

Biological Responses to Climate Change

An exhaustive consideration of the biological consequences of the kinds of physical change that are predicted for the Arctic is not feasible at this time, nor is it warranted for identifying how biological changes might effect major change in contaminant pathways. Here, ecosystem changes are highlighted that appear to have a strong potential to alter the exposure of Arctic biota to contaminants or to alter their resilience to that exposure. There is general agreement that the kinds of changes discussed below have, or will, take place in the Arctic but much less agreement concerning their probable scope and timing. The primary intent, therefore, is to provide examples of processes that ought to be included explicitly in models and to help focus future attention on biological connections of significance to contaminants.

Whereas aquatic food webs in the Arctic exhibit endemic contamination from biomagnifying chemicals, terrestrial food webs are among the world's cleanest (AMAP 2003b; de March *et al.*, 1998). Therefore, apex feeders that adapt to change by switching between land-based and aquatic food webs have a particularly large potential to change their exposure to contaminants such as organochlorine compounds (OCs) and mercury. Humans probably provide the best example of such flexibility but other animals (e.g., Arctic foxes (*Alopex lagopus*) and grizzly bears (*Ursus arctos*)) can also adjust diet to opportunity.

4.1. Terrestrial systems

In this report terrestrial systems are defined as including forests, grasslands, tundra, agricultural crops, and soils. Surface-air exchange between airborne contaminants and terrestrial systems is important in the overall fate and long-range transport of chemicals, especially for the semi-volatile chemicals which are split between the gaseous and condensed states. As a result of their high organic content, terrestrial phases (e.g., soils, forests, grasslands) act as reservoirs for many persistent organic pollutants (POPs) (Simonich and Hites, 1994), particularly polychlorinated biphenyls (PCBs), DDT, hexachlorohexane (HCH) and chlorobenzenes (AMAP, 2003b). Air-surface exchange of POPs into terrestrial phases is a dynamic process that controls air burdens of chemicals. Thus any change in the extent of vegetation cover associated with global warming will have implications for contaminant fate and transport. Wania and McLachlan (2001) have shown that forests have a unique ability to mitigate atmospheric concentrations of OCs by 'pumping' chemicals from the atmosphere into foliage and thence to a long-term reservoir in forest soil. This process is likely to be most important for OC compounds with $\log K_{OA}$ of ~ 9 to 10 and $\log K_{AW} \sim -2$ to -3 (where K_{OA} and K_{AW} are octanol-air and air-water partition coefficients – see Wania, 2001). Because these key properties are strongly temperature-dependent (see section 6.3.4. for greater detail) even a small change in climate may alter the dynamics of this process and thus the cycling of

contaminants. Terrestrial vegetation also has an indirect impact on contaminants by altering snow accumulation and soil temperature (Sturm *et al.*, 2001).

Arctic terrestrial animals have provided some of the clearest examples of large cycles in their populations (Krebs *et al.*, 2001; Predavec *et al.*, 2001) and it is against this natural background variability that the effects of global change will have to be evaluated. Warmer winter temperatures promote the growth of woody shrubs and encourage the northward migration of the tree line (MacDonald *et al.*, 1993; Serreze *et al.*, 2000; Vörösmarty *et al.*, 2001). Although the advance of the tree line (estimated at 100 km per °C warming (IPCC, 2002)) might be expected to occur slowly over time scales measured in centuries, the particular sensitivity of tundra to water-table fluctuations and permafrost melt could produce widespread alteration in ground cover more rapidly with, for example, the replacement of tundra by vascular plants (Gorham, 1991; Rouse *et al.*, 1997; Weller and Lange, 1999). Gradual climate change can affect species distribution, abundance, morphology, behavior, population diet and community structure (East-erling *et al.*, 2000; Predavec *et al.*, 2001). Although there appears to be no compelling evidence of recent large change in the Arctic tundra ecosystem, models suggest that tundra may decrease to one third of its present size (Everett and Fitzharris, 1998).

Warmer summer temperatures are likely to promote forest fires which will be accompanied by direct emissions of polyaromatic hydrocarbons (PAHs), polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and other POPs produced by combustion (see for example, Gribble, 1994; Yunker *et al.*, 2002). Forest fires will also damage terrestrial soils leading to erosion and an increased release of organic carbon, which in turn affect aquatic systems.

4.2. Aquatic systems

4.2.1. Lakes, rivers and estuaries

The changes in snow and ice cover and in the hydrological cycle will alter the light and nutrient climate of freshwater systems. These changes together with loss of permafrost, which will enhance the supply of nutrients and particulates to lakes, will increase aquatic productivity and particle flux (Douglas *et al.*, 1994; McDonald *et al.*, 1996; Schindler, 1997). Although the spring bloom will probably advance with early loss of ice cover, hydrological processes in a lake's drainage basin will probably also advance. Increased summer temperatures will disadvantage fish such as trout (*Salmo* spp.) and grayling (*Thymallus arcticus*) whereas winter temperature increase may enhance microbial decomposition. Shifts in the seasonal light/temperature cycle may also advantage or disadvantage species lower in the food web including phytoplankton, zooplankton and insects. Change in water level will have obvious effects on important fish

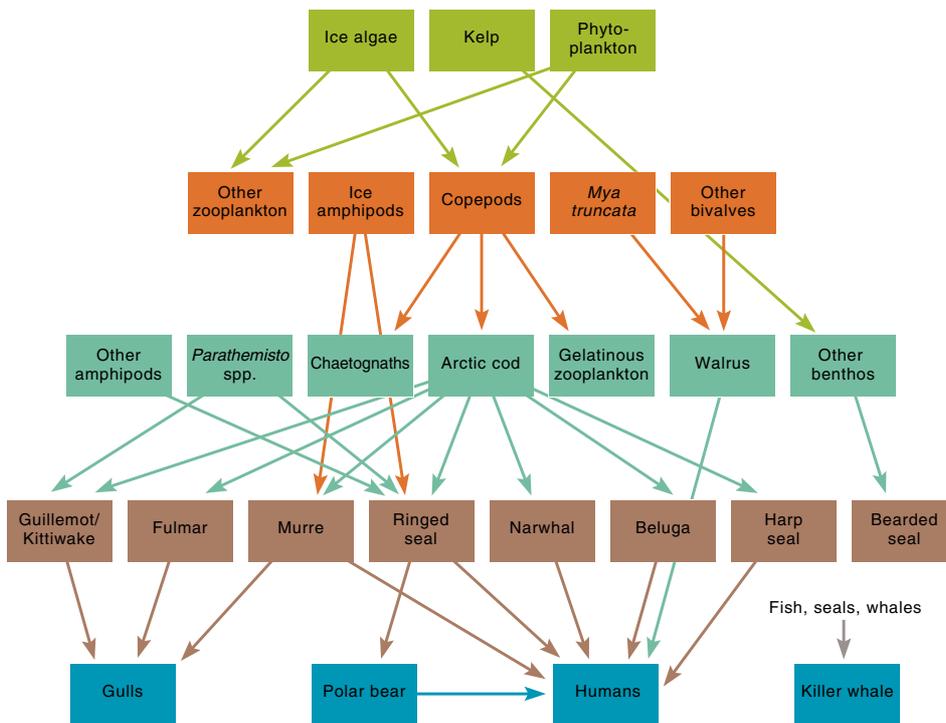


Figure 4.1. A simplified schematic diagram showing the marine food web (based on Welch *et al.*, 1992).

stocks, especially species dependent on small refugia for over-wintering (Hammar, 1989) or species dependant on freshwater coastal corridors for their life cycle; the Arctic cisco (*Coregonus autumnalis*) provides a relevant example of the latter (see Gallaway *et al.*, 1983). Warming and loss of nearshore or estuarine ice in the Beaufort Sea may eliminate indigenous fish which are then replaced by anadromous fish from the Pacific Ocean (see Babaluk *et al.*, 2000). Although warming is likely to result in widely-distributed shifts in zoogeographic distributions that have the potential to affect every step in the freshwater food chain, prediction will probably founder on 'counter-intuitive' surprises (Schindler, 1997).

4.2.2. The ocean

The effect of ice on Arctic marine ecosystems has long been understood by those who harvest the sea (Bockstoe, 1986; McGhee, 1996; Scoresby, 1969; Vibe, 1967). Change in ice climate, therefore, has a large potential to modify marine ecosystems, either through a *bottom-up* reorganization of the food web by altering the nutrient or light cycle, or a *top-down* reorganization by altering critical habitat for higher trophic levels (see, for example, Parsons, 1992). Any reorganization that changes the number of trophic levels in the food web or alters the flow of carbon between, for example, pelagic and benthic food webs would have particular significance for contaminants that biomagnify, such as mercury and the OCs; the complexity of the interaction between ice and aquatic ecosystems provides much scope for alterations in contaminant pathways (Figure 4.1). Arctic and sub-arctic marine ecosystems are also altered by ocean climate changes such as regime shifts involving the displacement of water masses and associated populations or temperature change (Figure 4.2; Dippper and Ottersen, 2001; Hare and Mantua, 2000; Helland-Hansen and Nansen, 1909; Hunt *et al.*, 1999; Loeng, 2001; Saar, 2000; Sakshaug *et al.*, 1991, 1994).

There are too many examples of how ice climate variation can affect ecosystem structure to list them all (see for example Sakshaug and Slagstad, 1992; Tynan and DeMaster, 1997) and it is not likely that all changes that have occurred in Arctic systems have been observed. The thickness and distribution of ice can influence the amount of organic carbon produced, the types of algae that produce it, and connections between the algal production and communities in the water column or sediments (Niebauer and Alexander, 1985). Ice controls wind mixing and light penetration especially when covered with snow, and it may also support upwelling at the ice edge but suppress upwelling beneath the ice. Through its annual cycle, ice formation decreases stratification in winter but increases stratification when the ice melts in spring. These physical factors impact upon the nutrient supply to surface water, the light climate, and the water stability which together control primary production. Furthermore, mats of algae that grow on the bottom of the ice support an epontic food web that ultimately feeds Arctic cod (*Boreogadus saida*), ringed seals (*Phoca hispida*) and polar bears (*Ursus maritimus*) or, alternatively, by being shed from melting ice in spring, support a benthic food web that feeds molluscs, walrus (*Odobenus rosmarus*), bearded seals (*Erignathus barbatus*) and king eiders (*Somateria spectabilis*). Similarly, primary production within the water column may be partially grazed to support a pelagic food web, or descend ungrazed and, together with fecal pellets and zooplankton carcasses, feed the benthos (Grebmeier and Dunton, 2000). The bifurcation between pelagic and benthic food webs is strongly influenced by the distribution of ice and its impact on nutrient and light climates. These processes, which have great potential to alter the timing and amounts of vertical particle flux in the ocean, are likely to have a greater impact on the sequestering of POPs into the Arctic Ocean than air-sea exchange or the so-called 'cold-condensation' effect. Dachs *et al.* (2002) show that in mid-latitudes, sinking particulate matter, which is

the dominant export pathway for POPs from the ocean surface layer, drives deposition at the ocean surface.

Shifts in benthic species distribution due to temperature, carbon flux or other climate-related change have the potential to alter completely the coupling between sediments and bottom water. In one well-documented example from a temperate region, the invasion of Echiura (*Listriolobus pelodes*) into coastal benthic communities off California, for as yet unknown reasons, resulted in aerated and biomixed sediments that reduced the evidence of wastewater impacts regionally (Stull *et al.*, 1986).

4.2.2.1 Bottom-up trophic change

The projected loss of ice for the Arctic Ocean, particularly over the shelves, intuitively should increase primary production in the marginal seas through enhanced mixing, light penetration and upwelling. In other words, Arctic shelves would begin to look more 'temperate'. Greater new production implies greater particle flux and greater secondary production, but the complexity of marine ecosystems should forewarn of possible surprises. Massive blooms of jellyfish were observed in the Bering Sea during in the 1990s (Brodeur *et al.*, 1999; Hunt *et al.*, 1999) and their emergence was ascribed to sea-surface temperature increase and loss of ice cover – the same two key changes poised over the Arctic Ocean.

Parsons (1979) has drawn attention to the fundamental ecological differences between western seaboard in the Northern Hemisphere, where coastal water exhibits divergence and upwelling, and eastern seaboard which are convergent. The former have been of greater commercial interest but are also characterized by jellyfish (Parsons, 1979). The Arctic Oscillation (AO) does not cause reversal of large-scale wind circulation but does produce more divergent Arctic Ocean margins under AO⁻/anticyclonic conditions and less divergent margins under AO⁺/cyclonic conditions. The inherently noisy events of coastal upwelling and downwelling could then act together with the AO in a form of 'stochastic resonance' (Rahmstorf and Alley, 2002) to enhance upwelling during AO⁻ conditions. This enhanced upwelling might then have the capacity to produce large-scale modal shifts in shelf ecosystems and their commercial potential. Changes in ocean climate, such as those associated with the AO/NAO, have long been known to affect fisheries in sub-polar seas either directly through water property changes (T, S) or indirectly through changes in community structure (Hare and Mantua, 2000; Klyash-torin, 1998; Marteinsdottir and Thorarinsson, 1998).

A dramatic example of large-scale, bottom-up biological change was witnessed during the SHEBA drift across the Beaufort and Chukchi Seas in 1997 to 1998 (Melnikov *et al.*, 2002). Compared to Soviet observations from drifting stations that passed over the same region 20 years earlier, there was a marked decrease in large diatoms in the water column and microfauna within the ice. The freshening and strong stratification of the surface water, due to river discharge diverted into the basin under the strong AO⁺ conditions of the early 1990s, reduced the supply of nutrients from below, and promoted species more typical of freshwater ecosystems. Consequentially, there was a high proportion of recycled

production and less new production. The loss of relatively large diatoms could reduce the size of herbivores, potentially inserting an extra 'small-carnivore' step at the bottom of the food web which would increase the number of trophic levels. Because biomagnification of OCs is often exponential (Fisk *et al.*, 2001a), slightly higher concentrations at low trophic levels (e.g., copepods) can have a large impact on apex feeders. Stratification, which is altered at the basin scale under AO/NAO shifts, affects plankton composition and vertical flux dramatically as evident from studies in the Barents Sea (Wassmann, 2001). For example, Wassmann *et al.* (1990) showed that algal blooms by *Phaeocystis* sp. along the Greenland coast and in the Barents Sea tend not to get grazed resulting in a large transfer of organic carbon to the benthos. Climate change in the form of either loss of ice cover or increase in stratification has the potential to alter the quantity of available food and to redistribute its flow between epontic, pelagic and benthic habitats.

The Bering Sea provides another outstanding example of recent change from the bottom-up permeating an entire ecosystem. In view of the Bering Sea's vulnerability to airborne contaminants from Asia (Bailey *et al.*, 2000; Li *et al.*, 2002), it is particularly regrettable that the observations of ecosystem change since the 1970s were not matched by contaminant pathway studies. Evidence from stable isotope records in bowhead whale (*Balaena mysticetus*) baleen suggests that the carrying capacity of the Bering Sea ecosystem began to decline in the mid 1970s (Figure 4-2a, Schell, 2000). This change may relate to a larger picture of change throughout the North Pacific (Hare and Mantua, 2000) and, in particu-

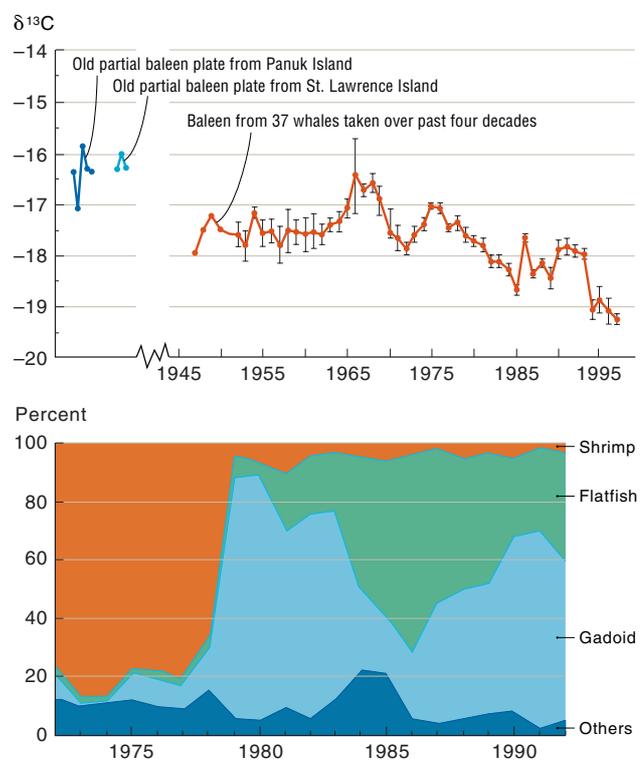


Figure 4-2. Examples of significant change within Arctic and sub-arctic ecosystems. This figure illustrates a) a change in the food web structure probably commencing during the 1970s as reflected by a decrease in the $\delta^{13}\text{C}$ of baleen from bowhead whales (Schell, 2000) and b) significant fish population changes in the Gulf of Alaska since 1970 (modified from Anderson and Piatt, 1999).

lar, to the switch in the Pacific Decadal Oscillation (PDO) from cold to warm phase in the mid 1970s. The change in regime rapidly permeated the entire ecosystem of the Bering Sea altering fish community structure (shrimp and crab populations declined while pollock, cod and flatfish populations increased significantly Figure 4-2 b), and seabird and mammal populations (Springer, 1998). More recently, blooms of small phytoplankton (*Emiliana huxleyi*) were observed in 1997 and 1998 (Saar, 2000). Because these phytoplankton are smaller than the diatoms that typically bloom in the Bering Sea, they were grazed by smaller copepods instead of larger euphausiids which in turn probably led to die-offs of the short-tailed shearwaters (*Puffinus tenuirostris*) that feed on the latter (Stockwell *et al.*, 1999). Similarly, the alteration of primary production both in quantity and distribution probably decreased food availability for fish, whale, seal and walrus populations forcing die-offs, migration or redistribution throughout the food web (Botsford *et al.*, 1997; Grebmeier and Cooper, 1995; Grebmeier and Dunton, 2000; Hare and Mantua, 2000; Rugh *et al.*, 1999; Stabeno and Overland, 2001). Large as these ecosystem changes appear to have been, they may pale in comparison to the natural fluctuations that have occurred during the past two millennia (Finney *et al.*, 2002). Furthermore, these long-term proxy data provide a strong warning that relationships between biological populations and physical forcing established from short observational records may not hold up over a longer period when other non-linear factors may have a chance to operate (initial conditions, or other cyclical forcing, for example). Clearly, the dramatic changes in the Bering Sea system could spill over into the Chukchi Sea, and the decline of Bering inflow by ~15% since the 1940s (Figure 3-20 a) suggests a matched decline in new and advected production in the Chukchi Sea simply due to reduced nutrient and organic carbon supply.

In the Barents and Nordic Seas it has long been recognized that fish populations respond to climate variability (Helland-Hansen and Nansen, 1909). Indeed, the distribution of capelin (*Mallotus villosus*), the single most important food species for Arcto-Norwegian cod, is known to vary from year to year dependent on the inflow of Atlantic water (Sakshaug *et al.*, 1994). Fluctuations in large- and regional-scale atmospheric pressure conditions affect winds and upper ocean currents (Figures 3-2 and 3-17), modify water temperature, alter drift patterns of fish larvae, and change availability of prey items. Mixing during summer alters the nutrient cycle and the coupling between primary production and benthos (Peinert *et al.*, 2001; Wassmann, 2001). Details are important. For example, while long and unrestricted larval drift is crucial for the Arcto-Norwegian and Icelandic component of cod stocks at West Greenland, larval retention on favourable banks is the key for recruitment to stocks residing in small and open systems (Ottersen, 1996). The 600 to 1200 km drift of Arcto-Norwegian cod larvae from spawning grounds to nursery grounds where they settle on the bottom provides much opportunity for interannual variation; pelagic juveniles in the Barents Sea exhibit a typical westerly distribution in some years while, in other years they distribute to the east (Ådlandsvik and Sundby, 1994). Ottersen and Sundby (1995) showed that southerly wind anomalies during

the period of pelagic drift from the main spawning grounds in the Lofoten area in northern Norway to the nursery grounds in the Barents Sea leads to above average year-class strength. This was attributed in part to temperature and in part to added supply of zooplankton-rich water from the Norwegian Sea into the feeding areas of the Barents Sea.

For older fish, other factors may contribute to inter-annual variation. During periods of high abundance, fish density may cause the geographic range of Arcto-Norwegian cod to expand or shift. Temperature has been reported to cause displacement of Arcto-Norwegian cod – toward the east and north during warm periods and toward the south-western part of the Barents Sea in cold periods (Ottersen *et al.*, 1998). These shifts may not be caused by temperature itself but, rather, by temperature-induced changes in the distribution of prey organisms (Ottersen, 1996).

Loeng (2001) has discussed the types of change that may well occur in the Nordic seas should ocean temperature rise, as projected, by 1 to 2°C (Figure 4-3). In the Barents Sea the feeding area of capelin will be displaced to the northeast and the spawning ground may move eastward along the northern coast of Russia. Cod will distribute more toward the northeast partly because acceptable ocean temperature will be found there and partly because their main food item, capelin, will move in that direction. These displacements will put such stocks closer to contaminant sources in the eastern Barents Sea. In the Norwegian Sea, the Norwegian spring spawning herring (*Clupea harengus*) may return to the migration route they used prior to the mid 1960s, when ocean temperature around Iceland was over 1°C higher than today. Presently, adult herring over-winter in a Norwegian fjord before commencing their spawning migration along the Norwegian coast followed by a feeding migration into the Norwegian Sea. With temperature increase, the herring may over-winter after the feeding migration just east of Iceland as they did before 1965,

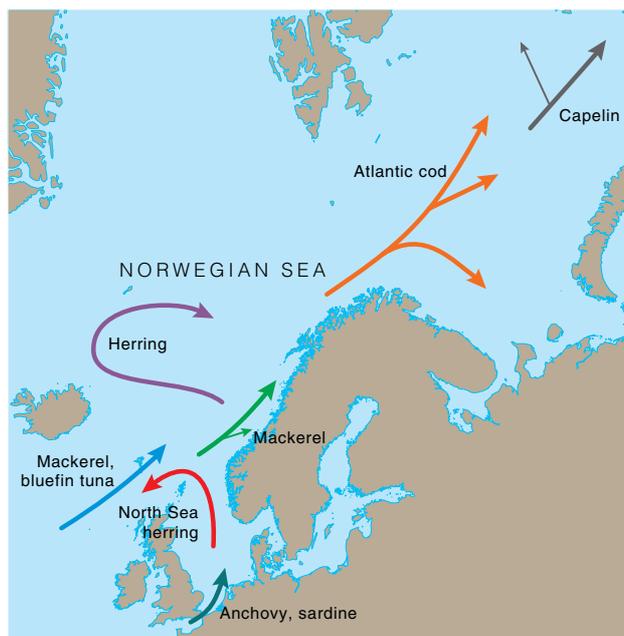


Figure 4-3. Possible changes in the distribution of selected fish species in the Nordic and Barents Seas resulting from an increase in sea temperature of 1 to 2°C (modified from Loeng, 2001).

and not return to the Norwegian fjord, completely altering their exposure to contaminants. New species may invade. Presently, mackerel (*Scomber scombrus*) is scarce along the coast of northern Norway, but with ocean warming might migrate as far as the Barents Sea. Blue whiting (*Micromesistius poutassou*), bluefin tuna (*Thunnus thynnus*) and sharks (Elasmobranchia) may also become more frequent visitors to this area.

4.2.2.2. Top-down trophic change

Ice-covered seas have a unique capacity for top-down trophic change. To understand and predict how the partial or complete loss of ice will impact upon the trophic structure requires a detailed understanding of how top predators take advantage of ice (Carmack and Macdonald, 2002; Lowry, 2000; Vibe, 1967). In an incisive review, Tynan and deMaster (1997) discuss how whales, walrus, seals, bears and cod, are likely to be affected by change in ice climate and show that their response to change depends on how 'plastic' their dependence on ice might be.

Change in the *landfast ice* may give the advantage to either seals or to bears (Carmack and Macdonald, 2002) with the result that Arctic cod would be subject to more, or less, predation, respectively. Walrus use *drifting ice* to haulout in winter because it provides better access to benthos, but they also use terrestrial haulouts in ice-free periods, perhaps with detrimental energy costs (Lowry, 2000; Tynan and DeMaster, 1997). In contrast, eiders (*Somateria* spp.) and other benthic-feeding birds prefer *open water* with a relatively shallow bottom (<50 m) (Dickson and Gilchrist, 2002; Grebmeier *et al.*, 1988; Suydam *et al.*, 2000). Loss of ice (landfast or drifting) in critical regions or at critical times of the year, or movement of the ice edge to deeper water where benthos can no longer be accessed, therefore, can mean a substantial rearrangement of the top of the food web advantaging some animals, disadvantaging others and possibly causing wholesale migration (Dyke *et al.*, 1996b, 1999; Dyke and Savelle, 2001; Fay, 1982; Lowry, 2000; Moore and Clarke, 1986; Tynan and DeMaster, 1997; Woollett *et al.*, 2000). With benthos not readily available, walrus might turn to predation on seals thereby raising their trophic position considerably (Muir *et al.*, 1999), or with absence of ice, killer whale (*Orcinus orca*) predation on bowhead whales might decimate their population leaving their prey (zooplankton) as food for something else. Early breakup in the Bering and Beaufort Seas during 1995 to 1998 probably led to the observed abandonment of seal pups in 1998 and the decline or starvation of walrus.

The Hudson Bay polar bear population provides perhaps one of the clearest warnings of the consequence of

change. Polar bears rely on ringed seals for food, and ringed seals prefer landfast or stable first-year ice for pupping (Finley *et al.*, 1983; Stirling, 2002; Wiig *et al.*, 1999). The loss of landfast ice in spring, the loss of food supply for seals, or the inability of bears to access seals during the few critical weeks in spring when pupping occurs, means life or death and can produce large population shifts (Harwood *et al.*, 2000; Smith and Harwood, 2001; Stirling *et al.*, 1999). In Hudson Bay, bears probably accumulate most of their annual energy requirements during the few months of late spring prior to breakup when they can access older pre-weaning ringed-seal pups or naïve post-weaning pups – exactly the period of time that has seen recent dramatic change (Figure 3-23). Furthermore, permafrost is a critical habitat for bears because they dig maternity dens in frozen peat, and this habitat is threatened by warming or increased incidence of fire initiated by more frequent lightning strikes. In Hudson Bay, at the southern limit of their population, polar bears presently appear to be in a very precarious position (Stirling and Derocher, 1993; Stirling *et al.*, 1999).

Arctic cod is the most important forage fish in the Arctic Ocean food web (Figure 4-1; Bradstreet *et al.*, 1986; Tynan and DeMaster, 1997; Welch, 1995). The loss of ice, in either the marginal seas or, as projected by models, for the entire ocean (Figure 2-2b, Flato and Boer, 2001), would have a massive impact on the distribution and life history of Arctic cod and, therefore, on seals, beluga (*Delphinapterus leucas*) and birds who depend heavily on them. One thing is clear: the ice edge is an especially critical habitat for cod and marine mammals and it is this region that is most vulnerable to change.

Finally, climate change can alter the routes and destinations of migratory species. For example, under the AO+ conditions of the early 1990s, Pacific salmon (*Oncorhynchus* spp.) began to enter Arctic rivers (Babaluk *et al.*, 2000). Similarly, bowhead whales and belugas range widely in search of food and their range varies enormously in time and space with changes in ice climate (Dyke *et al.*, 1996b; Dyke and Savelle, 2001; McGhee, 1996). Nor are long migrations limited to whales. Harp seals (*Phoca groenlandica*) of the Northwest Atlantic undergo 8000 km round trips to feed on Arctic cod in Baffin Bay (Finley *et al.*, 1990) and bird species migrate inordinately long distances often depending on critical areas along their migration pathways where they may ingest contaminants (see, for example, Braune *et al.*, 1999; Savinova *et al.*, 1995; Springer, 1998). The extent to which migratory species are able to adapt to potentially rapid changes in key staging areas may be of critical importance to their future (Carmack and Macdonald, 2002).