

Oceanography of the Canadian Shelf of the Beaufort Sea: A Setting for Marine Life

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ABSTRACT. Conservation of marine biodiversity in the Beaufort Sea demands that we understand what individual organisms require of their physical and geochemical environments in order to survive. Specifically, how do the extraordinary spatial and seasonal variations in ice cover, temperature, light, freshwater, turbidity, and currents of the Beaufort Sea define unique places or times critical to marine life? We start with the traditional “bottom-up” approach, which is to review the strongly seasonal physical forcing of the system, and from it to infer the resultant oceanographic regimes and seasons. This approach, while valuable, remains incomplete: this is due partly to limitations of the data and partly to our limited understanding of this complex system. The oceanographic features (e.g., upwelling regions, recurrent polynyas, coastal currents, sediment types and distributions) define the backdrop that animals “know and understand” in the sense of interacting with one another and finding food and habitat. We therefore seek clues to the underlying oceanographic processes in the behavioural patterns of fish, marine mammals, and birds. This “top-down” approach also has limitations, but it offers the opportunity to seek those connections in the system where climate change is likely to have its greatest impact on biological populations.

Key words: Beaufort Sea, global warming, upwelling, sea ice, nutrients, sediments

RÉSUMÉ. La conservation de la biodiversité marine dans la mer de Beaufort passe par notre compréhension des éléments nécessaires à la survie des organismes individuels au sein de leur environnement physique et géochimique. En particulier, comment les variations spatiales et saisonnières extrêmes dans le couvert glaciaire, la température, la lumière, l'eau douce, la turbidité et les courants de la mer de Beaufort définissent-elles des espaces uniques ou des périodes critiques à la vie marine? On commence avec l'approche traditionnelle «ascendante» qui consiste à examiner les pressions physiques largement saisonnières qui s'exercent sur le système, et on déduit les régimes et saisons océanographiques qui en découlent. Cette approche, tout en étant intéressante, reste incomplète, en partie à cause du manque de données et en partie à cause de notre compréhension insuffisante de ce système complexe. Les caractéristiques océanographiques (p. ex., les zones de remontée d'eau profonde, les polynies récurrentes, les courants côtiers, les types de sédiments et leur distribution) définissent l'arrière-plan que les animaux «connaissent et comprennent» au sens où ils y interagissent les uns avec les autres pour y trouver nourriture et habitat. On recherche par conséquent, dans les schémas de comportement des poissons, des mammifères marins et des oiseaux, des indices témoignant des processus océanographiques sous-jacents. Cette approche «descendante» a aussi ses limites, mais elle offre l'occasion de rechercher au sein du système les liens où le changement climatique est susceptible d'avoir le plus grand impact sur les populations biologiques.

Mots clés: mer de Beaufort, réchauffement climatique, remontée d'eau profonde, glace de mer, nutriments, sédiments

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INTRODUCTION

The Canadian Shelf in the southeastern Beaufort Sea is a broad rectangular platform (width ~120 km; length ~530 km) bordered by Amundsen Gulf to the east, Mackenzie Canyon to the west, the Mackenzie River delta to the south, and the Beaufort Sea to the north (Fig. 1). This shelf provides habitat for a dynamic biological community of resident (e.g., seals, bears, fish) and migratory (e.g., birds, fish, whales) populations (Dickson and Gilchrist, 2002; Harwood and Smith, 2002; Stirling, 2002). These animals are adapted not only to endure the environmental extremes characteristic of this region (e.g., ice cover, large temperature range, winds), but also to exploit them. Two aspects

of the physical environment of the Canadian Shelf merit special mention with respect to the marine life. First, it is a great estuary that draws its water and associated properties, such as nutrients, organic carbon, plankton, and sediments, from both an oceanic source in the Arctic Ocean (Carmack et al., 1989) and a coastal source in the Mackenzie River (Omstedt et al., 1994; Macdonald et al., 1998). Second, it is subject to extreme annual and interannual variations in both its ice cover and its river inflow (Fig. 2). The source of the water drawn to this shelf has great significance for the biota, not only in constraining the opportunity for growth (primary production) but also as a source of, or corridor for, “seed” populations. The surface domain of this region of the Arctic Ocean is clearly

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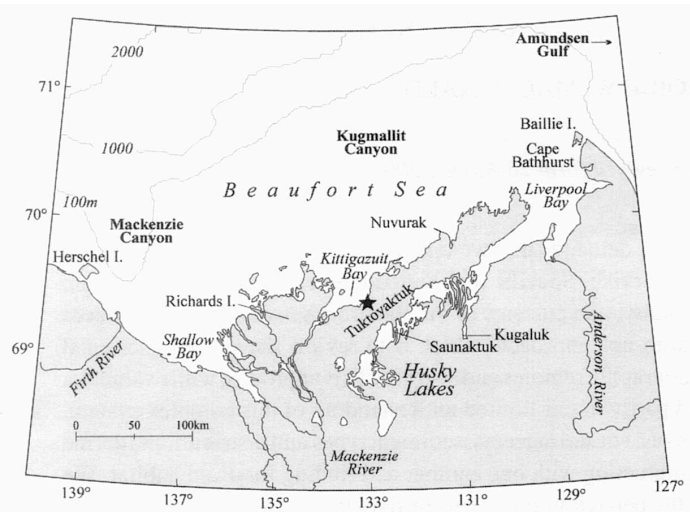


FIG. 1. The Canadian Shelf, showing the coastline, bathymetry, and place names used in text.

supplied by the Pacific Ocean (cf. McLaughlin et al., 1996), but the deeper water below 200 m or so originates in the Atlantic Ocean (Macdonald et al., 1989). These water sources explain why biological species from both the Atlantic and Pacific Oceans can be found in the Beaufort Sea, but not why there is a low frequency of Pacific macroalgal communities in contrast to a high frequency of Pacific animal species (Dunton, 1992). The dominant influence of a major river, the Mackenzie, ensures the presence of freshwater biota—including anadromous fish—at least in the nearshore area (Parsons et al., 1988, 1989; Bodaly et al., 1989). The objectives of the present paper are (a) to describe physical and chemical variability of the Canadian Shelf, (b) to relate these to the requirements of marine biota, and (c) to speculate on the challenges and opportunities that climate change may provide to biota.

Earlier studies have established the basic circulation of the Beaufort Sea (cf. Giovando and Herlinveaux, 1981). Offshore, the clockwise Beaufort Gyre dominates the mean, large-scale movement of sea ice and surface water (cf. Coachman and Aagaard, 1974, for description of structure; and McLaren et al., 1987, for discussion of variability). Below the surface waters, however, the flow reverses to counter-clockwise, forming the so-called Beaufort Undercurrent (Aagaard, 1984). This flow moves waters of both Pacific and Atlantic origin eastward along the continental margin (Coachman and Barnes, 1961; Aagaard, 1989) and provides an offshore source of nutrients to shelf waters (Macdonald et al., 1987). The importance of mesoscale eddies as a transport mechanism within the Beaufort Sea has been stressed by Newton et al. (1974), Hunkins (1974), Manley and Hunkins (1985), D’Asaro (1988), Aagaard (1989), and Aagaard and Carmack (1994). Temporal and spatial variability in water mass properties in the adjacent Canada Basin have been documented by Melling (1998) and McLaughlin (2000).

On the Canadian Shelf, the circulation is highly variable, and mean velocities are generally small compared to

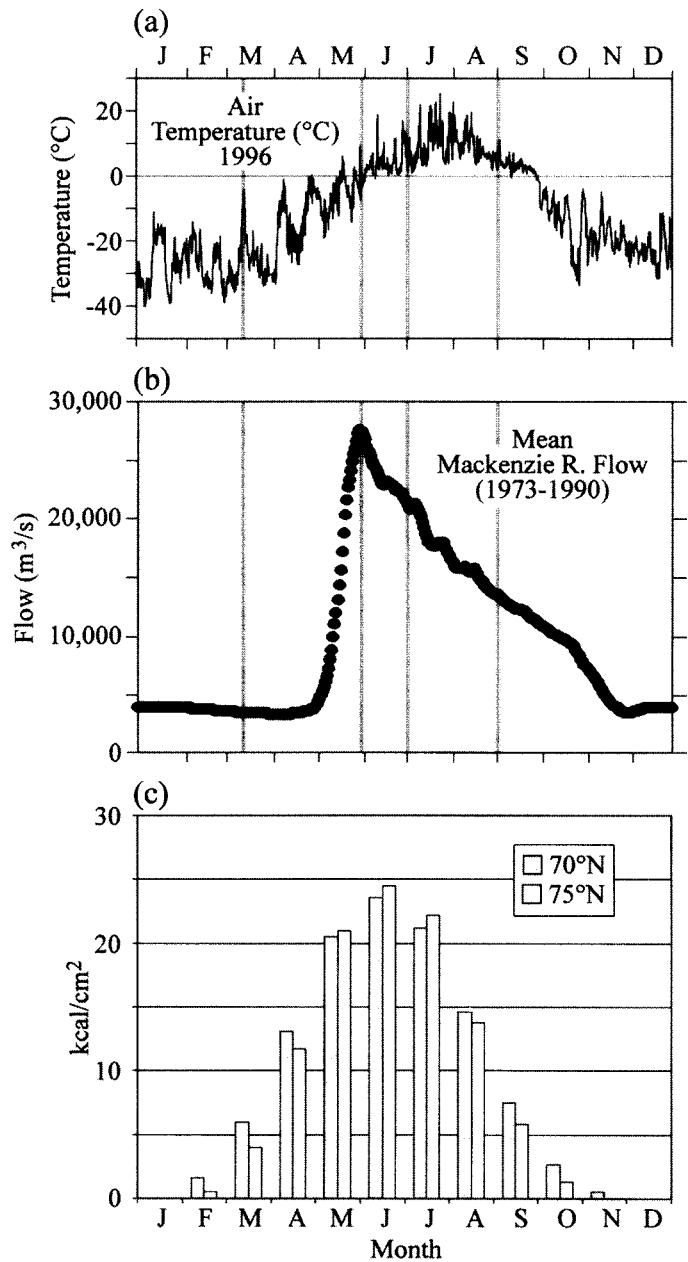


FIG. 2. Annual cycles of (a) air temperature (at Tuktoyaktuk), (b) Mackenzie River discharge, and (c) incident solar radiation. The grey vertical lines in the top two panels refer to the four seasons discussed in the text and represented in Fig. 3: end of winter, spring freshet and break-up, summer open water season, and fall mixing and freeze-up.

the fluctuating field (Melling, 1993). Flow events related to synoptic-scale wind forcing along the Beaufort coast have been reported by Cameron (1951), Hufford (1975), Giovando and Herlinveaux (1981), Kozo and Robe (1986), and Kulikov et al. (1998). Tidal currents on the Canadian Shelf are generally weak, as is typical of Arctic seas, except in the vicinity of the shelf break north of Cape Bathurst, and thus are not a major source of mixing energy (Henry and Foreman, 1977; Kowalik and Prushutinsky, 1994). During summer, inflows from the Mackenzie River dominate surface property distributions (Omstedt et al., 1994). During winter, when the sea is ice-covered, wind

effects are diminished, and density-driven flows due to brine release are possible (Melling and Lewis, 1982; Melling, 1993). The shelf is cut by two major submarine canyons, the wide Mackenzie Canyon and the narrow Kugmallit Canyon, which are potential sites of upwelling (Macdonald et al., 1987; Carmack and Kulikov, 1998).

The present overview is aimed not towards giving a definitive review of physical and geochemical processes, but rather towards providing a framework for understanding interactions between the physical environment and marine biota. We examine a number of key questions pertaining to nutrient regimes, underwater light, and pelagic, benthic, and sea-ice habitats. What is the temporal and spatial variability in circulation and ice? What is the seasonal disposition of Mackenzie River water? What is the influence of submarine canyons (Mackenzie and Kugmallit) on cross-shelf flow, upwelling, and productivity? What is the influence of ice, river input, and wind resuspension on bottom sediments and benthic habitat? What are the joint effects of wind and thermohaline forcing of water motions that drive shelf/basin exchanges? Finally, we ask: How might the timing, location, and magnitude of seasonal events change under an altered climate?

SEASONS ON THE SHELF

The oceanography of the shelf can be viewed as having four seasons, which are produced by the interaction between the two predominant cycles: runoff and air temperature (cf. Macdonald, 2000; Fig. 2a, b). Air temperature plays an obvious role in the sea-ice freeze/melt cycle. Of equal importance to biology on the shelf is the annual runoff cycle, because it supplies important properties (e.g., nutrients, sediments, plankton), influences circulation, regulates vertical stratification (an important control on primary production), and affects the underwater light climate. The following description, based on four seasons, is admittedly an oversimplification, but it illustrates our view that the timing of seasonal events such as freshet, breakup, and freeze-up is more important to biota than standard quantifiable measures (e.g., annual discharge, ice thickness). Thus, climate change—and other changes brought on by human activities—may impact biota by altering the timing and coupling of environmental cycles, rather than by changing their magnitudes.

The End of Winter

The end of oceanographic winter (Fig. 3a) corresponds approximately to the time when freezing-degree days stop accumulating, typically in late April. Although river inflow in winter is low relative to that of summer, substantial quantities of runoff—over 5000 m³ per second—enter the nearshore ocean. The physical structure of the system manifest at this time is recurrent from year to year. Landfast ice reaches its maximum thickness (2 m) and extends

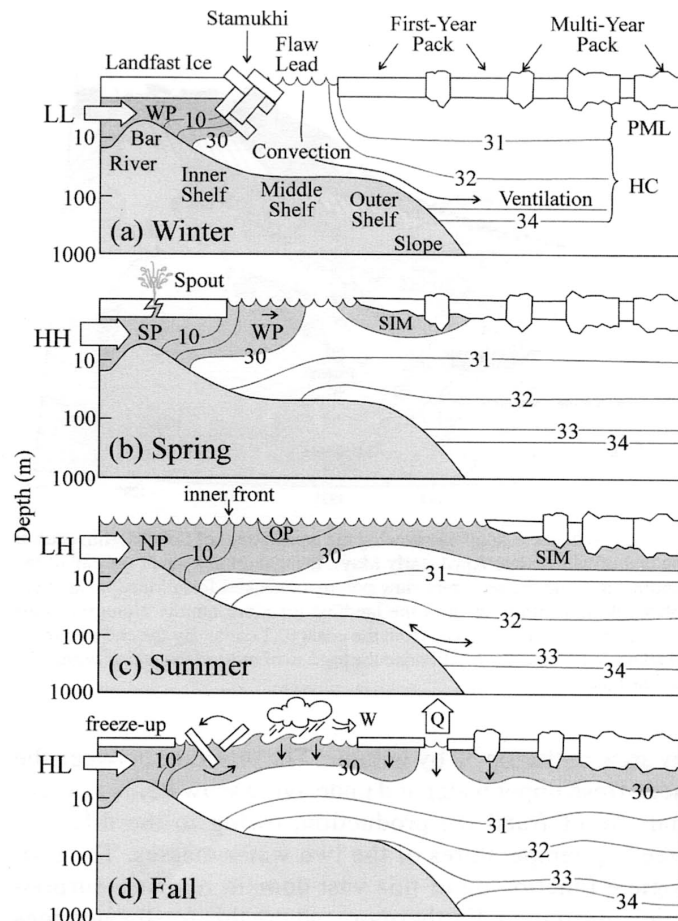


FIG. 3. Schematic sections of ice cover and water column structure across the Canadian Shelf for (a) the end of winter; (b) spring freshet and break-up; (c) summer open water season; and (d) fall mixing and freeze-up. Abbreviations: HH = higher high river discharge; HL = higher low river discharge; LH = lower high river discharge; LL = lower low river discharge; NP = new plume water; OP = old plume water; Q = surface heat flux; SIM = sea ice melt; SP = spring inflow (warm and turbid); W = wind; WP = winter inflow (cold and clear).

approximately to the 20 m isobath. A *stamukhi*, or rubble ice field, formed by ice convergence, defines the outer boundary of landfast ice. The *stamukhi* field extends downward, forming an inverted ‘dam’ of broken ice plates and floes, some of which extend to the bottom. Seaward of the *stamukhi* lies a flaw polynya, or area of intermittently open water. Finally, beyond the flaw lead, is the freely drifting polar pack. In summary, three pelagic domains are evident in late winter: the inner shelf domain below the landfast ice, the middle shelf domain within the flaw polynya, and the outer shelf domain below the drifting pack.

Within the inner shelf domain, the river’s winter inflow spreads out under the landfast ice to form a large pool of fresh or brackish water impounded by the *stamukhi* (see Fig. 4, for aerial extent). This “floating freshwater lake” contains about 70 km³ of winter inflow spread over an area of 12 000 km² (Macdonald et al., 1995). These statistics would rank this seasonal lake—here called Lake Herlinveaux in recognition of the pioneering work of the late Richard Herlinveaux—in the top 20 lakes of the world

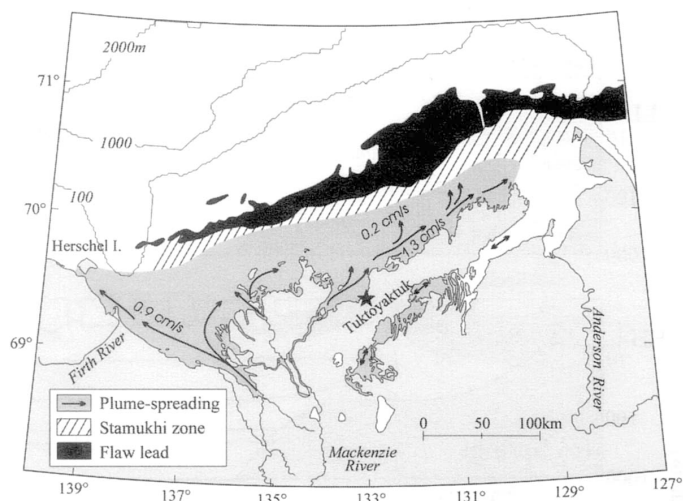


FIG. 4. A schematic diagram showing the areal extent of Lake Herlinveaux at the end of winter (late April–early May), the stamukhi zone at the end of the landfast ice, and the recurrent flaw polynya (adapted from Macdonald et al., 1995). Winter inflow invades the landfast ice more rapidly along the coast (~1.3 cm/s) than it does away from the coast (0.2 cm/s). By the end of winter, Mackenzie River water has flooded the top 5 m of most of the region within the landfast ice.

by area, or the top 30 by volume. The interface between the near-fresh upper water and underlying seawater is a potential site of frazil ice production, owing to the different freezing temperatures of the two water masses. The ecological functioning of this vast domain remains, surprisingly, unstudied. Furthermore, where this freshwater goes during and after breakup and what effect it has on the biological cycle of the middle to outer shelf are also unknown.

In the flaw polynya beyond the stamukhi, ice divergence through winter enhances ice production (~3 m or more; see Melling and Lewis, 1982). The salt rejected as brine then convectively mixes the surface layer down to 40–50 m, possibly also creating brine plumes that then drain along the bottom to enter the Arctic Ocean halocline or deeper. The depth and intensity of winter mixing in this domain thus critically depends on the stamukhi barrier, which prevents winter inflow from entering the divergent zone and thereby providing stability (Macdonald et al., 1995; Macdonald, 2000).

In the outer shelf domain, beyond the flaw polynya, a complex mix of first-year and multi-year pack ice covers the surface waters. The upper waters exhibit a winter mixed layer, but its depth is typically limited to 30–50 m. Although this mixed layer overlies nutrient-rich waters of Pacific Ocean origin, the winter convection does not establish good communication with this nutrient source, and surface values remain relatively low.

From a biological perspective, we can see that the entire system is poised for primary production but cannot yet achieve it owing to limitations in the physical environment. Although ample solar radiation (Fig. 2c) and nutrients (Fig. 5a–c) are available for growth, primary production remains limited. Under the landfast ice, the

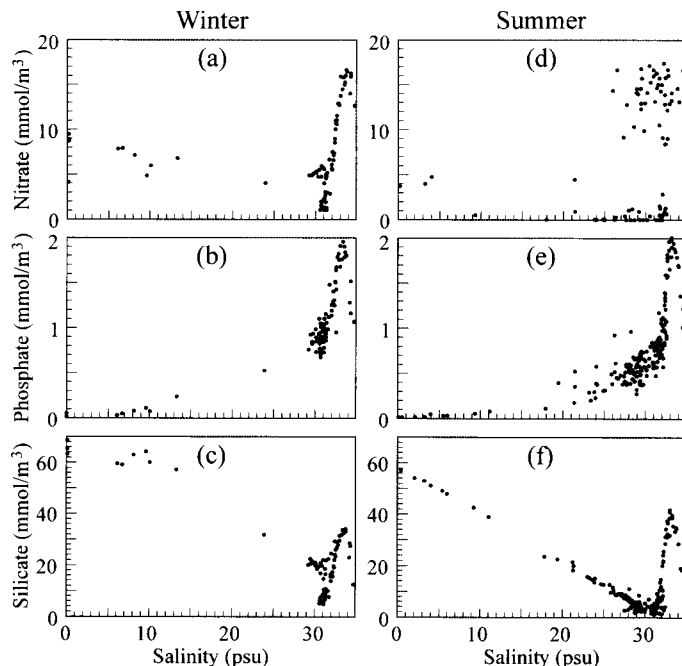


FIG. 5. Correlation diagram of nitrate, phosphate and silicate versus salinity across the Canadian Shelf near 133°W in (a–c) April 1987 and (d–f) September 1987 (data taken from Macdonald et al., 1988 a, b). The Mackenzie River can be seen as a strong supplier of silicate (f), but it supplies little nitrate (a and d) and even less phosphate (b and e).

water is shaded by ice and snow cover, and algal growth is limited to the bottom few centimetres of the ice. Although this production may be important as an early-season source of food, it appears to contribute only about 10–15% of the annual primary production (Horner and Schrader, 1982). In the flaw lead domain, deep convective mixing (that is, lack of surface stratification) does not provide a stable light climate for phytoplankton growth. Farther offshore, the pack ice limits light, but there are also fewer nutrients available as a remnant of the previous summer's uptake (Fig. 5a–c).

Spring Freshet and Breakup

Breakup commences in the headwaters of the Mackenzie River in late April and moves progressively northward downriver to the delta, where it occurs in late May (Fig. 3b). We surmise most events at this time from the river's hydrology (Fig. 2b) and from remote sensing (Dean et al., 1994; Pfirman et al, 1995). This is because field data are very difficult to obtain: when the ice and water are in such a dynamic state, sampling is hazardous to personnel and moored instruments.

Between mid-May and June the river discharge peaks, and the estuary goes rapidly into flood. Such floodwaters, derived mainly from the melting of snowpack, are relatively warm and very turbid when they reach the Mackenzie Delta and coastal Beaufort Sea. Because the estuary and the nearshore remain covered with landfast and bottom-fast ice, the river water is forced, often violently, to find a way into the nearshore, either under the ice or on top

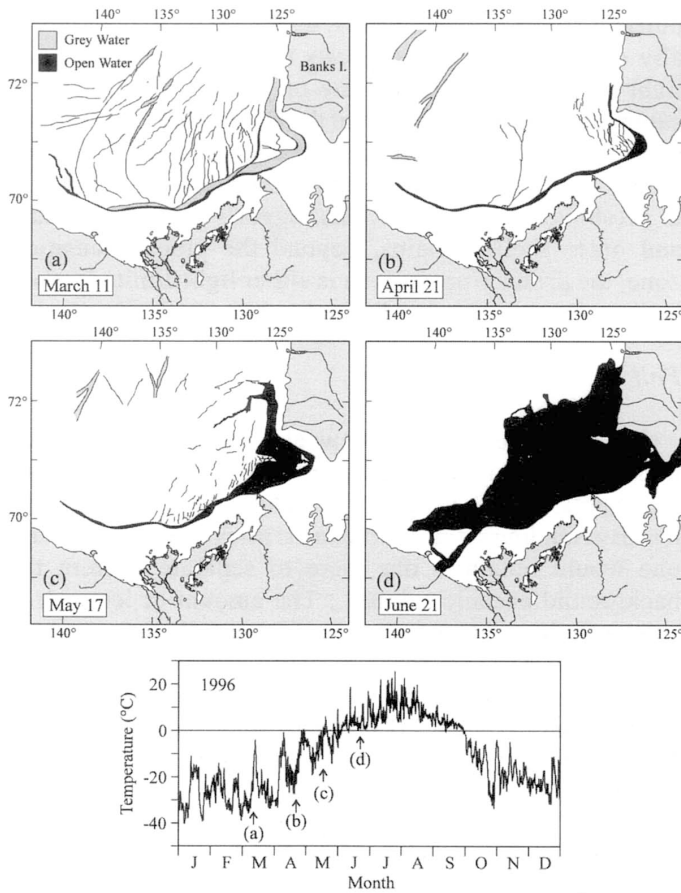


FIG. 6. Sequence of spring breakup over the Canadian Shelf, showing the evolution of the flaw polynya from (a) late winter, when its structure is evident in the system of leads in the water, but ice continues to form and cover open areas, to (b) early spring when ice no longer forms to (c, d) late spring and early summer when substantial areas of water can open depending on winds. Note that the landfast ice along the coast remains in place, trapping the Mackenzie inflow (after Milne and Herlinveaux, 1975).

of it by overflowing. Metre-high geysers of turbid river water rising through cracks and holes in the ice are frequently observed at this time. This pulse of warm and turbid water displacing the cold and clear winter plume of Lake Herlinveaux thus announces the end of winter. However, as the sea ice has not yet seriously begun to melt from solar insolation, latent heat in the river water advances the melting of ice by perhaps as much as two months in the delta, and by lesser amounts away from the river mouth (Antonov, 1978; Dean et al., 1994). Breakup in the middle shelf and outer shelf domains spreads from existing open water in the flaw polynya and leads, where heat is more rapidly absorbed (Fig. 6).

Biological events during this period are likewise poorly studied. Nutrients are sufficient to allow phytoplankton growth, but light is generally limited by the invasion of turbid river water and the lingering ice cover. The dispersal of water from Lake Herlinveaux (stored from the previous winter) over the shelf will influence water column stability, nutrient distributions, and the dispersion of biota, but none of these aspects have yet been examined in sufficient detail (cf. Macdonald et al., 1999). Even though

the coastal zone opens early because of heat from the Mackenzie River, beluga cannot return to these coastal areas until offshore ice conditions permit their migration along the Alaskan shelf, typically in late June or early July.

Summer Open Water Season

As breakup progresses, the landfast ice disappears, and enough heat enters the shelf surface waters, either from the river or from the sun's radiation, to cause much of the ice to melt, leaving its trace as meltwater widely distributed across the shelf (Fig. 3c). The river continues to supply large amounts of freshwater (Fig. 2b), which is evident in plumes (Macdonald et al., 1989), fronts (Carmack et al., 1989), and a strongly stratified surface layer at 5–10 m (Fig. 7). The surface stratification is supported by both runoff and ice melt. At the beginning of this season, in late July or early August, the shelf may still be mostly ice covered, whereas by the end of September, the shelf is usually completely clear of ice.

At this time, the Mackenzie estuary behaves much like any estuary of a large river impinging on an open shelf, the only difference being an additional, broadly distributed freshwater source in ice melt. The plume invades the nearshore, and its distribution and manner of entering the middle shelf or leaving the shelf altogether are very much affected by winds and by the extent of open water (Giovando and Herlinveaux, 1981). In the absence of winds, the incoming river water will tend to bend eastwards under the influence of the Earth's rotation (Coriolis force) and flow along the Tuktoyaktuk Peninsula toward Amundsen Gulf. Easterly winds draw deeper waters to the shelf surface (upwelling) and drive plume waters offshore. Under favourable ice conditions, the Mackenzie plume can be seen to extend to the shelf edge and hundreds of kilometres into the interior ocean (Macdonald et al., 1989, 1999). In contrast, westerly winds (favourable to downwelling) drive plume waters against the coast, enhancing the eastward flow of plume waters along the Tuktoyaktuk Peninsula.

The structure of the Canadian Shelf in summer reveals three distinct oceanographic domains, as shown in Figure 7a–c for a nested section extending from the mouth of the Mackenzie River in Kugmallit Bay across the inner, middle, and outer shelf domains. This section, obtained in September 1987, shows salinity and light transmissivity, in this case the percent transmittance (% Tr) of a 660 nm beam over a 25 cm path-length. The Mackenzie River itself is free of seawater intrusions landward of the transverse bar across Kittigazuit Bay. Seaward of the transverse bar, a 2 to 4 m thick layer of turbid, relatively fresh Mackenzie River mixtures spreads outward 5 to 10 km over the intruding salt-wedge of seawater mixtures (salinity < 20; % Tr < 25). At depths between 8 and 12 m, the water column is mixed to the bottom, with salinities of 20 to 25. Within this transition band, wind mixing (as well as sediment re-suspension) extends to the bottom. Water in this salinity range is denser than the incoming river water

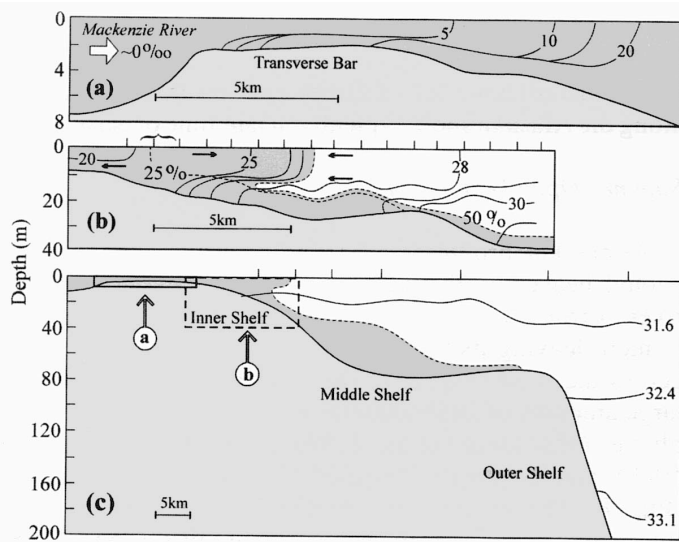


FIG. 7. Nested sections of salinity across the Canadian Shelf in summer, showing the (a) inner, (b) middle, and (c) outer shelf domains. Shading shows typical distributions of suspended sediment (measured as % transmission) associated with the Mackenzie plume and bottom re-suspension. Horizontal length scales are shown for each insert.

(and thus underflows shoreward), but lighter than water farther offshore (and thus overflows seaward). We caution that visual interpretations of the spreading of the Mackenzie plume (for example, in satellite images) must therefore consider both ‘new’ sediment carried by the river and ‘old’ sediment re-suspended in the transition band. Salinities in the range 26–28 and transmissivities of less than 50% Tr mark the outer boundary of the Mackenzie plume. The salinity isolines 31.6, 32.4, and 33.1 represent the base of the winter mixed layer, the core of Bering Sea Summer Water, and the core of Bering Sea Winter Water, respectively (for discussion, see Carmack et al., 1989). A near-bottom layer of turbid water—likely associated with bottom re-suspension—is observed to extend across the full width of the Canadian Shelf.

The summertime pattern described above ignores the consequences of temporal variability. For example, the cumulative effects of variable winds over the course of the summer season result in complex and rapidly changing distributions. Plume structure in late summer can often be seen in satellite imagery and in water properties extending up to 400 km away from the shore (cf. Macdonald et al., 1999; T. Weingartner, pers. comm. 2000). Considerable variation also occurs from year to year in stratification and freshwater distribution, forced primarily by winds. In years when ice remains close to shore, the Mackenzie plume likewise is constrained to the nearshore, whereas when complete clearing of ice from the shelf waters occurs, the plume often spreads to the edge of the shelf and beyond (Macdonald et al., 1987, 1989).

Nutrient distributions in late summer reveal a complex pattern of nitrate and phosphate depletion across the shelf (Fig. 5d–f). At low salinities (that is, within the plume), phosphate values remain near zero, as is characteristic of

nutrient-limited inland waters, while nitrate values generally remain high. This suggests that either phosphate or light (or both) govern the rate of primary production in summer on the inner portion of the Canadian Shelf. Farther offshore, at surface salinities between 26 and 30, nitrate values are bimodal, being either near zero or relatively high (above 10 mmol m⁻³). This suggests that in the middle and outer shelf domains, beyond the plume transition zone, the primary production is either light-limited (when ice is present) or nitrate-limited (when ice is absent).

Fall Mixing and Freeze-up

In mid-September, a few weeks before freeze-up, ice melt from summer is broadly distributed across the Canadian Shelf, contributing 0–2 m standing stock of freshwater. (By standing stock, we mean the thickness of freshwater one would obtain if one were to separate it from the background oceanic salinity.) The amount of ice melt is somewhat less than the amount of ice usually present at the end of winter (2 m). This is because estuarine circulation has carried some ice melt away, and winds have blown both ice and ice melt off the shelf (Omstedt et al., 1994; Macdonald et al., 1989, 1995). In addition to ice melt, freshwater from runoff also remains in shelf waters; the amount of its contribution depends on the yield (annual volume flow divided by shelf area) and on how much of the season’s inflow has escaped the shelf during summer and autumn. For the Canadian Shelf, this works out to perhaps 1–3 m of freshwater, which together with the ice melt may account for a total standing stock of 2–4 m of freshwater (Macdonald et al., 1989; Macdonald, 2000).

Storms throughout summer and early autumn (Fig. 3c) mix the ice melt and runoff into the top 10 to 20 m of the water column and weaken the structure, although fronts and coastal plumes are still evident (Carmack et al., 1989). Below 20 m, there often remains a cold, saline remnant of the previous year’s polar mixed layer. Most importantly, depending on how ice-free the shelf has been during the summer and on the strength, duration, and direction of winds, a portion of the freshwater has been forced off the shelf, to be replaced by saltier water from the interior ocean. This “pre-conditioning” of the shelf (Melling, 1993; Macdonald et al., 1995) sets the stage for the following winter, when the formation of two or more metres of ice withdraws an almost equivalent amount of freshwater. At freeze-up, only a thin layer of ice is present, and ice therefore can grow quickly everywhere as temperatures rapidly drop (see Maykut, 1986). Later, as the ice thickens, the rate of ice growth slows down except in regions like the flaw lead, where divergence presents new open water. This pre-conditioning influence, by affecting offshore stratification, may even extend into the following summer.

Intense storms in fall can also force on-shelf upwelling, as documented by Kulikov et al. (1998). An easterly wind blowing along a straight east-west coastline (in the Northern Hemisphere) causes an offshore (Ekman) flow in the

upper layer, and a corresponding rise in the deeper water shoreward occurs. Mackenzie Canyon (and perhaps Kugmallit Canyon) plays an important role in amplifying upwelling across the shelf. For example, Kulikov et al. (1998) observed upwelling amplitudes in Mackenzie Canyon exceeding 600 m, three to four times greater than those observed elsewhere along the shelf. When the wind stops, some of the dense water returns down canyon to the ocean basin, creating a wave-like response in the offshore ocean, and some remains and mixes into shelf waters to supply production. Macdonald et al. (1987) identified the eastern flank of the Mackenzie Canyon as an important upwelling region in both 1974 and 1975. It has been hypothesized that primary production initiated here is followed by production at secondary and higher levels as the water moves eastward across the shelf (T.R. Parsons, pers. comm. 2000).

Freeze-up commences in early to mid-October, after air temperatures have dropped below the freezing point of water, the water has cooled to its freezing temperature, and freezing-degree days start to accumulate (Fig. 3d). River inflow has by now decreased almost to its low, winter values (Fig. 2b), and the runoff, instead of entering an open estuary where it can be mixed by winds, spreads under the nearshore (landfast) ice in a relatively quiescent environment.

It is not well known how river and sea meet under the ice, especially in late winter, when 2 m of ice covers the estuary. Late in the season, the ice can rest on the bottom in the shallow areas of Kittigazuit and Shallow Bays, so that outflow must occur via conduits under the ice. This means that tides and storm surges provide important controls on the shape and distribution of the flow conduit(s) for water passing between the ice and sediment and perhaps leading to pulsing events in the outflow. Certainly, where more than one river channel leads to the ocean, the ice can modulate flow between channels according to how channel geometry interacts with a progressively thickening ice cover.

Once the freshwater enters the nearshore, it spreads out under the landfast ice as an expanding plume. Using the distribution of $\delta^{18}\text{O}$ in landfast ice at the end of winter, Macdonald et al. (1995) showed that the Mackenzie plume spreads more rapidly along the coastline (1.3 cm per second) than away from it (0.2 cm per second); but in neither case does the plume spread very quickly. At these slow velocities, the plume takes most of the winter to fill the landfast ice zone out to the rough ice (stamukhi) found at the outer edge in about 20 m of water depth. The disposition of river inflow, landfast ice, stamukhi at the end of the landfast ice, and flaw lead beyond the stamukhi appears to be common to all Arctic shelves (cf. Reimnitz et al., 1994; Rigor and Colony, 1997). It is here suggested that the scenario described above is repeated on most Arctic shelves, with local variation controlled by the topography and scale of the shelf and by the strength of winter inflow.

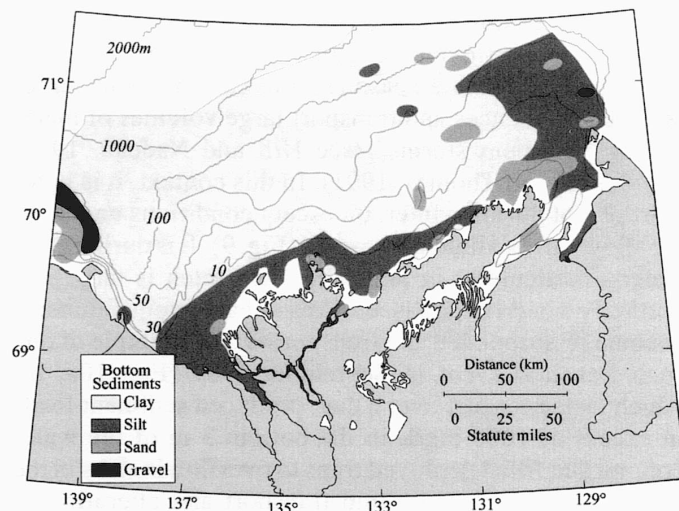


FIG. 8. Particle size distribution of bottom sediments over the shelf. Note that much of the shelf is fine clay, with regions along the Mackenzie delta and the eastern shelf exhibiting coarser silt. Gravel is found only in very small areas (adapted from Pelletier, 1975).

THE BOTTOM AND SHORELINE

Three processes dominate benthic and coastal habitats on the Canadian Shelf: dispersal and re-suspension of river-borne sediments (Hill and Nadeau, 1989; Macdonald and Thomas, 1991), ice scouring (Harper and Penland, 1982; Hequette et al., 1995a), and coastal erosion and retreat (Harper, 1990; Solomon, 1994; Dallimore et al., 1996).

Sediments on the Canadian Shelf

Bottom sediment types (Fig. 8) reflect the importance of the Mackenzie River, which at $\sim 130 \times 10^6$ tonnes/yr (Carson et al., 1998) is by far the most sediment-rich river in the Arctic. The accumulating sediments on the shelf are predominantly clay or silt, with sand and particularly gravel restricted to relatively few locations (Pelletier, 1975). Although coastal erosion is an important 'local' sediment supply near the shoreline, its estimated contribution (7×10^6 tonnes/yr) is dwarfed by that of the Mackenzie River. There is an ample supply of fine sediment from the Mackenzie River, but it seems likely that gravel is supplied only very slowly by ice rafting (Pelletier, 1975) or has been produced in the past by winnowing on beaches that have subsequently been drowned (S.M. Blasco, pers. comm. 2000). Gravel deposits therefore have special significance as nonrenewable—or slowly renewed—refugia for benthos, and for other animals that favour these habitats (e.g., for whale rubbing). This requirement of gravel for animal habitat must be taken into account when industry considers dredging and extraction of gravel deposits.

Although much of the sediment supplied by the Mackenzie River can be accounted for in the Holocene accumulations on the shelf (Macdonald et al., 1998), it is clear

that re-suspension and transport of shelf sediments is episodic and very dynamic. This is particularly true on the inner shelf, where late-season storms can completely alter sediment sequences and transport large volumes of material in “sediment storms” (see Hill and Nadeau, 1989; Macdonald and Thomas, 1991). In this context, it is noteworthy that during winter, quiescent conditions under the ice allow little sediment transport (Fig. 9). It is during open water—particularly in late fall, when fetch is large and northerly winds can produce waves—that bottom sediments become re-suspended and transported. An example of one such transient event in September 1987 (Fig. 10a, b), which lasted for just over a day, produced sediment loads in excess of 1000 mg/L in the bottom 3 m of the water column and filled deployed traps to overflowing. As in the case of scouring, such rapid transport and alteration of sediments favours opportunistic species that can either avoid such events or recolonize quickly after them.

Bottom Scouring

The main disturbance to the seafloor on the inner Arctic shelves is scouring by drifting ice keels and pressure ridges (Reimnitz et al., 1977; Lewis and Blasco, 1990; Hequette et al., 1995a; Blasco et al., 1998), producing long gouges and basin-shaped depressions. Although the Canadian Shelf is 100% scoured from shore to beyond the 50 m isobath, with some scours observed in water as deep as 72 m (Lewis and Blasco, 1990; Blasco et al., 1998), active scouring occurs predominantly in the depth range of 15 to 45 m and has its greatest intensity around the 20 m isobath, which coincides with the location of the stamukhi (Fig. 11). Within the 2 m isobath very near shore, ice can ground on the sediment in late winter, and suspension or frazil freezing and anchor ice in shallow waters can also disturb sediment (Reimnitz et al., 1987). It is reported for the Alaskan shelf that ice scour completely reworks the sediments to a sediment depth of 0.2 m every 50 years (Reimnitz et al., 1977). For the Canadian Shelf, Blasco et al. (1998) report that the scour intensity drops off considerably in water deeper than about 35 m: for a 100 year period, 99% of the seabed is disturbed between 8 and 25 m, but only 5% or less deeper than 40 m. Active scouring and the interaction of ice with sediments therefore create a unique, rough habitat that produces uneven sedimentation rates, with particles being re-suspended from topographical highs to be redeposited in topographical lows. Furthermore, the massive disruption of sediments produced by scouring favours opportunistic species that can rapidly recolonize scour-impacted locations, and it limits or even prohibits the growth of macro algae. These scours, therefore, represent a unique type of disturbance to benthic habitat with consequences to the food-web structure (AMAP, 1998). The so-called “black pools of death” provide another example of habitat disturbance associated with ice-scoured topography (Conlan et al., 1998). Brine rejected from sea ice can be trapped in depressions to

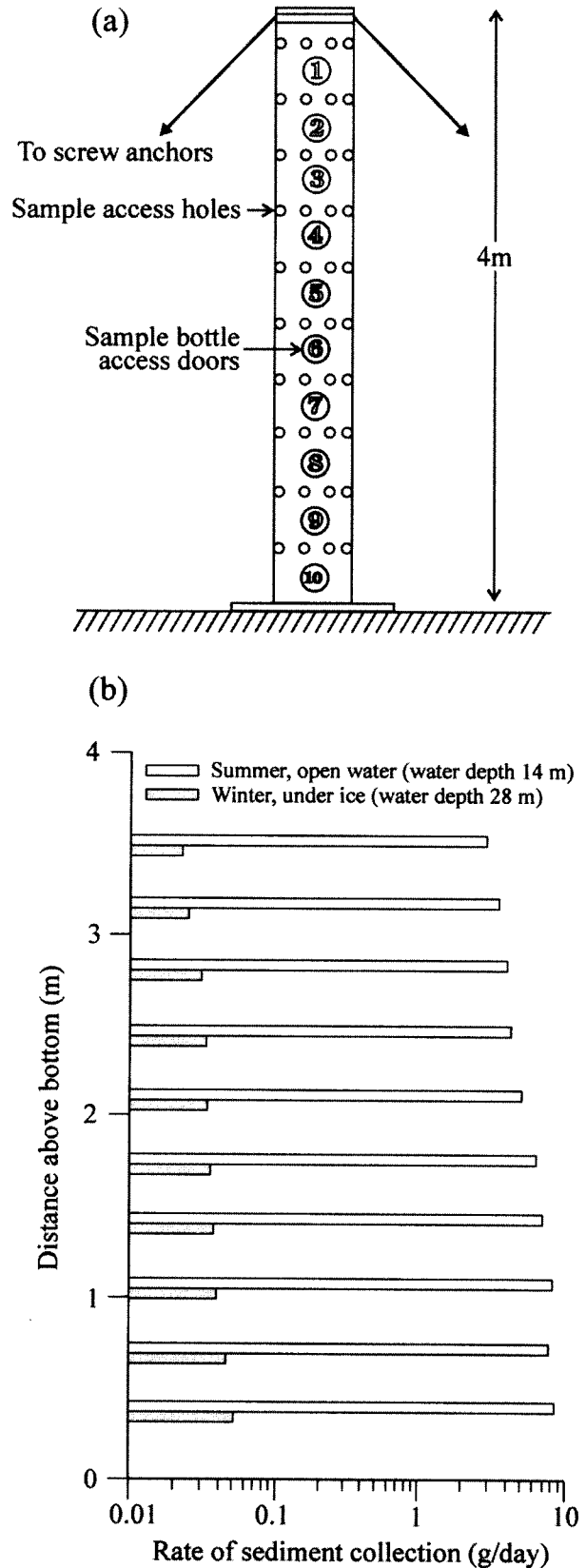


FIG. 9. The contrast between summer and winter for the transport of re-suspended sediments. Suspended sediment was trapped at closely spaced intervals using a bottom-mounted PVC pipe with pockets, as described by Kenney (1985). During summer, winds can produce waves and water currents, which produce turbid water near the bottom (Fig. 7), whereas in winter, quiescent water under the ice remains clear.

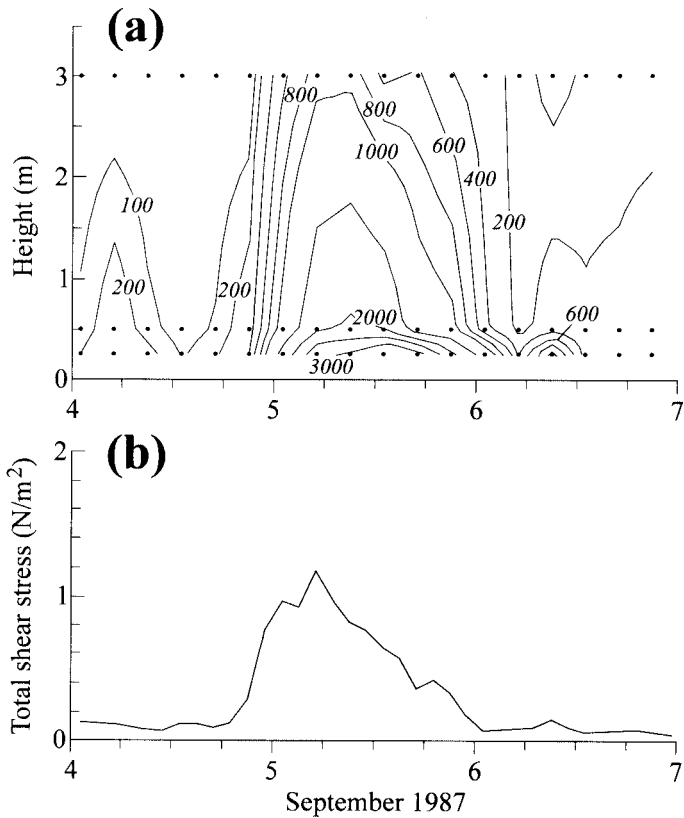


FIG. 10. A plot of re-suspended sediment concentration near the bottom (mg/L) vs. time throughout the period of a short-lived storm (4–7 September 1987).

stratify them. Subsequently, these depressions trap organic matter, but the stratification limits O₂ renewal and the pockets go anoxic, killing macrobenthos and any swimmers that inadvertently enter this trap. A final point regarding the stamukhi and ice scouring relates to consequences of warming. Should warming occur and landfast ice become thinner, while snowfall remains the same, it is almost certain that the stamukhi will retreat shoreward, as will processes associated with it, such as scouring and freshwater impoundment.

Coastal Erosion

Landscape stability is a major concern for the coastal Canadian Shelf. Most of the coastline along the southern Beaufort Sea coast exhibits retreat rates greater than 1 m/yr, with a maximum rate of 18 m/yr observed at Shallow Bay in the Mackenzie Delta (Harper et al., 1985; Fig. 12). Relentless and rapid retreat provides a dynamic and unstable beach habitat that can be seen as a result of rising sea level (RSL) (Hequette et al., 1995b), an ongoing process to which the land has not yet adjusted (Fig. 13). Retreat of cliffs, melt out of coastal permafrost, and breaching of coastal lakes are all active products of coastal drowning. Each of these is vulnerable to storms and storm-surges (Harper et al., 1988; Solomon, 1994), which are affected by climate change.

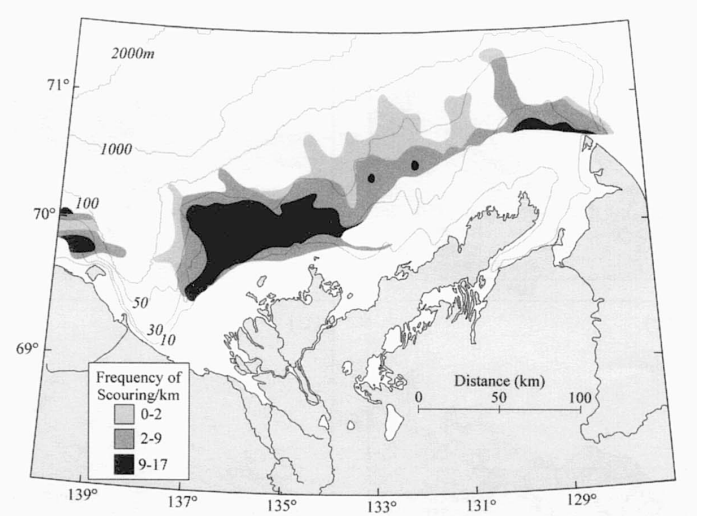


FIG. 11. Map showing the distribution of bottom scouring. Note that the most intense frequency of scours can be found within the stamukhi zone and in the flaw polynya beyond it (8 to 35 m) (adapted from Milne and Herlinveaux, 1975).

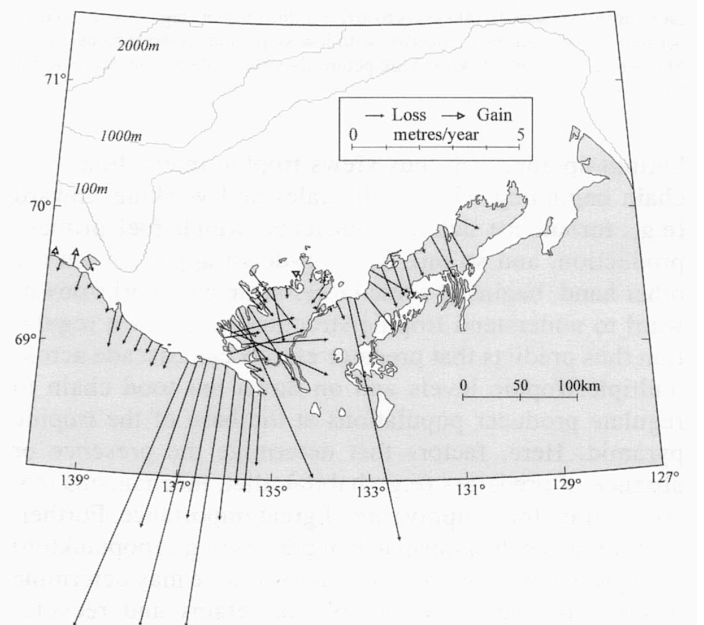


FIG. 12. Diagram representing the rate of coastal erosion. Arrows show the rate of retreat in m/yr (see scale in the box). Rates typically exceed 1 m/yr, but in some locations exceed 10 m/yr (data were obtained from Harper et al., 1985).

DISCUSSION

Links to Biota

The term ‘biodiversity’ refers to the variety of the biota that comprise an ecosystem. To link biodiversity to climate requires that we consider all scales, from that of the molecular to that of the climate. This ‘working through scales’ is typically done in either ascending (bottom-up) or descending (top-down) order. Bottom-up regulation posits that the base of the trophic pyramid depends on resource availability and is grounded on the primary producers. The

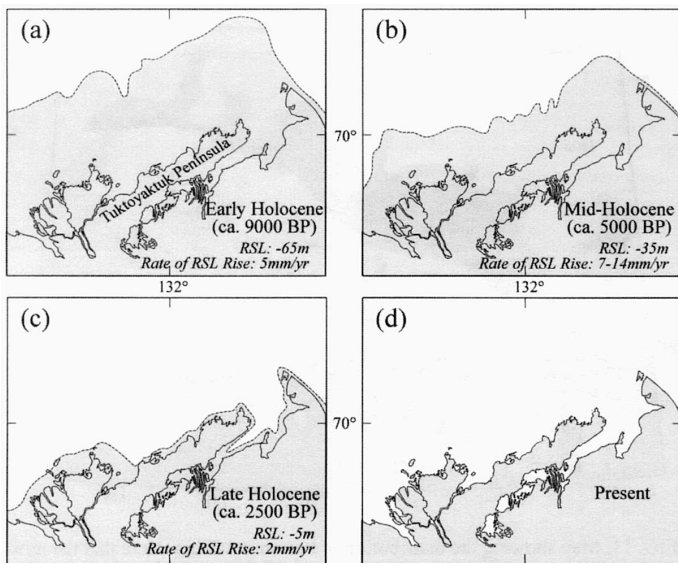


FIG. 13. A schematic diagram showing how the coastline has evolved during the past 9000 years (RSL = rising sea level). At the end of the last ice age, the shelf was apparently above sea level, but the sea has transgressed at uneven rates during the past 10 000 years to arrive at the present stage. Poorly bonded permafrost-rich sediment, together with low slope, makes the regions off the Mackenzie Delta and Tukttoyaktuk peninsula vulnerable to inundation (after Hequette et al., 1995b).

bottom-up approach thus views trophic interactions as a chain beginning with small scales and working upward (e.g., turbulence delivers nutrients, which fuel primary production, and so on). The top-down approach, on the other hand, begins at some larger scale and works downward to understand trophic structure. Top-down regulation thus predicts that predator effects can cascade across multiple trophic levels and on down the food chain to regulate producer populations at the base of the trophic pyramid. Here, factors that determine the presence or absence of predators (e.g., habitat, diet, mechanisms that concentrate food supply) are of great importance. Further, the timing match or mismatch of grazers (e.g., zooplankton) with producers (e.g., phytoplankton) alone may determine whether the upper water column retains and recycles resources or exports them to the benthos (Wassmann, 1998, 2001). As noted below, this may exert a key control on the distribution of animals adapted to pelagic or benthic environments, as well as on the partitioning of energy within the ecosystem (cf. Welch et al., 1992).

Here, we consider the biota in relation to the physical environment: how animals presently exploit their habitats and how these animals might respond to climate variability. Ice provides a dominant control for biological populations and their distributions. However, that control, and its interaction with ocean and atmosphere, produces a broad range of possibilities for variability. This is because ice may both enable biological growth (ice-edge upwelling, denning locations, ice algae production, stable surface for migration and hunting) and limit it (light, vertical mixing by wind, bottom scour, unstable surface) (see, for example, AMAP, 1998; Hunt, 1991; Forbes et al., 1992). Furthermore,

animals that have adapted themselves to take advantage of the ice (bears, seals, walrus) or the water (birds, whales) or both (seals, whales) exhibit different degrees of adaptability to change. Finally, drifting ice and landfast ice must be considered separately, as they are distributed differently, provide different habitats, and are subject to change in different ways.

In spring, many bird species (e.g., eiders, loons, long-tailed ducks, gulls) rely heavily on leads as staging areas where they can find a dependable supply of food (Dickson and Gilchrist, 2002). In particular, the eastern end of the Canadian Beaufort Shelf appears to provide the right benthic substrate for the molluscs and crustaceans upon which the birds prey. Furthermore, there must be appropriate environmental conditions to allow the birds to access the food (e.g., low turbidity, regions reliably clear of ice early in the season, water depths under 50 m). Finally, there must also be ample primary production and strong coupling of this food with the benthos (vertical carbon flux) in order to maintain the biomass and thereby provide a reliable forage site for birds early in the year (see, for example, Grebmeier et al., 1988). An ample supply to the benthos may require both high production in the surface waters (bottom-up regulation) and a mismatch in time or space with pelagic micro-grazers that would otherwise recycle new carbon in the upper ocean (top-down regulation). For example, even though ice algae account for only 10–15% of the primary production for the shelf, inefficiently grazed algal mats shed from rotting ice may provide almost all of the carbon flux that nourishes the benthos. A small shift in ice climate might increase net production for shelf waters and, at the same time, deprive the benthos and the animals that rely on it. Hundreds of thousands of birds depend on access to this benthic food supply at this time of year, when the extent of open water is highly variable and the ecosystem very susceptible to the impacts of climate change. Nesting and rearing chicks provide a different challenge. For example, loons must nest within 8 km of a reliable supply of fish (Dickson and Gilchrist, 2002). Some potential but unused habitat (e.g., cliffs along the coast of Banks Island) may become occupied should global warming increase the regional productivity or shift the ocean from a benthic (invertebrate) to a pelagic (fish) dominated system.

Since walrus (and bearded seals) have many of the same requirements as the diving birds that prey on benthos, they are often found in large numbers at locations where a rich benthic community is accessible (e.g., see Joiris et al., 1997; AMAP, 1998; Dyke et al., 1999; Gilchrist and Robertson, 2000). At present, however, the eastern Beaufort shelf must lack an environmental component required by walrus, as they are seen only very rarely in this region despite a benthic population capable of supporting many birds. The contrast between birds and walrus likely lies in how the ice is used by the two types of animals: birds require open water, but do not require ice, whereas walrus require both open water and ice on which to haul out near their

feeding locations. Within this crucial difference can be seen the potential for change should the ice climate become more enabling for walrus and more limiting for birds.

Other species, such as seals and bears, also depend on ice as a surface platform, but they depend on it in different ways. Changes in the distribution or timing of ice cover may favour one group or the other, but not necessarily both. Bears require the ice for almost all of their seal hunting, the time of spring pupping being the most critical period, but they may also use multi-year ice for denning, as an alternative to sites on land (Lentfer, 1975; Amstrup and Gardner, 1994). Seals absolutely require the ice only for pupping, but can otherwise survive in open water. Ringed seals, the most important prey for bears, are not considered to be a highly mobile species (Smith and Hammill, 1981) and have a strong preference for landfast or seasonal ice (Kingsley et al., 1985). Change in landfast ice extent or duration, therefore, would have a direct influence on ringed seals and a secondary influence on the bears that hunt them. Newborn ringed seals have been shown to be vulnerable to early breakup, which decreases their chance of survival (Smith and Harwood, 2001). Similarly, warmer springs that prematurely melt out pupping dens may expose seal pups to bear predation, causing a decline in that year-class. Likewise, heavy ice may limit access of seals to their food supply (either directly or indirectly, by reducing primary production) and therefore produce a population decline (Harwood et al., 2000). Such declines will be followed by a similar decline in the natality of polar bears and the survival of subadults (Stirling, 2002). The ecological consequences to populations upon which seals prey (e.g., reduced grazing pressure on cod) are unknown, but likely significant. Thus, even though we recognize the importance of ice and its vulnerability to change, our ability to predict how the coupled ice-ecosystem will respond to climate perturbation is limited by our incomplete understanding of how individual species use the ice and how adaptable each species is to change in the ice climate.

Whales are migratory. Drawn to the Arctic for food, mating, and defence, they face a special challenge in being able to access resources and travel safely through the Arctic despite high variability in the ice climate and distribution (e.g., see Moore et al., 2000). Recent satellite tagging studies reveal remarkable migration pathways for beluga (Richard et al., 2001). These results emphasize that whales are able to navigate for hundreds of kilometres under the Arctic pack in search of preferred feeding habitats. Clearly whales are exploiting locations where food aggregates (e.g., fronts, upwelling zones, shelf breaks, and ice edges), and they must find such locations to meet their energy requirements (see Harwood and Smith, 2002). Climate change, therefore, could have an impact on bowhead or beluga whales by increasing or decreasing their food supply or by moving it somewhere else, simply by altering the distribution of these physically controlled habitats either in space or in time. At the same time, reduced ice cover might lead to an expanded range for

killer whales, making them more prevalent in the Beaufort Sea to the detriment of bowhead or beluga whales.

Anadromous fish are especially vulnerable to change because they are tied to the hydrological cycle and its timing and they must travel between rivers and coasts, both of which have ice cycles in the Arctic. For example, arctic cisco hatch in the Mackenzie River, migrate west along the coast in a brackish corridor to the Colville River, where they mature, and then return to the Mackenzie (Fig. 14; Gallaway et al., 1983). This complex migration pattern is intimately linked to the supply of freshwater and its distribution in coastal waters, which is partly controlled by the ice (Fig. 15). Another example of how change in ice conditions may alter the competition for river spawning grounds concerns recent reports of Pacific sockeye and pink salmon invading the Arctic Ocean (Babaluk et al., 2000).

Climate Change

During the 1990s, growing evidence of climate change was documented in the Arctic Ocean's water column (Carmack et al., 1995, 1997; McLaughlin et al., 1996; Morison et al., 1998; Steele and Boyd, 1998), its ice cover (Kwok and Rothrock, 1999), and the coupling between the two (Aagaard and Carmack, 1994; Proshutinsky and Johnson, 1997; Macdonald et al., 1999). These observations and their significance to those who live in the Arctic are confirmed by traditional knowledge (McDonald et al., 1997).

Climate models predict that climate warming will occur first and most intensely in high-latitude regions (Walsh and Crane, 1992). The influence of climate warming on Arctic physical systems may be magnified by 'critical temperatures' involving the melting of sea ice and snow. Physically, this involves two positive feedback mechanisms: the first is the so-called albedo feedback mechanism associated with the melting of snow and ice; the second is associated with the release of natural greenhouse gases (e.g., methane, CO₂) stored in the permafrost and hydrate layers at high latitudes. Climate warming will also affect the hydrology of the Mackenzie River. One may speculate that the annual discharge would increase as precipitation increases, but the predicted change (about 25%; see Maxwell and Barrie, 1989; Miller and Russell, 1992) is less than the annual variability and would be difficult to detect (Macdonald et al., 1998). Probably of greater significance would be changes to the amplitude of the annual freshet, which would decrease as the length of the melt season increases. Furthermore, direct alterations to hydrology by upstream damming would increase winter inflow, with potentially significant effects on coastal oceanography (Omstedt et al., 1994). Hydrological changes will accompany changes in evaporation within the basin and increases in the permeability of the basin soils as permafrost retreats northward.

The disproportionate influence of warming on the Arctic's physical systems—especially on the floating ice and the hydrological cycle—will cascade into disproportionate

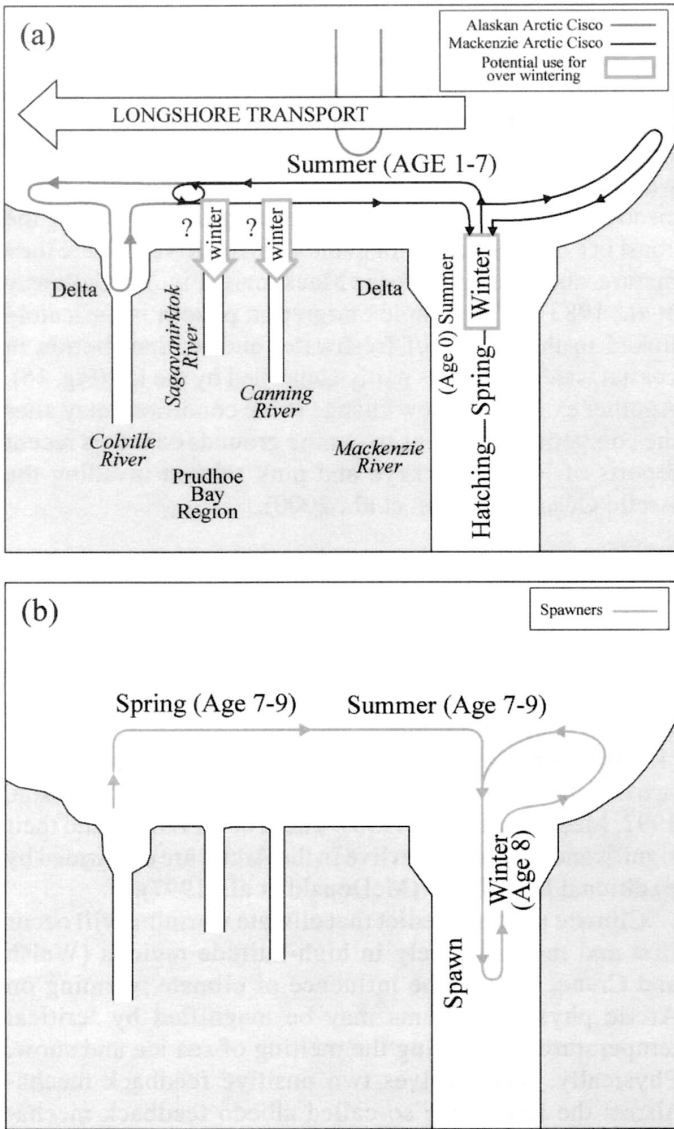


FIG. 14. A schematic diagram showing the dependence of the arctic cisco during its life cycle upon the network of northern flowing rivers (Mackenzie, Canning, Sagavanirktok, Colville). To migrate from one river to another, the cisco probably requires predictable corridors of water that is brackish or fresh. Changes in ice climate, hydrology, or water currents could put this life cycle at risk (after Gallaway et al., 1983).

effects on the Arctic's biota. Change in the physical environment will predictably lead to changes in species abundance, community structure, seasonal distributions, geographic range, migration patterns, and reproductive success. The potential to remove, or alter, an entire habitat—floating ice—in a very short time through climate change is unparalleled, and Tynan and DeMaster (1997) and Stirling et al. (1999) have given cogent examples of the consequences of such change to Arctic marine mammals.

Humans have occupied the Arctic for perhaps the past 4000 years, relying critically on the sea for food (McGhee, 1996). Given that the ice climate has varied substantially during that period (Dyke et al., 1996; Tremblay et al., 1997), it seems vitally important to ask how the marine ecosystem responded to the changing ice and how the

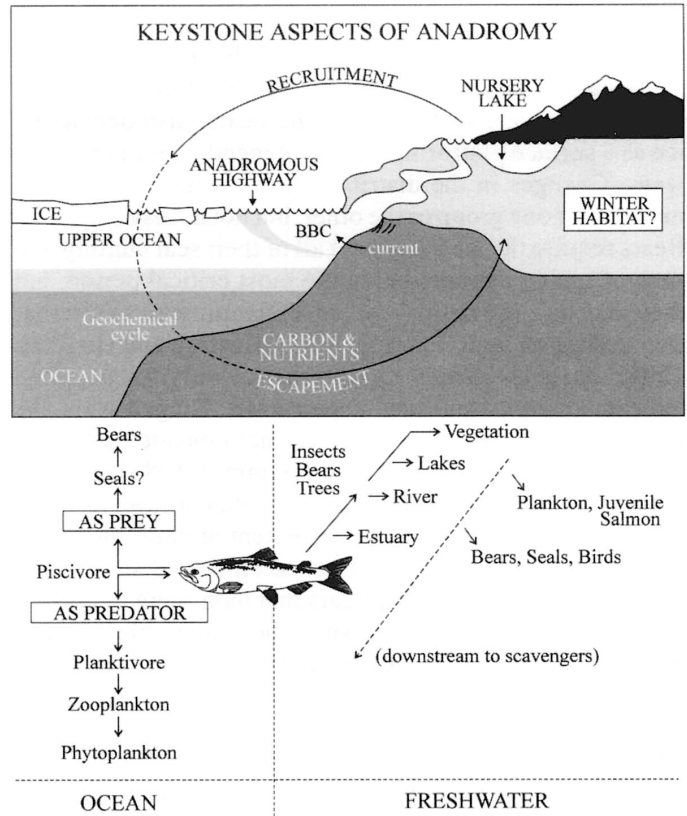


FIG. 15. A schematic diagram illustrating how anadromous fish interact with both the freshwater and marine environments in the Arctic and their role as a keystone species. Both environments and their coupling are vulnerable to change in the ice and hydrological cycles. Migration of anadromous fish along the coast likely takes place in brackish, buoyancy-boundary currents (BBC).

people then adapted. Although the record is sketchy, especially in the Beaufort Sea (Dyke and Savelle, 2001), and although we will probably never know the details of the human struggle to survive, a compelling story of how change in ice climate enabled some populations and limited others appears to have played out during the past two millennia (McGhee, 1996). The Dorset Culture, superbly adapted to the cold climatic conditions during the first millennium, developed reliable methods of harvesting resources from the ice (e.g., seals, fish). Heavy ice conditions restricted migratory species, and there is no evidence that whales contributed to the Dorset's survival. With the Medieval Warming, which occurred toward the end of the first millennium, ice conditions became lighter, and bowhead whales rapidly extended their range (Dyke et al., 1996; Dyke and Savelle, 2001). The changed circumstances that favoured marine migratory species may also have provided the foundation for the Thule migration (Dyke and Savelle, 2001). Marine-based hunting (from kayaks or umiaks) developed in Alaska was advantaged, whereas hunting solely from the ice was disadvantaged. Within a remarkably brief period, the Dorset Culture disappeared, to be replaced by the ancestors of the Inuit. The lesson here is that changing ice conditions may affect seemingly similar populations in very different ways, depending on how each population balances its ice and

open-water requirements and how adaptable it is to changing that balance.

It is commonly assumed that climate change in the ocean works from the bottom up (e.g., nutrients, underwater light conditions), whereas human impacts (e.g., fishing, whaling, organochlorine contaminants) work from the top down (see Parsons, 1992). The special role of sea ice as a habitat, however, requires that we anticipate the potential for climate change to work in both modes in the Arctic. For example, climate warming will result in longer ice-free periods, particularly in the seasonal ice zone over the shelves. From a bottom-up perspective of climate warming, we can expect that:

- Increased open water will increase wind mixing, upwelling, and wintertime brine rejection (convection), and thus increase the availability of nutrients to phytoplankton.
- Increased open water will increase the availability of underwater light to phytoplankton, especially in the seasonal ice zone.
- Decreased ice cover will decrease ice algae production, with consequences to the pelagic and benthic food web.
- Increased rainfall predicted under global warming will increase the export of inorganic and organic terrestrial material (POC, DOC) to coastal domains.
- Rising sea level, combined with increased temperatures and open-water areas, will accelerate coastal erosion, affecting underwater light in the coastal domain.
- Increased storms, especially in autumn, will lead to greater mixing, greater supply of nutrients, enhanced sediment transport, and more rapid coastal erosion.
- Runaway feedback mechanisms may be initiated in the Arctic. An example is the release of methane (a potent greenhouse gas) from permafrost. With climate warming and melting of permafrost, more methane will be released, thus accelerating global warming.

From a top-down perspective, we can expect that:

- Shifting water mass fronts and currents will affect fish migration and behaviour, and the redistribution of such grazers will impact underlying trophic structures.
- Altered habitat conditions in both rivers and coastal seas may affect the distribution of anadromous fish, with consequences to their prey communities.
- Marine mammals (e.g., seals, bears) that depend on an ice platform will be seriously affected by loss of habitat, or will have to migrate elsewhere, with serious consequences to their prey and predators.
- Whales that depend on open water for migration will expand their ranges in response to decreases in ice concentration.
- Land-based mammals (e.g., caribou) that rely on a dependable seasonal platform of ice for migration will face the hazards of crossing weak ice and will have to adapt.

- A warmer climate will attract extractive, resource-based industries (e.g., oil, mining, transportation), with impacts on marine animals and social and economic consequences for humans.

Final Remarks

Aboriginal Peoples have long held that all of nature is interconnected. We now know this to be true of the oceans surrounding North America. Low-salinity waters from the Pacific Ocean flow northward through the Bering Strait, carrying nutrient-rich waters into the Arctic Ocean. This water floods the upper layers of the Beaufort Sea, and much of it eventually exits eastward from the Arctic Ocean through the Canadian Arctic Archipelago and passes via the Labrador Sea into the North Atlantic, where it may eventually condition the marine habitat of Atlantic fishes. This interconnectivity has both bottom-up and top-down connotations, showing that we cannot truly understand the significance of changes that occur in one ocean without viewing the entire system. Perhaps nowhere on earth do ecosystems provide a better sentinel for change than in the Arctic Ocean, connected as it is to the Pacific and the Atlantic; here non-linearity (sensitivity to initial conditions) is the rule rather than the exception. Predictions—i.e., whether change will help or harm bears, birds, whales, seals, cod, clams, or humans—are at this time impossible to make, underscoring the need to observe Arctic shelves and to attempt to understand their functioning if we are to meet our obligation of sound governance.

What of our ability to protect and manage the living resources of the Arctic? Wilson et al. (1994) argue that because fish are part of a complex adaptive system, the information demands of stock recruitment models are so great as to be impractical. In an analysis of fishing strategies used by 32 aboriginal societies worldwide, they further note only one instance where people regulated their catch through the use of a global quota. Elsewhere, fishing standards are set by rules of where and when and how, are determined by need, and are enforced by community regulation. The ability of aboriginal cultures to adapt to change, proven by their survival, and to successfully manage the animal resources required for that survival, leads us at least to ask if we should reverse the statement of René Descartes and say, “Sum ergo cogito”—I am, therefore I think.

ACKNOWLEDGEMENTS

We dedicate this manuscript to the memory of Richard (Dick) Herlinveaux, a pioneer in the study of the Beaufort Shelf, an avid student of physical/biological systems, and one of the last of the *true* oceanographers. We gratefully acknowledge helpful discussions with and improvements suggested by Lois Harwood, Rita Horner, Ian Stirling, and Tom Weingartner. The perspectives given here, developed over a number of years, were based on fieldwork funded

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