Chukchi sector, due to the projected retention or reduction of sea ice, respectively. The future for ice-obligate species in the GIN and Siberian sectors is uncertain, although survivorship may be augmented by the anticipated retention of sea ice refugia in the former or by the number of days during which sea ice is available in the latter. Ultimately, if a sea ice refugium is critical to

survival, the range of ice-obligate marine mammals may be reduced to the Canadian Archipelago and GIN sectors, with potential for population extirpation in the Chukchi and Siberian sectors.

We scored the oceanographic parameters of shelf flow and primary production in our evaluation of resilience for ice-associated and seasonally migrant marine mammal species in an attempt to include additional ecosystem variability. Although ice-associated species may find trophic regimes similar to extant conditions near the sea ice refugia in the Canadian Archipelago and the GIN sector, resilience was scored as positive only in the latter due to productivity. Resilience for ice-associated species was scored as uncertain or negative for all other sectors. Seasonally migrant species achieved positive resilience evaluations in both the GIN and Chukchi sectors, due to the anticipated increase in ice-free days and measured high primary production in those regions. Conversely, resilience for migrant species was rated as negative in the Siberian sector and Canadian Archipelago, due to sluggish flow dynamics and low primary production in both regions.

These resilience scenarios represent only a crude summary of the potential for climate change to impact Arctic marine mammals. At this time, details of population dynamics, including estimates of animal numbers as well as health and body condition indices, are insufficient to allow a more detailed evaluation for most populations. However, novel research tools such as satellite telemetry, passive acoustic detection, and analytical chemistry can provide the means to improve assessments of species’ resilience to climate change. For example, satellite tagging and passive acoustics can effectively provide a window into the broad-scale seasonal movements and habitat selection of Arctic species (e.g., Suydam et al. 2001, Laidre et al. 2004, Moore et al. 2006). Similarly, examination of dietary variability and individual animal health by way of isotopic, fatty acid, and contaminant analyses (e.g., Burek et al. 2008) can provide a wealth of information about marine ecosystem trophic pathways. Human subsistence communities provide a strong link here, in that, as consumers of marine mammals, they are the first-line investigators of this system (Harwood et al. 2000, Hovelsrud et al. 2008, Metcalf and Robards 2008). A coordinated research response to climate change could more effectively use Arctic marine mammals as sentinels for the ecosystem.

FUTURE DIRECTIONS

The means to quantify marine mammal resilience to climate change varies by species, but can be considered in the aggregate with regard to species’ relationships to ice (Table 3). For ice-obligate species, projected reductions in sea ice are anticipated to result in declines in breeding success (e.g., Johnston et al. 2005) and body condition (e.g., Derocher et al. 2004). Because these species are the focus of subsistence harvests, the means

TABLE 3. Anticipated climate-related changes for ice-obligate, ice-associated, and seasonally migrant marine mammal species.

Species category	Anticipated change	Indicator	Monitoring approach	What we learn
Ice-obligate				
Polar bear†‡§	declines in recruitment and body condition	blubber thickness; tissue and stomach samples	measurements and biopsy during harvest; biochemical analyses; documentation of local knowledge	the level of energetic challenge posed by sea ice reduction; exposure of subsistence communities to toxins
Walrus§				
Bearded seals				
Ringed seals				
Ice-associated				
Bowhead whale†§	migration alteration and occupation of new feeding areas	harvest timing; tissue and stomach samples	documentation of local harvest and knowledge; visual and acoustic surveys; satellite tracking	changes in migration timing and trophic dynamics; exposure of subsistence communities to toxins
Beluga†‡§				
Narwhal‡§				
Seasonally migrant				
Gray whale†‡§	novel occupation of Arctic latitudes and longer residence times	harvest or detection of novel species	documentation of local harvest and knowledge; visual and acoustic surveys; satellite tracking	evidence of sympatry and potential for competition between arctic and temperate species; changes in trophic dynamics and availability of novel species to local hunters
Harbor seal†‡§				

Notes: Indicators and monitoring approach lead to what we learn. Suggested sentinel species listed are those with strong baseline data, for at least some populations, from census (indicated by a dagger, †) satellite tracking (indicated by a double dagger, ‡) and/or harvest monitoring (indicated by a section symbol, §).

to monitor effects of climate change are immediately at hand in the record stored in their tissues. Routine measurements of blubber thickness and extraction of tissue samples for biochemical analyses can provide data to directly investigate the level of diet variability associated with sea ice reduction. In the case of ice-associated marine mammals, the timing of hunts combined with the suite of measurements and analyses suggested for ice-obligate animals will provide information on changes in migration timing, trophic dynamics, and exposure of subsistence communities to toxins. Finally, seasonally migrant species are conspicuous indicators of ecosystem change (Laidre et al. 2008), and hunts or detections of these species by visual or acoustic means can provide a way to assess the potential for competition between Arctic and temperate species as well as to investigate changes in ecosystem trophic structure. In all cases, paired studies between sectors in which resilience scenarios predict different outcomes may be particularly useful in identifying causal mechanisms of observed changes in marine mammal numbers, distribution, and relative abundance.

Marine mammals as Arctic ecosystem sentinels

Reports of terrestrial species acting as climate change sentinels have become fairly commonplace (e.g., Root et al. 2003, Jonzén et al. 2006). Success in using marine mammals as Arctic marine ecosystem sentinels will depend upon selecting appropriate indicator species and parameters, ideally ones with extant population time series or routine availability for sampling via subsistence hunts (Table 3). In the ice-obligate category, polar bears are an obvious choice, as they have been the focus of international study for decades (e.g., Derocher et al.

2004). Multi-decadal time series are also available for some populations of bowhead whales (ice-associated) and gray whales (seasonally migrant), making them ideal candidates as sentinels (George et al. 2004, Rugh et al. 2005).

For example, evidence supports the idea that the eastern North Pacific gray whale population has responded to climate change at ocean basin scales. In brief, this population, which is thought to be at or near carrying capacity, has demonstrated: (1) southbound migration timing shifting one week later, coincident with the late 1970s regime shift in the North Pacific Ocean (Rugh et al. 2001); (2) calving rates that are positively correlated with early-season ice-free conditions in the Chirikov Basin (Perryman et al. 2002); (3) absence of feeding whales in the Chirikov Basin coincident with a decline in benthic infauna (Moore et al. 2003); and (4) the aforementioned detection of calls during winter northeast of Barrow, Alaska (Moore et al. 2006). When integrated with long-term physical and biological measures, this record of responses by gray whales strengthens the capability to track ecosystem alterations and their effects at regional scales (e.g., Grebmeier et al. 2006).

All other species recommended as sentinels (Table 3), including walrus, bearded seals, and ringed seals (ice-obligate), beluga and narwhal (ice-associated), and harbor seals, are taken by subsistence hunters. As noted above, measurements and tissue collected during hunts can provide key data for tracking effects of climate change on Arctic ecosystems. Furthermore, the involvement of marine mammal hunters can demonstrate the connections between marine mammals and people and between Arctic ecosystems and the rest of the world (for

further discussion of hunter and public involvement, see Hovelsrud et al. [2008], Metcalf and Robards [2008], Ragen et al. [2008]).

CONCLUSIONS

In a review of evidence for regime shifts in relation to resilience of complex ecosystems, Folke et al. (2004:575) conclude that "Active adaptive management and governance of resilience will be required to sustain desired ecosystem states and transform degraded ecosystems into fundamentally new and more desirable configurations." Resilience is a component of ecological stability commonly assessed as the rate at which a community recovers from perturbation (Neubert and Caswell 1997, Steiner et al. 2006). As such, resilience would seem to be nearly impossible to "govern," even in ecosystems less given to variability extremes than the Arctic. Nonetheless, the regional resilience scenarios and sampling protocols outlined here are a provisional framework for the kinds of conservation actions described in Ragen et al. (2008).

The Arctic climate has changed demonstrably in the last 50 years, with further projected changes of a magnitude not seen during the time frame of human history. These changes affect humans around the globe. We have an opportunity to enlist Arctic marine mammals and the people who depend upon them in a high-profile demonstration of the effects of a warming planet on an ecosystem often regarded as pristine. We should act decisively in research planning, resource management, and communication to seize this opportunity.

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