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An Ecological and Oceanographical Assessment of the Alternate Ballast Water Exchange Zone in the Hudson Strait Region

Évaluation écologique et océanographique de la zone alternative pour l'échange des eaux de ballast de la région du détroit d'Hudson

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ABSTRACT

This work considers the ecological risks of non-indigenous species introductions associated with ballast water exchange in the Hudson Strait region of Arctic Canada by vessels enroute to Hudson Bay and the Canadian eastern Arctic. Under the *Canada Shipping Act* (P.C. 2006-495 June 8, 2006) Ballast Water Control and Management Regulations, ballast water can be exchanged within Hudson Strait east of 70°W longitude where the water is at least 300 m deep. This Alternate Ballast Water Exchange Zone (ABWEZ) is used by ships that have not conducted a mid-ocean ballast water exchange outside Canada's Exclusive Economic Zone (EEZ).

Very little is known of the oceanography and ecology of Hudson Strait and the Hudson Bay complex in general. Even less is known of potentially invasive biota being carried there in ballast water. Based on information that is available, there are a few physical parameters that can be used to consider where best to locate an alternative ballast water exchange zone for the region. These include depth, temperature, salinity, distance from shore, currents, tidal range, and ice cover. Within Hudson Strait, each of these parameters offers a range of possibilities that can make it easier or harder for invasive species from warmer coastal waters to establish.

The deep, cold, relatively saline and seasonally ice-covered waters of the existing ABWEZ are removed from shore and subject to strong eastward currents. They remain the preferred exchange zone within Hudson Strait. These same characteristics also mean that the biota taken up during the exchange may be less likely to establish in the shallower, warmer, less saline coastal waters near Churchill.

All vessels entering the Canadian Eastern Arctic via Hudson Strait should follow the same procedures as transoceanic vessels, namely ballast water exchange for vessels with ballast on board and saltwater flushing of ballast tanks for ships with no ballast on board. This precautionary approach should be followed until ballast water treatment is implemented for these vessels or research demonstrates that the risk is acceptable. Otherwise the spread of non-indigenous species from domestic coastal waters is uncontrolled.

Further research is recommended to assess the risk of species introductions associated with ballast water exchange in Hudson Strait and with its release by foreign and domestic vessels within the Hudson Bay complex. The relative merits of conducting ballast water exchange east of Hudson Strait in the Labrador Sea, rather than within Hudson Strait, should also be considered.

RÉSUMÉ

Cette étude considère les risques écologiques de l'introduction d'espèces allogènes liée à l'échange des eaux de ballast dans la région du détroit d'Hudson de l'Arctique canadien par les navires en route vers la baie d'Hudson et l'Arctique de l'Est canadien. Selon le *Règlement sur le contrôle et la gestion de l'eau de ballast* de la *Loi sur la marine marchande du Canada* (C.P. 2006-495 8 juin 2006), l'eau de ballast peut, dans le détroit d'Hudson, être renouvelée dans une zone située à l'est du méridien par 70° de longitude ouest et où l'eau atteint une profondeur d'au moins 300 m. Cette zone de renouvellement des eaux de ballast est utilisée par les navires qui n'ont pas procédé à un renouvellement de leurs eaux de ballast en pleine mer en dehors de la zone économique exclusive (ZEE) du Canada.

En matière d'océanographie et d'écologie, on sait très peu du détroit d'Hudson et du complexe de la baie d'Hudson en général. On en sait encore moins des espèces animales et végétales potentiellement envahissantes acheminées jusque-là dans les eaux de ballast. Les données disponibles mettent en avant quelques paramètres physiques (notamment, la profondeur, la température, la salinité, l'éloignement du rivage, les courants, la hauteur des marées et la couverture de glace) qui peuvent être utilisés pour envisager le meilleur endroit où définir une zone d'échange des eaux de ballast dans la région. Au sein du détroit d'Hudson, chacun de ces paramètres offre de multiples possibilités susceptibles de faciliter ou de contrarier l'établissement d'espèces envahissantes issues d'eaux côtières plus chaudes.

Les eaux profondes, froides, relativement salines et couvertes de glace de façon saisonnière de la zone d'échange des eaux de ballast existante sont éloignées du rivage et soumises à de forts courants d'ouest en est. Cette zone constitue la principale zone d'échange du détroit d'Hudson. Ces caractéristiques signifient par ailleurs que les espèces animales et végétales aspirées lors d'un échange pourraient être moins susceptibles de s'établir dans les eaux côtières moins profondes, plus chaudes et moins salines à proximité de Churchill.

Tous les navires entrant dans la zone de l'Arctique de l'Est canadien par le détroit d'Hudson devraient se conformer aux mêmes procédures que les navires transocéaniques, à savoir l'échange des eaux de ballast pour les navires disposant d'eau de ballast à bord, et une chasse des citernes de ballast à l'eau de mer pour les navires sans eau de ballast à bord. Cette approche de précaution devrait être adoptée jusqu'à la mise en œuvre d'une procédure de traitement des eaux de ballast ou jusqu'à ce que des études scientifiques démontrent que le risque couru est acceptable. En l'absence de telles procédures, la dispersion d'espèces allogènes issues des eaux côtières intérieures s'opère de façon incontrôlée.

Des recherches supplémentaires devraient être entreprises afin d'évaluer le risque d'introduction d'espèces associé à l'échange des eaux de ballast dans le détroit d'Hudson et à la dispersion d'espèces par des navires étrangers et canadiens au sein du complexe de la baie d'Hudson. En outre, il serait utile de considérer les avantages que pourrait présenter un échange des eaux de ballast dans la mer du Labrador à l'est de la baie d'Hudson plutôt que dans le détroit d'Hudson.

INTRODUCTION

The exchange of ballast water by ships provides a mechanism for the transfer of biota from one region to another, with potentially damaging effects to the receiving ecosystem. Vessels containing ballast from foreign waters are normally required to conduct a mid-ocean exchange (**MOE**[1]) of their ballast water outside Canada's Exclusive Economic Zone (**EEZ**), which extends up to 370 km (200 nautical miles) offshore. The rationale for this exchange are that it should replace foreign coastal species contained in the ballast water with oceanic species that are less likely to survive when the ballast is discharged into Canadian coastal waters, and that oceanic communities are less diverse and abundant than coastal communities (Levings *et al*. 2004; Simard and Hardy 2004). The large, rapid salinity change can also be lethal to residual biota adapted to low salinity freshwater and coastal environments, further reducing their concentrations in the ballast tanks (Ruiz and Reid 2007; Santagata *et al*. 2008).

Ballast water exchange is considered an interim solution to the ballast water problem (NRC 1996, 2008; Levings *et al*. 2004, Bailey 2007; Ruiz and Reid 2007). Work is ongoing to develop alternate technology-based methods to treat ballast water, but it may be several years before such technologies are available and widely used (Ruiz and Reid 2007; Lloyd's Register 2008; NRC 2008). Ballast water treatment is required under the International Convention for the Control and Management of Ships' Ballast Water and Sediments, which was adopted by the International Maritime Organization (IMO) in 2004 (http://www.imo.org). Assuming this Convention is ratified by 30 states, representing 35% of the gross tonnage of the world's merchant shipping, newly constructed ships will have to start fitting approved Ballast Water Treatment systems onboard starting in 2010, with all ships requiring treatment systems by 2016. Until all ships are fitted with treatment system, ballast exchange is required by the Convention.

Current Ballast Water Control and Management regulations under the *Canada Shipping Act* (P.C. 2006-495 June 8, 2006) require ships travelling outside Canada's EEZ, whether coastal or transoceanic, to exchange their ballast water and to flush tanks that contain residual amounts of ballast water with saltwater before entering Canadian waters. When mid-ocean exchange is not recommended due to safety concerns, such as weather conditions and subsequent threats to ship stability, vessels from outside the EEZ bound for ports in eastern Canada north of 60°N latitude are allowed to exchange ballast in an alternate ballast water exchange zone (ABWEZ). There are two such zones to accommodate vessels westbound into the Canadian Eastern Arctic, one in Lancaster Sound and the other in Hudson Strait—only the latter is discussed in this work (Figure 1). While ships that operate exclusively in waters under Canadian jurisdiction are exempt from ballast water exchange, their ballast water poses an unknown but potentially significant pathway for the transfer of non-indigenous species within Canadian waters (Lavoie *et al*. 1999; Levings *et al*. 2004; see also Ruiz and Reid 2007 and NRC 2008).

Ballast water is taken aboard vessels for trim, stability, maneuverability, crew comfort, and other reasons (Carlton 1992; Levings *et al*. 2004). Vessels of all types carry ballast water. The amount and frequency of ballast water exchange (ballasting and de-ballasting) varies widely with vessel type, cargo, weather and crew experience and

[1] Terms in bold are defined in the Glossary of Acronyms.

practice. The water in a ship may come from numerous geographically separate uptake areas, either mixed in one tank or unmixed in different tanks. The age of water and sediment in a ballast tank can range from hours to many months. The exchange frequency depends on the frequency of port calls, displacement requirements, port characteristics, and the type of cargo.

Ballast tanks are large void spaces that are designed to contain water and usually located around the outer hull of a ship (Ruiz and Reid 2007). There are many different configurations of ballast tanks across and within ship types, and their structural complexity can make them subject to sediment accumulation. The capacity of a ship to carry ballast water and sediment varies with vessel type (Carlton 1992). Fully loaded, a cargo vessel may only carry a few cubic meters of residual water and sediment, whereas a ballasted large crude or bulk carrier may have a capacity greater than 200,000 m^3 (C. Wiley, DFO/TC, pers. comm. 2008). The quality of ballast water and sediment typically depend on the quality of the source water (Carlton 1992). Contamination of the ballast by pollutants is rare once it is aboard the vessel but changes may occur in its temperature, salinity, nutrients, and oxygen. These changes can alter the composition of biological communities in the ballast.

Ballast water exchange (**BWE**) replaces the coastal water in the ballast tanks with water from a mid-ocean region where the salinity is above 30 and the water at least 2000 m deep (Ruiz and Reid 2007). In ships with ballast (**BOB**) the water is exchanged by re-ballasting (or empty-refill) or by dilution (flow-through). In the former, the tanks are completely emptied and then refilled, at sea, in the latter mid-ocean water is pumped into a full or partially full ballast tank and allowed to overflow the tank for at least three tank volumes. Where the ballast water tanks are empty except for residual ballast water and sediment (**NOBOB**) the tanks are flushed by covering the bottom of the tank with a shallow layer of high salinity water (>30), allowing it to slosh around, and then discharging it (tank flushing).

Planktonic and **nektonic** organisms from the area of ballast water intake are entrained with the ballast water and carried into the ship's ballast tanks (Carlton 1992; Levings *et al*. 2004; Ruiz *et al*. 2007). During the subsequent voyage the species assemblage in each tank changes as some species die off while others survive and mature. When the ballast is exchanged near the destination port the species assemblage that is discharged into the receiving waters may be very different from that initially entrained. If these biota are discharged into a favourable environment some may survive, reproduce, and eventually become established. The potential for biota in ballast to invade depends on their species-specific characteristics, inoculum density and frequency, and physical and chemical similarities of the source and receiving waters (Levings *et al*. 2004).

Ballast water exchange is an effective method for reducing the initial coastal and freshwater plankton assemblages in ballast tanks (average of 80-99%) (Gray *et al*. 2007; Ruiz and Reid 2007; Ruiz *et al*. 2007; see also Locke *et al*. 1991; Levings *et al*. 2004; Johengen *et al*. 2005. However, some coastal biota remain in the tanks after exchange and a small subset of species only exhibit small reductions in abundance following exchange. Residual water and sediment in NOBOB vessels can also serve as a reservoir for non-indigenous species (Johengen *et al*. 2005), but flushing these tanks with saltwater may lower the abundance of these species (Bailey *et al*. 2007). The efficacy of ballast water exchange for eliminating waterborne bacteria, viruses, and protists is unclear (Ruiz and Reid 2007).

The impact of introduced species on the receiving ecosystem can be severe and widespread (Carlton 1992). These species can affect native species by competing with them for resources or space, preying upon them, poisoning them, disrupting their habitats, altering their gene pool through hybridization, and/or introducing parasites or diseases to which they have little resistance. Lacking natural predators, the introduced populations may expand quickly into adjacent areas and their rate of population increase may be high. This can lead to dramatic changes in community function and in the value of coastal waters for food, recreation, and industrial uses. The zebra mussel, which was introduced to North America in ballast water, is an example of a species that has caused widespread ecological and economic damage.

The impacts of species introductions into Canadian Arctic waters in ballast water have not been studied. However, some potentially **invasive** species have been identified and their habitat requirements, risk of establishment, and possible impacts have been considered (North/South Consultants Inc. 2006). Unfortunately the list of potential invaders may be much longer, and surprises are likely. Species that pose the greatest risk of invading the HB complex are likely those having multiple modes of reproduction, wide environmental tolerances (e.g., salinity, temperature, light), and strong associations with human-facilitated modes of dispersal (e.g., ship traffic). Animals that feed on a broad range of items and biota with a previous history of invasion may also be more apt to invade.

The destination of ships traveling westward through Hudson Strait is the Hudson Bay complex (hereafter HB complex). This large Canadian inland sea has typical Arctic characteristics, including cold, dilute waters and complete, seasonal ice cover. Hudson Strait, Ungava Bay, Foxe Basin, Hudson Bay, and James Bay are its main sub-regions (Figure 2). It is connected to the Labrador Sea by Hudson Strait, with a smaller connection to the Arctic Ocean via Fury and Hecla Strait. Over 32,700 people, mostly Aboriginal, inhabit the coasts (2001 Canada Census). Many of them harvest its natural resources for subsistence. While Hudson Strait is the designated ABWEZ and, as such, is at greatest risk from species introductions, the larger HB Complex is also at risk.

This work considers the ecological risks of **non-indigenous** species introductions associated with ballast water exchange in the Hudson Strait region of Arctic Canada. Although it considers the risks of these introductions, it is not a "risk assessment" in the sense that it does not focus on the likelihood of an invasion occurring, and the extent and magnitude of impacts if one does occur. This document provides a broad review of relevant information from the scientific literature and other sources on the ecology, oceanography and shipping patterns in Hudson Strait and the rest of the HB complex. It does not survey potential invaders or consider the relative merits of conducting ballast water exchange outside the HB complex in the Labrador Sea. The quantity and quality of the relevant information available for Hudson Strait region are assessed, and significant information gaps are identified. Within this context, recommendations are made regarding the suitability of the existing ABWEZ.

PHYSICAL AND CHEMICAL OCEANOGRAPHY

The ability of introduced species to establish viable populations is determined in part by the physical and chemical conditions of the exchange site. It is also affected by intrinsic and extrinsic biological factors, but these are very complex and their consideration is beyond the scope of this work. This section describes the physical and chemical environment in Hudson Strait and the HB complex in general to illustrate the limitations these conditions place on introduced biota. Because this region is large, remote and seasonally ice covered the level of oceanographical research effort has been very low relative to the Atlantic and Pacific coasts. This limits understanding of many key processes, particularly with respect to seasonal and inter-annual change, and it limits modeling potential.

BATHYMETRY

The HB complex is shallow for such a large marine area, except in Hudson Strait (Figure 3). A 400 m sill across the east end of the Strait limits exchange of deep water between the HB complex and the Labrador Sea (Drinkwater 1986). Ungava Bay, which extends south from Hudson Strait, consists of a submerged plateau less than 150 m deep with a deeper channel that extends in a south-westerly curve from the east entrance, varying in depth from 200 to 400 m. The seafloor in Hudson Strait drops to 1000 m deep north of Ungava Bay and then rises progressively to about 400 m where the channel extends into southwestern Foxe Basin and Foxe Channel. To the north, large areas of eastern Foxe Basin are less than 20 m deep while in western Foxe Basin there is a deeper channel that ranges in depth from about 50 m in the north to 150 m in the south (Sadler 1982; Prinsenberg 1986c). Fury and Hecla Strait, which flows into northern Foxe Basin, is over 100 m deep. Surface exchange between Foxe Basin and Hudson Bay, to the south, occurs through Roes Welcome Sound, which has a sill at 60 m depth (Defossez *et al.* 2005). Deepwater exchange between Hudson Strait and Hudson Bay is limited by a sill at 185 m depth across the northeast exit to the bay (Prinsenberg 1986b).

Hudson Bay is comprised of two saucer-shaped basins separated by a ridge-like feature that extends from the south shore and rises to a depth of < 40 m at the Midbay Bank (Stewart and Lockhart 2005). A broad coastal shelf extends to 80 m depth offshore the coasts of Québec (20-50 km), Manitoba and Kivalliq (50-70 km), and Ontario and the northern islands (100 km). The bottom slopes gradually from the shelf to a smooth sea floor with an average depth of 250 m (Josenhans and Zevenhuizen 1990). A deep, trench-like feature, the Winisk Trough, extends offshore from the Winisk River estuary towards Coats Island. In the north this trough is about 1.6 km wide with steep walls that drop from the seafloor to a depth of 370 m. In southeast Hudson Bay, where the depth seldom exceeds 120 m, enclosed bathymetric deeps (>200 m depth) parallel and resemble the adjacent cuesta coastline (Josenhans *et al.* 1991). James Bay, which extends south from Hudson Bay, is seldom deeper than 50 m and extremely shallow for such a large marine area.

COASTLINE AND SEAFLOOR

Where the HB complex is underlain by Precambrian rock the coasts and seafloor tend to be irregular, often rugged, with more exposed bedrock and greater relief and/or coastal development (Dionne 1980; EAG 1984; Martini 1986; Stewart and Lockhart 2005). These coastlines can be divided into "complex" and "well-developed cliff and headland" sections. Much of the HB complex, including most of the seafloor, is underlain by Paleozoic sedimentary rock of the Hudson Platform that is covered by unconsolidated materials. These coastlines are typically "low-lying". The submarine geology and physiography tend to be extensions of coastal formations and features (Pelletier 1986; Josenhans and Zevenhuizen 1990).

Complex coast sections consisting of small headlands and bays occur along the northwest coast of Hudson Strait, north coast of Foxe Basin, west coast of Hudson Bay, and east coast of James Bay (EAG 1984; Martini 1986; Stewart and Lockhart 2005). Local relief is generally <30 m and the shores are a mixture of exposed bedrock and unconsolidated materials. These coastlines offer the greatest variety of landforms and biological habitats. Their tidal flats, intertidal salt marshes, and subtidal eelgrass meadows (*Zostera marina* L.) have particular ecological importance. Major rivers that dissect the complex coasts include the Eastmain, La Grande and Povungnituk in Québec, and the Thelon and Kazan in Nunavut.

Coastal sections with well-developed cliffs and headlands occur on the islands and south and northeast shores of Hudson Strait, the east coast of Ungava Bay and on Akpatok Island, the northeast coast of Southampton Island, the mainland and islands near Repulse Bay, in the Belcher Islands, and along the northwest and southeast coasts of Hudson Bay (EAG 1984; Martini 1986; Stewart and Lockhart 2005). Local relief can exceed 100 m and topography ranges from gently rolling hills to steep cliffs that rise abruptly from the sea to 500 m above sea level. Exposed bedrock is common in these areas and tidal flats are lacking. The cliff and headland coasts support important cliff-nesting bird species that are not common elsewhere in the HB complex. Grande rivière de la Baleine is the only major river that dissects these coastal sections.

Low-lying coastal sections occur in southern Ungava Bay, along the east coast and on the islands of Foxe Basin, along the southern shores of the islands in northern Hudson Bay, from Arviat in Nunavut to southern James Bay, and on the larger islands of James Bay (EAG 1984; Norris 1986; Martini 1986; Stewart and Lockhart 2005). These coasts are characterized by very gradual slopes, low relief, shallow nearshore waters, and extensive tidal flats that give way inland to low-lying, marshy coastal plains. These low-lying coasts provide vital habitat for many migratory waterfowl and shorebird species. They are dissected by large rivers (e.g., Nelson, Churchill, Albany, Moose, Nottaway, and Nettilling) that carry much of the runoff into the HB complex and provide important estuarine habitats for fish and marine mammals.

TIDES

Powerful tides that originate in the North Atlantic Ocean surge into the HB complex twice daily (semidiurnal) via Hudson Strait (Dohler 1968; Drinkwater 1988). These tides progress as a Kelvin wave counter-clockwise around Foxe Basin and Hudson/James Bay, and overshadow local tides and any tidal influence from the Arctic Ocean. In Leaf Bay, at the head of Ungava Bay, the maximum recorded spring rise was 16.7 m, the highest in the world (Dohler 1968; Canadian Hydrographic Service 1982; NIMA 2002; Kuzyk *et al*. 2008). In Hudson Strait the spring tide range is 7.9 m at the eastern entrance, increasing to 12.5 m along the north shore at Kimmirut, and then decreasing to 4.9 m in the west at Nottingham Island. In Foxe Basin, the spring range is

7 m in Foxe Channel in the south, and declines to between 3 and 3.4 m in the north at Rowley Island. In Hudson Bay, the range increases from 3 m near the exit to Hudson Strait to 4 m along the west coast at Churchill Harbour and then decreases to about 2 m along the east side of James Bay and in the Belcher Islands and to 0.5 m at Inukjuak (Dohler 1968; Godin 1974). The tides set up strong currents at the eastern entrance to Hudson Strait (up to 2 m/s; Drinkwater 1986), in Foxe Basin (0.3 m/s; Prinsenberg 1986c), at the entrance to the Hudson Bay (0.9 m/s), and within the Bay (0.3 m/s) (Prinsenberg and Freeman 1986). Polynyas may form where currents exceed 1.5 m/s (Prinsenberg 1986c).

CIRCULATION AND WATER MASS CHARACTERISTICS

Circulation and water mass characteristics within the HB complex are strongly influenced by the freshwater dynamics, which vary seasonally and geographically in response to ice formation and melt, freshwater runoff from the land, and inputs of marine surface water (Harvey *et al.* 2006). The large freshwater input and the extensive formation and melting of sea ice lead to pronounced vertical layering of the water masses. This stratification is moderated in Hudson Strait and shallow eastern areas of Foxe Basin by tidal mixing, but is particularly strong in Hudson Bay and James Bay. Summer surface salinity values over most of the HB complex are low relative to the Atlantic and Pacific, where they typically exceed 34 psu (World Ocean Atlas 2005) (Note: salinity units reported vary according to the source). In northern Hudson Strait, Foxe Basin, and northwest Hudson Bay this is predominately due to sea ice meltwater (Tan and Strain 1996). While in southern Hudson Strait, Ungava Bay, northeast Hudson Bay, and James Bay it is predominately from runoff and rainfall.

The HB complex receives a very large input of freshwater runoff, about 940 km^3/y or roughly one-fifth the river discharge into the Arctic Ocean (Déry *et al.* 2005; Straneo and Saucier 2008a). Most of this freshwater is input over a 6 months period (May-October) (Prinsenberg 1986c). It has a strong influence on the timing and pattern of ice breakup, surface circulation, water column stability, species distributions, and biological productivity (Prinsenberg 1988; Stewart and Lockhart 2005). There are extensive freshwater plumes off the larger river mouths in Hudson Bay and James Bay year-round. They spread farther and deeper under the ice than under the ice-free conditions of summer, despite runoff rates that are an order of magnitude lower. In southern and western James Bay, which are shallow and receive a great deal of sediment laden runoff, the water clarity is low relative to other parts of the HB complex, except in shallow eastern Foxe Basin where wave action stirs up bottom sediments.

Seawater of Pacific origin enters the HB complex via Hudson Strait (Baffin Island Current) and Fury and Hecla Strait, after being cooled and diluted by passage through the Arctic Archipelago (Jones *et al.* 2003). The water passing through Fury and Hecla Strait is well-mixed by the tides before it flows into Foxe Basin (Figure 4). Very high currents, up to 3 m/s, have been observed in the Strait (Collin and Dunbar 1964; Sadler 1982). In winter, this circulation may be temporarily disturbed or reversed during the passage of atmospheric storms (Godin and Candela 1987). The inflow to Foxe Basin is rather small, 0.04 Svd in the winter (Sadler 1982; 1 Svd = 10^6 m^3/s) and 0.1 Svd in the summer (Barber 1965), but has a substantial influence on the circulation, filling the northern half in one year and driving the counterclockwise gyre (Prinsenberg 1986c). This lighter, less saline Arctic water flows south on the surface along the coast of Melville Peninsula. When it reaches southern Foxe Basin, some of the water flows west via Frozen Strait and Roes Welcome Sound into Hudson Bay; some flows northeast to join water entering Foxe Basin from the Hudson Strait; and some continues through Foxe Channel and into Hudson Strait (Prinsenberg 1986c; Tan and Strain 1996).

In eastern and central Foxe Basin, where the water is relatively shallow, the water mass is homogeneous in summer due to strong tidal and wind mixing; whereas to the west and south the water is stratified (Campbell 1964; Griffiths *et al.* 1981; Prinsenberg 1986c). Seasonal changes in surface temperature are very small, from –1.7°C to about 3.1°C. In the spring, surface salinities as low as 4 have been observed offshore, reflecting dilution by meltwater and river runoff. By late summer and early autumn, surface salinities have returned to 29.0-32.0.

The density of the surface water increases during the winter due to cooling and brine rejection by ice formation. These density effects are greatest in eastern Foxe Basin where the water is shallow and thick ice forms. The cold, saline water (t = –1.97°C, S = 34.07) flows downhill to become the bottom water in deeper areas of Foxe Basin and Foxe Channel (Campbell 1964; Prinsenberg 1986c). Intermittent flow of this dense water over the 185 m sill that separates Foxe Channel from Hudson Bay likely maintains the homogeneous bottom layer in Hudson Bay.

Surface water from Foxe Basin enters Hudson Bay in the northwest via Roes Welcome Sound and circulates cyclonically (counter-clockwise) around Hudson Bay (Tan and Strain 1996; Prinsenberg 1986b; Wang *et al.* 1994; Saucier *et al*. 2004). Some of this water enters James Bay while the rest is deflected north to exit northeast into Hudson Strait. A westward, wind-driven return flow across the top of Hudson Bay has been predicted and there is a small, perhaps intermittent, intrusion of water from Hudson Strait at the northeast corner of Hudson Bay. This circulation is maintained by inflow/outflow forcing that likely occurs year-round, and reinforced during the open water season by wind and buoyancy forcing. Estimates of the average residence time of water in Hudson Bay range from 1 or 2 to 6.6 years (Drinkwater 1988 = 3.5 y, Jones and Anderson 1994 = 3-4 y, Prinsenberg 1984 = 6.6 y, Ingram and Prinsenberg 1988 = 1-2 y).

In spring and summer, the water entering northwestern Hudson Bay is diluted by meltwater and runoff from the land, warmed by the sun, and mixed by the wind as it circulates cyclonically around Hudson Bay and James Bay. This produces strong vertical stratification of the water column that is characteristic of these areas in summer, particularly offshore. Summer surface temperatures typically range from 1 to 9°C and salinities from 21 to 32, but salinities can be lower close to shore and in bays receiving discharge from rivers (Figure 5) (Barber 1967, Anderson and Roff 1980a, Prinsenberg 1986a). A strong pycnocline (density gradient) develops at about 20 m depth that slows vertical mixing, thereby limiting nutrient additions to surface waters and biological productivity. Inshore areas generally have lower water temperatures, salinities, and clarities and higher chlorophyll ***a***, ATP (adenosine triphosphate), and pelagic biomass than the offshore areas (Stewart and Lockhart 2005). These differences may be attributable to mixing processes which bring colder, deeper, relatively nutrient-rich water to the surface, and to dilution and nutrient addition by freshwater runoff. In winter, lower runoff, salt rejection from the growing ice cover, and surface cooling weaken the vertical stratification and permit very slow vertical mixing (Roff and Legendre 1986). There is little coastal development or bottom relief to promote mixing or upwelling that might increase the availability of chemical nutrients in the surface waters. Temperature and salinity are relatively stable below a depth of 50 m, but small changes related to the seasonal disappearance of the pycnocline have been observed to 65 m in James Bay and 100 m in Hudson Bay. The water becomes progressively colder and more saline with depth, approaching the same deep water type (T = -1.4°C, S > 33) at about 100 m.

In the Churchill River estuary temperature and salinity vary widely over the year (Kuzyk *et al*. 2008). Salinity in the upper few meters can range from near 0 during the spring freshet to 17 or 18 in winter and pre-melt. Below the halocline at 5 to 6 m salinity can range from 29 in the fall to 33.5 in winter and pre-melt. In 2005, water temperatures during the winter and pre-melt period were consistently near freezing.

In summer, the warm, dilute water from James Bay is recognizable as it flows northward along the west coast of Quebec and into Hudson Strait. The bottom water in James Bay is subject to considerable seasonal and interannual variation in temperature and salinity, due in part to the relative shallowness of the bay. The large runoff rates of the James Bay region (0.01 Svd) account for 61% of the freshwater brought into Hudson Bay (Prinsenberg 1986a).

Most water exchange with other large marine ecosystems (**LME**s) is via Hudson Strait. Cold, saline (32.5 < S < 33.5) water from the Baffin Island Current flows northwest into the region along the north side of Hudson Strait (Drinkwater 1988; Straneo and Saucier 2008a, 2008b). Some of this inflow penetrates into Foxe Basin, where it contributes to a small counter-clockwise loop before joining the southward outflow of Arctic water on the western side of the basin (Prinsenberg 1986c). The rest crosses the Strait to join warmer, less saline water from Hudson Bay (<30) and Foxe Basin (<32) that flows southeast out of Hudson Strait.

There is a marked cross-channel gradient in the surface temperature and salinity of Hudson Strait, with higher temperature, lower salinity and stronger stratification in the south, where the flow is concentrated near shore (Figure 6) (Drinkwater 1986, 1988; Straneo and Saucier 2008b). Some of this water enters Ungava Bay from the west and flows cyclonically around the Bay, where it is diluted by runoff before exiting to the northeast. Recent river runoff is concentrated in a narrow wedge along the south side of Hudson Strait (Tan and Strain 1996). Mid-way along the strait the bulk of the fresh water passes within 20 km of shore (Straneo and Saucier 2008b). The average summer current along the south shore is intense, reaching a maximum of 0.3 m/s in the Cape Hopes Advance area (Drinkwater 1988). This freshwater forcing is seasonal (June to March) and accelerates as the freshest waters pass, peaking in November and December (Straneo and Saucier 2008b). As this warm, dilute surface outflow from Hudson Bay passes through the Strait it is mixed with colder surface water from Foxe Basin and colder, higher-salinity deep water. Warmer, high salinity water from the Labrador Sea penetrates into the eastern half of the Strait below about 200 m (Figure 7) (Drinkwater 1988). Vertical mixing is intense near the eastern entrance of Hudson Strait (Collin and Dunbar 1964). Arctic properties (low temperature and salinity) of the combined flow are fed into the Labrador Current at the north end of the Labrador Shelf and carried southward to exert their influence on the coastal ocean climates of Atlantic Canada (Stewart and Lockhart 2005).

SEA ICE

The HB complex is essentially ice-covered in winter and ice-free in summer. Most ice forms locally and multi-year ice is rare in Hudson Bay and absent from James Bay (Markham 1986). Ice formation progresses from northwest to southeast, beginning in early October in northern Foxe Basin, spreading into northern Hudson Bay and Hudson Strait by mid-October, and finally into southern James Bay and eastern Hudson Strait by early December (Figure 8). The extent and thickness of the ice increase rapidly during November and December, with maximum coverage in late April or early May. Maximum ice thickness varies but generally increases from south to north, ranging from about 1 m in southern James Bay (Moosonee 71-130 cm) to 2 m in northern Foxe Basin (Hall Beach 156-293) (Prinsenberg 1988; Loucks and Smith 1989). Maximum ice thickness in Hudson Strait and Ungava Bay increases from about 125 cm in the east to over 150 cm in the west. More ice is produced than is indicated by the thickness data, some of it as ice pressure ridges that can reach heights of 3 to 3.5 m (Prinsenberg 1988).

Landfast ice forms along most of the coastline, extending farther offshore from protected or shallow coastlines than from exposed or cliff and headland coasts (http://www.natice.noaa.gov/). In winter and early spring the ice floes that cover most of the HB complex are kept in constant motion by the wind (Markham 1986; Stewart and Lockhart 2005). The pack ice in Hudson Strait and Ungava Bay tends to be less concentrated than elsewhere in the region, enabling more overwintering by whales and walrus. Icebergs are common in Hudson Strait and Ungava Bay but extremely rare elsewhere in the region. Ice scouring of nearshore ecosystems to a depth of 5 to 10 m below the low tide mark is common in Arctic coastal waters (e.g., Conlan *et al*. 1998; Heine 1989), and the scour zone is very wide in the areas of Hudson Strait and Ungava Bay that have extreme tidal ranges.

Openings in the sea ice are vitally important to overwintering species and early spring migrants. Leads develop along the shore and at fast ice edges when the wind blows offshore (Figure 9). They are most common in northern Hudson Strait from Cape Dorset to Big Island (62°43'N, 70°43'W) and along the west shore of Hudson Bay from Churchill to Coral Harbour (Markham 1986). Recurring polynyas form in Hudson Strait near the Digges Islands (62°35'N, 77°50'W); in the northwest and southeast of Foxe Basin; Hudson Bay near islands along the southeast coast and in the Belchers, in Roes Welcome Sound, and north of Coats Island; and in James Bay off the southwest tip of Akimiski Island (Martini and Protz 1981; Stirling and Cleator 1981; Prinsenberg 1986b; Nakashima 1988; Gilchrist and Robertson 2000).

Breakup begins in late May or early June along the coasts downstream from large estuaries and marine inflows (Figure 8). James Bay is normally ice free by early July; Hudson Bay, Hudson Strait and Ungava Bay by late July or early August; and Foxe Basin by mid-September. Winds and currents carry the melting ice south. In Hudson Strait/Ungava Bay the last ice to melt is usually concentrated in eastern Ungava Bay, and in Hudson Bay it is along the Ontario coast. Foxe Basin has a longer ice season and sometimes has remnant ice amidst the northern islands and along the north coast of Southampton Island in September (Prinsenberg 1986c). Depending upon weather conditions, the timing of freeze-up or breakup may be retarded or advanced by up to a month, but the basic pattern of ice formation is similar from year-to-year (Cohen *et al.* 1994; Stewart and Lockhart 2005).

Sea ice strongly affects the region's physical and biological oceanography, the surrounding land, and human activities (Stewart and Lockhart 2005). It determines the ecology of the nearshore and ice biota and it also influences pelagic systems under the ice and at ice edges. As the interface between air, ice, and water, ice edge habitats are areas of mixing that attract biota to feed. These areas are important sites of energy transfer. The presence of nearly complete ice cover with extensive areas of landfast ice and nearshore scouring will have a strong influence on whether species from more southerly ecosystems can establish in the region. Seasonal ice cover also influences the timing and routing of vessel traffic to and from the region.

SHIPPING PATTERNS

Ships that pass through Hudson Strait are almost all enroute to destinations in the HB complex (Figure 10). They rarely continue northward through Fury and Hecla Strait, although a tanker did pass through in 2007 and again in 2008 (F. Constantine, pers. comm. 2008). High tides and strong winds can make Hudson Strait a dangerous shipping route (NIMA 2002). Vessel traffic is largely confined to the open water season so there is seldom a requirement for ice-breaking. Most ships entering Hudson Strait from the east are involved in the import and/or export of commodities or in the annual sealift although some passenger ships, coastguard ice breakers, research vessels, and navy ships also pass through the strait. Ships that load in ports without discharging cargo release most of their ballast water into the harbour (Levings *et al*. 2004). Consequently, ships arriving in ballast to load grain or other commodities will exchange more ballast water than those carrying goods or materials into the region.

The number of ships passing through Hudson Strait are recorded by the Canadian Coast Guard (INNAV; http://www.innav.gc.ca/), but reporting is not yet mandatory so not all vessels report (C. Wiley, DFO/TC pers. comm. 2008). Access to this database is restricted. The total number of ship transits reporting passage at 'Hudson Strait Direction West', including 'Hudson Straight North Channel Direction West' (S. Bailey, DFO, pers. comm. 2008), were:

2005 - 31 (16 of these were in ballast enroute to Churchill—Port of Churchill)
2006 - 31 (at least 10 were in ballast enroute to Churchill—National Ballast Water Data Base)
2007 - 45 (19 were in ballast enroute to Churchill, another may have been with ballast--Port of Churchill)

All ships entering waters under Canadian jurisdiction are required to submit ballast water reporting forms giving their history of ballast water exchange (C. Wiley, DFO/TC pers. comm. 2008). These histories are recorded in the joint DFO / TC National Ballast Water Data Base, and are current since the 2005 shipping season. Ship loading data for 2005 and 2007 from the Port of Churchill (I. Sawatzky, Hudson Bay Port Company, Churchill, MB pers. comm. 2008) and the National Ballast Water Database (C. Wiley, pers. comm.) were available for comparison. In 2005, five ships that loaded agricultural products for export (grain, peas) and one that repeatedly loaded fuel oil for sealift within the HB complex were not listed in the latter database. In 2007, four vessels that loaded grain were not listed. Some of the unlisted vessels originated from Canadian ports and were not included in the database because they were not required to exchange their ballast water. However, several of the unlisted vessels last called at ports outside Canada (Appendix 1). While the National Ballast Water Database is very useful, it does not currently provide a complete record of vessels in ballast entering the HB complex.

IMPORT/EXPORT

The Port of Churchill is the only deepwater port in the HB complex. It is linked to southern Canada by the Hudson Bay Railway (HBRY), which is owned by OmniTRAX Inc. and services communities and resource-based industries in northern Manitoba (http://www.omnitrax.com/). Major rail customers include Hudson Bay Mining & Smelting, Tolko Industries, the Canadian Wheat Board, and merchandisers of specialty crops. Wheat and barley marketed by the Canadian Wheat Board and specialty crops are exported through the Port of Churchill, which is the railway's northern terminal. Other major commodities handled by HBRY include ores and concentrates, copper and zinc metal, logs, kraft paper, lumber, petroleum products and general merchandise. Scheduled intermodal service is operated.

The Port offers four deep-sea berths, including one tanker berth, and can take vessels with a cargo capacity of up to 57,000 tonnes deadweight (DWT). Its facilities include a grain elevator with storage capacity of 140,000 tonnes (5 million bushels), an 82,000 sq. ft. indoor storage facility, and a petroleum terminal with storage for 50 million litres plus rail and dockside distribution systems for various petroleum products (http://www.portofchurchill.ca/). Commodities can be delivered by rail to shipside. The Port is available for shipping and receiving ocean vessels from July until November and has three towing tugs available. Scheduling earlier or later in the season is available by using ice-class vessels or icebreakers. Dredging of the harbour, re-equipping the car unloading system, and repairing and strengthening the wharf have improved the Port facility and enabled the loading of panamax size vessels of 50,000 to 60,000 DWT (Omnitrax 2001a).

Deep sea vessels seldom arrive at the Port of Churchill earlier than the last week of July or depart later than the first week of November (Jones 1968; Niimi 2007) (Figure 10). Most of these ships load prairie grain bound for foreign markets although some have delivered oil or ore, loaded other commodities, or delivered to markets in eastern Canada (Appendix 1). The grain carriers are usually in ballast when they pass through Hudson Strait, although in 1998 one delivered copper ore (I. Sawatzky, pers. comm. 2008), and in 2007 and 2008 others delivered fertilizer (Kusch 2007; Canadian Wheat Board 2008). The volume of grain shipped varies widely from year to year and with it the number of ships using the Strait and Port.

Over the past decade the number of ships visiting annually to deliver or load commodities at the Port of Churchill has varied from 9 to 30 (Canadian Wheat Board 2006, 2008; I. Sawatzky, pers. comm. 2008). Over the period 1998 through 2005, the majority of ships that arrived at the Port of Churchill in ballast travelled from ports in the eastern Atlantic Ocean, some from the western Atlantic Ocean—including freshwater ports in the Great Lakes and St. Lawrence River system, and individual ships travelled from the western Pacific or Polar oceans (Figure 11; Table 1; Appendix 1). The overwhelming majority originated from temperate waters, with a few from tropical and sub-arctic waters. During the summer months when most of these ships would have embarked for Hudson Strait, the average surface water temperatures in these areas tends to be much warmer than in Hudson Strait or the HB complex in general (Figure 12), but the surface salinity can be higher or lower (Figure 13). While shipping patterns will change with demand, these data illustrate: 1) the potentially widespread origins of ballast water carried by these ships; 2) the current concentration of these sources in temperate waters of western Europe, the Mediterranean, and eastern North America; and 3) that these exchanges must occur over a very broad range of salinities.

All of the 38 vessels listed in the National Ballast Water Database as loading at the Port of Churchill over the period 2005 to 2008 had ballast water management plans (C. Wiley, DFO/TC, pers. comm. 2008). These vessels had from 3 to 24 ballast water tanks. Most vessels (28) had ballasted all of their tanks at their last port of call (source port). The pattern of port origins was similar to that for the period 1998 through 2005. Some vessels (7) had only ballasted some of their tanks at the last port of call and had ballasted their other tanks at the previous port or two. Ballasting data were not available for three other vessels. Exchange of ballast water at sea was conducted by the flow-through method or the empty-refill method. Vessels using the flow-through method usually keep their tanks full but dilute the ballast water they contain by pumping water equivalent to 3 times (300%) the tank volume through the tanks. Vessels that use the empty-refill method simply pump the ballast water out of the tank and then refill it. Some vessels used one method for some tanks and the other for the remainder. Neither method is 100% efficient, as there is always residual (unpumpable) water at the bottom of the tanks. Both methods have an estimated efficiency of about 95%, but this can vary depending upon the type of ship (Ruiz 2007). Two Churchill-bound vessels that used the flow-through method reported having flushed 100% rather than 300% of the tank volume--whether this was a reporting error is unknown. Source temperatures ranged from 8°C at Antwerp, Belgium to 34°C at Port Everglades, Florida. None of the 36 vessels that reported their ballast water exchange locations conducted their exchanges in the Hudson Strait ABWEZ, although one vessel did so immediately to the east in the Labrador Sea and another in northern Hudson Bay (Figure 14). With the exception of one ship that exchanged ballast water in the Pacific Ocean, the remaining ships exchanged ballast well off shore in the Atlantic—all but one of them north of the Equator. Twenty-eight of the vessels reported discharging ballast water at Churchill. They discharged an average of 13,400 MT.

SEALIFT

Coastal communities in the HB complex that lack a rail or road link to the south import most of the food, dry goods, and fuel needed for the upcoming year by sea during the open water season. This annual community resupply is known as the “sealift”. It serves all of the Nunavut communities, including Baker Lake, and those in Quebec from Kuujjuarapik north. Some of the sealift is carried by ships loaded in Atlantic Canada and transported through Hudson Strait (Figure 10, bottom). Most of these vessels return east in ballast, but in 2007 one ship transported grain from Churchill, MB to southern domestic markets (CBC 2007). The remainder of the sealift is carried by barges that are loaded in Churchill, MB or Wemindji, QC and towed to the communities by tugboat (Figure 10, top). These tugs and barges typically remain in the HB complex year-round. The number of sealift vessels visiting each community, and their routes and timing depend upon community requirements for the year. The companies involved and ship voyages required for the annual sealift change over time.

In 2008, Coastal Shipping Limited, Desgagnés Transarctik Inc. (DTI), and Nunavut Eastern Arctic Shipping Inc. (NEAS) all operated ships that carried sealift through Hudson Strait. Coastal Shipping Limited of St. John's, NL has delivered fuel to the Nunavut communities in the HB complex since 2001 (http://woodwards.nf.ca/coastalshipping.html; F. Constantine, pers. comm. 2008). The fuels, primarily Jet A, unleaded diesel and unleaded gasoline, are carried by tanker from refineries in Montreal, QC and Come By Chance, NL during August through early October. In recent years, three tankers of varying capacities have been involved in this resupply, the M/V Tuvaq (**net tonnage** 4,937 t), M/V Dorsch (3,548 t) and M/V Mokami (924 t) (http://forms.cta-otc.gc.ca/CVIS/Search_e.cfm?Mode=S). The M/V Mokami and M/V Tuvaq both have fully segregated ballast. Smaller communities may be visited once but larger ones require multiple visits. The small tankers are used to resupply Baker Lake.

Desgagnés Transarctik Inc. delivers dry goods from its base in Ste. Catherine, QC via Hudson Strait to all of the communities served by sealift in the HB complex (http://www.arcticsealift.com/). In 2008, most of these communities were visited twice, with Rankin Inlet and Kujjuaq being visited three times and Cape Dorset, Repulse Bay, and Hall Beach only once. The company operates a fleet of multi-purpose cargo vessels and tankers. Of these, at least the M/V Anna Desgagnés (LOA 173.50 m; 17,850 tonnes deadweight; ballast capacity 4,438 m^3), M/V Camilla Desgagnés, and M/V Rosaire A. Degagnés (LOA 138.07 m; draught 8.0 m; 12,744 tonnes deadweight) were involved in the 2008 sealift. The first vessels enter Hudson Strait in early July and the last depart by mid-November.

Nunavut Eastern Arctic Shipping Inc. (NEAS), an Inuit-owned company with its headquarters in Iqaluit, loads cargo at Valleyfield, Quebec to supply communities in the HB complex (http://www.neas.ca/). Goods are transported in three ships; the M/V Umiavut, which is a multi-purpose container vessel, strengthened for heavy cargoes (LOA 113.6 m; draft 8.54 m; cargo capacity 11,840 m^3 or 9,587 tonnes deadweight), the M/V Aivik a heavy lift vessel (LOA 109.9 m; draft 5.92 m; 13,388 m^3 or 4,860 tonnes deadweight), and the M/V Avataq (LOA 113.2 m; draft 8.54 m; cargo capacity 11,840 m^3 or 9,587 tonnes deadweight). In 2008 these vessels had at least two sailings into the HB complex. The first vessels typically arrive in eastern Hudson Bay in mid-July and the last leave eastern Hudson Strait in mid-November.

The Port of Churchill is also an important sealift access point for goods and materials carried by rail that are delivered by tug and barge within the HB complex (Figure 10, top). Nunavut Sealink and Supply Inc. (NSSI) (http://www.arcticsealift.com/en/NSSI.aspx) and the Northern Transportation Company Limited (NTCL) (http://www.ntcl.com/) conducted this portion of the 2008 sealift. Both companies carried dry goods from Churchill to communities in the Kivalliq Region of Nunavut, between mid-July and mid-October, and NTCL also supplied Sanikiluaq. In addition, the Moosonee Transportation Limited barged dry goods from Wemindji, QC to Kuujjuarapik, QC in mid-October (http://www.mtlmoose.ca/). In the past this firm has supplied many of the communities in James Bay and Hudson Bay.

Most sealift vessels enter the HB complex fully loaded with fuel or cargo, and do not require ballast water for stability or safe operation. When these NOBOB vessels off-load their cargo they take on water to stabilize the ship. If this water is discharged during at another community on the ship's route, biota from water and sediment that were residual in the tanks during the incoming voyage may be introduced (Bailey *et al*. 2005; Johengen *et al*. 2005; NRC 2008). Non-indigenous biota might also be spread from one area of the HB complex to another. This vector is limited by the fact that few sealift vessels currently load cargo in the region. The M/V Dorsch, which transported fuel from Churchill to other communities in the region in 2005, may have been an exception. However, this pattern of activity may change with time, and this risk should be considered further.

FUTURE OUTLOOK

Shipping patterns in the HB complex are likely to change over time (Gedeon 2009). Resource development, population growth, and a longer shipping season in response to climate amelioration could increase both import and export markets. Ship traffic into the HB complex LME via Hudson Strait may increase substantially in future, in response to economic development and climate amelioration. There is strong interest in diversifying international commodity shipments via the Port of Churchill to increase its viability. The Port has historically exported mostly grain. However, the successful delivery of a cargo of fertilizer from Estonia by a Russian ship from the Murmansk Shipping Company in 2007 (Friesen 2007; Kusch 2007), and two in 2008 (Canadian Wheat Board 2008), may herald the expansion of this trade corridor (Kusch 2008). The possibility of establishing a trade route between the Russian port of Murmansk and Churchill is being examined, as it offers a shorter, less congested route for transporting goods from Asia to the Midwestern United States (Farnham 2004; Friesen 2007). The amount of ballast water exchanged in Hudson Strait and released at ports in the HB complex would not necessarily increase in direct proportion to any increase in shipping, since any increase in imports relative to exports would tend to reduce the need for ballast (Niimi 2004). However, the number ballast water sources and volume of water from any one source might increase.

There is also strong interest in developing new metal and diamond mines in Nunavut. Developments have been proposed for deposits situated inland from the west coast of Hudson Bay, and near Mary River on Baffin Island north of Foxe Basin (Figure 15). These areas lack land transportation routes to the south. They would rely solely on shipping to obtain supplies and materials and to transport their products to market. If these developments proceed, ship traffic into the region via Hudson Strait could increase substantially. There will also be interest in lengthening the shipping season to improve economic returns.

The Baffinland Iron Mine Corporation (2007) hopes to export 12.6 MT of iron ore on average annually from the Mary River deposit, over the 25+ year life of the proposed mine. The ore would be carried in ice-reinforced ore carriers, each with a cargo capacity of about 135,000 MT. A fleet of 10 such vessels, operating year-round would be required to transport this quantity of ore (H. Cleator, DFO, pers. comm.) (Figure 10, bottom). In total, there could be up to 140 round trips annually by vessels transporting materials to and from the mine. During the summer of 2008, three ships carried a total of 113,000 MT or iron ore from the mine via Milne Inlet on the northern coast of Baffin Island to Europe (see also Gedeon 2009). However, once the mine is fully operational, the company hopes to ship ore to market via Steensby Inlet and Hudson Strait.

The development of mines in the Kivalliq and Baffin regions could increase the odds of ships needing to use ABWEZ in Hudson Strait. With the additional ship traffic, the volume of ballast water released along the west coast of Hudson Bay- perhaps even in Baker Lake or Wager Bay, and along the north and west coasts of Foxe Basin would increase. Oceanographic conditions in these areas are harsher in terms of temperature, salinity, and ice cover than those near Churchill. They are less influenced by fresh water--Baker Lake and Chesterfield Inlet excepted, and tend to have steeper, rockier shorelines, with deeper nearshore waters.

In the late 1970s similar interest related to oil development in the High Arctic prompted studies of Fury and Hecla Strait as a potential year-round shipping route (D.F. Dickins Engineering and Albery, Pullerits, Dickson and Associates Ltd. 1979; Dey 1981). Vessel traffic to and from the HB complex via Fury and Hecla Strait has been rare but it does occur (F. Constantine, pers. comm. 2008). If it were to increase in the future, vessels traveling from outside the EEZ into the HB complex via this route would likely use ABWEZs in Lancaster Sound or the Beaufort Sea for the emergency exchange of ballast water. These ABWEZs may also be used in future by domestic coastal traffic to avoid unwanted species introductions. Increased use of this route could increase the traffic from other northern regions and thereby the cross-transfer of Atlantic and Pacific biota.

There is currently no active oil extraction or exploration within the HB complex, on its islands or along its coasts. However, ship-borne drilling and seismic exploration was conducted in Hudson Bay in the 1970s and 1980s (Stewart and Lockhart 2005). Wells have been drilled in central Hudson Bay, on Rowley Island in northern Foxe Basin, and on Akpatok Island in Ungava Bay. The best source rocks found to date in the Hudson Bay Basin are the petroliferous Ordovician shales that outcrop on Southampton Island (Nelson 1981; Dewing and Cooper 1991). Shipping traffic into and out of the region related to oil exploration and development could increase in future as world oil supplies dwindle and new sources are sought and developed. Climate amelioration, particularly if Hudson Bay were to become ice free year-round, could make the region much more attractive for hydrocarbon exploration. During the exploratory and development phases ballast discharge would be limited as ships would arrive loaded or be involved in exploratory research. However, if a resource were developed tankers might be used to transport product and would likely arrive in ballast, which could increase use of the ABWEZ.

RISK ASSESSMENT

The primary objective of an ABWEZ in Hudson Strait is to enable vessels to travel safely to communities and ports in the HB complex. Otherwise vessels are required to exchange their ballast outside the territorial limit.

Detailed knowledge of international ship traffic patterns, while useful, is not essential to the determination of risks associated with the use of Hudson Strait for ballast water exchange. This is a fundamental difference between Arctic exchange zones and those located along the Atlantic or Pacific coasts of Canada (Brickman *et al*. 2004; Levings and Foreman 2004; Simard and Hardy 2004). Ecosystems along the east and west coasts of Canada receive ships carrying biota from oceanographically similar coastal areas that are separated by strong physical, chemical, and biological barriers and great distances. Hudson Strait does not. It receives ships carrying biota from other

Arctic and Subarctic regions, or from significantly warmer ecosystems to the south (Table 1).

Arctic and Subarctic coastal species with environmental tolerances that would enable them to establish in the HB complex are typically present already, or are represented by a closely-related species with a similar life history. This is because the barriers to species' movements posed by differences in water temperature, salinity, nutrients, and distance between coastlines are much weaker in the Arctic circumpolar region than they are between continents at lower latitudes. Polar currents that distribute water and ice also distribute many marine and ice-adapted species. Brackish corridors that form under the ice and along coastlines in the spring enable brackish water species to move widely along the coasts; currents along these shores can also transport pelagic larvae long distances (Craig 1984). Intercontinental distances between northern coastal waters (e.g., Bering Strait) are much shorter than they are farther south (e.g., Pacific Ocean), making intercontinental movements easier for Arctic and Subarctic coastal species than for temperate or tropical species.

Lower average and minimum temperatures, thick seasonal ice cover, and long periods of low light conditions limit the establishment of biota from warmer waters in the HB complex. The seasonal presence of thick sea ice creates an ecosystem that is remarkably different from that of temperate and tropical seas. It limits incoming light and exchange with the surface, scours benthic habitats, and causes large seasonal fluctuations in the salinity of the upper water layer. The strong outflow from Hudson Strait into the Labrador Sea also creates a barrier to natural immigration by North American coastal species that have limited mobility.

From a biological perspective a key objective of locating a ballast water exchange zone in Hudson Strait is to avoid introducing non-indigenous biota to Foxe Basin, Hudson Bay and James Bay, and into the Hudson Bay watershed. Of these areas, James Bay and eastern Hudson Bay offer the most hospitable conditions for species introduced from temperate waters. They are warmer, have lower salinity, shorter periods of ice cover, and receive more incoming solar radiation over the year (Stewart and Lockhart 2005). The coasts slope gradually seaward and their waters are shallow well off shore. The complex eastern coastline offers a variety of different coastal habitats. Large rivers that drain into James Bay and Hudson Bay also create large estuaries.

Current regulations under the *Canada Shipping Act* (P.C. 2006- 495 June 8, 2006) exempt domestic ships from the requirement to exchange ballast, provided they remain in waters under Canadian jurisdiction. This is an important loophole in the regulations which have been designed to protect against the transfer and spread of non-indigenous species in Canadian waters (Lavoie *et al*. 1999; Levings *et al*. 2004; Ruiz and Reid 2007). It means that domestic ship traffic, with or without ballast on board, is facilitating the transport of non-indigenous biota into the HB complex by enabling these organisms to circumvent natural barriers posed by coastal morphology, salinity, temperature, currents, and other factors. It could for example lead to the discharge of biota from the Great Lakes into Baker Lake or from the St. Lawrence Estuary into Churchill Harbour. These ships may have shorter transit times than transoceanic vessels, enabling greater survival of non- indigenous species thus further increasing the risk of introductions. Research is needed to assess these risks and in the interim a precautionary approach should be followed, whereby domestic vessels exchange (BOB) or flush (NOBOB) their tanks before entering the HB complex.

When managing the risk of species introductions into the HB complex, two key questions must be addressed:

- "Where might indigenous species be most at risk from introductions?", so these areas can be avoided.

And,

- "Where are conditions least favourable for the establishment of non-indigenous biota, particularly those from coastal temperate environments?", since these are the biota most likely to be absent from the HB complex, to be carried there in ballast, and to establish if released into southern Hudson Bay.

Optimally exchange should take place where organisms that do survive are swept out of Hudson Strait into the Labrador Sea, rather than into southern Ungava Bay, which might provide more hospitable habitat for establishment. These questions are considered in the following sections.

GENERAL DESCRIPTION OF RISKS

Risks to indigenous biota from the introduction of non-indigenous species include competition for food and space; parasite or disease introduction; predation, toxicity, and the uncoupling of important biological linkages (e.g., Carlton 1992; Claudia *et al*. 1992; NRC 1996; Hallegraeff 1998; Sax *et al.* 2007). These can lead to ecological disruptions that impact local resource harvesting and economics. These impacts have been reviewed by many authors and will not repeated here. Instead, three recent examples of successful invaders will be briefly discussed. The first of these, an algal genus was chosen because it was not identified in a recent study that examined the potential dispersal of aquatic invasive species into Hudson Bay (North/South Consultants Inc. 2006). Invasions of this genus vectored by ballast water have constituted a particularly "nasty surprise" in many areas of the world. The second species, the European green crab (*Carcinus maenas*), also was not identified in that study. The recent risk assessment for this species in Canadian waters considered Atlantic and Pacific waters but not those in the Arctic (Therriault *et al*. 2008). The third species is the rainbow smelt (*Osmerus mordax*), a recent invader to Hudson Bay and perhaps the only invasive species that has been identified from the HB complex.

Dinoflagellate algae of the genus *Alexandrium* (formerly *Gonyaulax*)—in particular *A. tamarense (formerly G. excavata*) on the Atlantic coast and *A. catenella* (cold temperate waters—California to Alaska) and *A. acatenella* (Pacific), cause red tides and produce neurotoxins (White 1980; Martin and White 1988; Faust and Gulledge 2002). Blooms of these toxic algae can impact shellfish, fish, mammals, and birds that come in contact with it (White 1980; Trainer and Baden 1999; Kimm-Brinson and Ramsdell 2001; Shumway *et al*. 2003). Bivalve molluscs that consume these algae accumulate the toxins in their soft tissues, and when eaten can cause paralytic shellfish poisoning (PSP). The introduction of a Japanese species of red tide dinoflagellate has had considerable impact on Australian shellfish industries (Williams *et al*. 1988; Hellegraeff and Bolch 1991; Hallegraeff 1998). *A. acantenella* may also have been introduced recently from temperate areas of Asia into the Mediterranean basin, where it is spreading (Penna *et al*. 2005).

Dinoflagellates of the genus *Alexandrium* have not been recorded from the Hudson Bay region (Bursa 1961; Anderson 1979; Roff and Legendre 1986), nor has PSP been found in the testing of mussels (Jamieson 1986; Giroux 1989; M. Hentzel, DFO Winnipeg, pers. comm. 1993). Introduction of these dinoflagellates could have a significant, long-term negative impact on the quality of edible molluscs in the HB complex. Latent toxicity in molluscs could affect the safety of subsistence harvests, damage commercial harvest potential, and cause mortality among other species that eat affected molluscs. Monitoring of ballast water for harmful phytoplankton organisms can be confined to the resistant cyst stages of a limited number of toxic dinoflagellate species (Rigby and Hallegraeff 1994).

The European green crab has successfully invaded the Atlantic and Pacific coasts of Canada where it inhabits sheltered coastal and estuarine habitats and semi-exposed rocky coasts (Klassen and Locke 2007). This small crab can survive in a broad range of temperatures (<0 to >35°C) and salinities (4 to 52‰), although larval development may be limited at temperatures <9°C and salinities <20‰). These tolerances and the species' high reproductive potential and planktonic larvae facilitate its natural and anthropogenic dispersal. Modelling studies suggest that habitat conditions along the entire Atlantic coast of Canada may be suitable for these crabs (Therriault *et al*. 2008). These studies did not examine Ungava Bay or other areas of the HB complex which may also offer suitable habitat. The introduction of these crabs could induce trophic changes, as they are voracious omnivores (Klassen and Locke 2007). Reductions in shellfish abundance have been reported following their introduction, and they can concentrate the biotoxins that cause diarrheic and amnesic shellfish poisoning. The potential trophic impacts of green crab becoming established are unpredictable in the HB complex, where the only indigenous crab species hitherto reported is *Hyas coarctatus* (see Squires 1990). Damage to eelgrass beds by green crabs rooting in soft sediment and dislodging vegetation would be of particular concern.

While the impacts of species introductions into Canadian Arctic waters in ballast water have not been studied, the recent invasion of southwest Hudson Bay by the rainbow smelt is instructive. These small, anadromous fish, presumably from the Atlantic population, were illegally introduced into headwaters of the Nelson River watershed in northwest Ontario and have spread downstream to Hudson Bay (Campbell *et al*. 1991; Franzin *et al.* 1994; Remnant *et al*. 1997; Zrum 1999; Stewart *et a*l. 2001). They are now venturing along coast against the prevailing currents (R. Remnant, North/South Cons. Inc., Winnipeg, pers. comm. 2003), and may be spawning in the lower Nelson River basin (Zrum 1999). While rainbow smelt are excellent food fish in their own right and support commercial and recreational fisheries in the Great Lakes and Atlantic Canada, their spread is a concern for commercial fisheries in the Hudson Bay region (Franzin *et al*. 1994; Stewart and Watkinson 2004). These smelt compete directly for food with various commercially harvested species, particularly whitefishes and ciscoes, and prey upon their eggs and larvae. Walleye (*Sander vitreus*) that eat rainbow smelt deteriorate quickly in gillnets, and are unmarketable if not cleaned within hours of capture (R. Remnant, North/South Cons. Inc., Winnipeg, pers. comm. 2003). Elsewhere, the introduction of rainbow smelt has reduced the populations of pelagic and benthic planktivores and increased the growth and fat content of game and commercial fish that begin eating it (Stewart and Watkinson 2004). This increases mercury content of the latter and reduces their quality for human consumption. Colonization by smelt of freshwater systems entering the Hudson Bay complex is limited in many areas by waterfalls or dams that pose insurmountable barriers to upstream fish movement. But, there are some notable exceptions such as Baker Lake and the Thelon River.

RISKS TO THE ECOLOGY OF HUDSON STRAIT AND THE HUDSON BAY COMPLEX

The vulnerability of indigenous biota to species introduced through ballast water exchange will depend on which species is (are) introduced, its' (their) ecological impacts, and the linkages of these impacts to the indigenous species. Relative to the Atlantic and Pacific coasts, very little is known of spatial and temporal patterns in the oceanography or ecology of the HB complex. Constraints on research posed by seasonal ice, and the costs and logistical difficulties of studying this large, remote area are very high (Stewart and Lockhart 2005). The following sections attempt to place the life history requirements of key indigenous taxa in time and space relative to potential introductions in Hudson Strait and the HB complex in general.

Plants

Biological production by phytoplankton, ice algae, benthic algae, and benthic macrophytes is limited by thick seasonal ice and snow cover that attenuate incoming light, ice scour that limits benthic plant growth, and strong vertical stratification that restricts mixing of nutrients from deeper layers into the euphotic zone (Anderson and Roff 1980a+b; Roff and Legendre 1986). The light energy available for photosynthesis changes seasonally with the angle of the sun and a high percentage of that light is reflected (albedo) by snow, ice, wet surfaces, fog, and cloud (Maxwell 1986; Bergmann *et al.* 1991). At Churchill the mean daily net radiation is positive from mid-March through October and negative for the remainder of the year (Maxwell 1986). This period decreases with increasing latitude.

The annual primary production may be moderately high in Hudson Strait and Foxe Channel, where the open-water period is longer (late July through October) than elsewhere in the HB complex and the water is generally stratified but with considerable tidal mixing. In late summer, centric and pennate diatoms can be present in much higher numbers in Hudson Strait than in Hudson Bay or James Bay (Harvey *et al*. 1997). The horizontal distributions of both surface nutrients and chlorophylls during the summer in Hudson Strait are principally controlled by tidal mixing (Drinkwater and Jones 1987). Where mixing reduces vertical stability the surface nutrients are high and surface phytoplankton biomass accumulates, probably through increased primary production. The highest summer surface concentrations of chlorophyll-***a*** in Hudson Strait are observed west of where Gabriella Strait flows between Baffin Island and Resolution Island (Figure 16). During August, there appear to be strong blooms in this area.

Primary production in Hudson Bay is comparable to seasonally open-water areas of Canada's Arctic Archipelago (Subba Rao and Platt 1984) and low relative to other oceans at the same latitudes, such as the North Sea. During the summer, chlorophyll-***a*** concentrations at the surface tend to be highest nearshore, particularly in bays and estuaries where there is more mixing and nutrient input from the land, and near islands where there is periodic entrainment or upwelling of deeper, nutrient-rich water (Figure 17). In productive inshore areas of Hudson Bay the annual primary production by phytoplankton may be about 35 g C m^{-2}, and total production may reach 70 g C m^{-2} (Roff and Legendre 1986). Little is known of the annual primary production in Foxe Basin which is a more dynamic environment than Hudson Bay, with stronger tides and more ice. During the summer higher surface chlorophyll-a concentrations are observed in the shallower, eastern areas and in the Fury and Hecla Strait area.

Productivity under the ice and above the pycnocline in Hudson Bay may be limited by the availability of nutrients, particularly nitrogen (Maestrini *et al* 1986; Demers *et al.* 1989; Gosselin *et al.* 1990; Bergmann *et al.* 1991; Welch *et al.* 1991). Such nutrient limitation is less likely in Hudson Strait where there is greater mixing. Ice algae start growing in spring as light intensity increases (Roff and Legendre 1986). Early in the season the low irradiance limits photosynthesis so that algal patches tend to develop in lighted areas under thin snow-ice cover (Gosselin *et al.* 1986). Later in the season the maximum growth occurs in areas that offer protection from photoinhibition. High concentrations of ice flora are often associated with brine channels within the ice, where nutrient concentrations may be much higher than in surrounding water (Demers *et al*. 1989). During and immediately after the spring bloom, ice algae are an important food source for the planktonic copepods *Calanus glacialus* and *Pseudocalanus minutus* (Runge and Ingram 1991; Tourangeau and Runge 1991).

Phytoplankton blooms typically occur when the upper water column is relatively stable and nutrient rich (Legendre *et al.* 1981, 1982). In exposed areas, these conditions may only occur under the ice in late April and May, but in sheltered embayments they may also occur intermittently during the summer. In offshore waters of western Hudson Strait and of Hudson Bay the maximum occurs below the pycnocline where nutrient concentrations are higher and clear water allows sufficient light penetration for photosynthesis (0.1-1% of surface light) (Anderson 1979; Anderson and Roff 1980b; Roff and Legendre 1986; Harvey *et al*. 1997). This is one of the most northerly reports of a subsurface maximum and may contribute significantly to the annual production. In southeastern Hudson Bay, James Bay, and coastal waters of Hudson Bay the mid-summer chlorophyll ***a*** maximum generally occurs in the upper 20-25 m (Grainger 1982), at or above the pycnocline (Anderson and Roff 1980b). Where tidal mixing is weak as it is in northern Hudson Bay, the phytoplankton become nutrient limited and their summertime biomass remains low (Drinkwater and Jones 1987). Species typical of fresh water are common in the offshore waters of Hudson Bay, where they may develop in melt pools on the ice or be distributed under the ice by spring runoff (Gerrath *et al*. 1980).

Ice scour prevents the establishment of a rich bottom flora in shallows and nearshore, and soft bottoms may be limiting to species that need a solid substrate for attachment (Bursa 1968; see also Heine 1989). Sunlight, nutrient availability, and water temperature may also affect the establishment of bottom fauna. The number of benthic macroalgal taxa is low relative to other seas at similar latitudes. Macroalgae grow on the seafloor of Hudson Bay to a depth of at least 75 m (Barber 1983).

Belcher Islands' Inuit harvest seaweed (*Rhodymenia* spp.) and kelp (*Laminaria* spp.) for food in October (Wein *et al*. 1996; McDonald *et al*. 1997), but other subsistence harvests of marine plants from the HB complex are poorly document. There has been interest in the commercial harvest of kelp along the west coast of Hudson Bay, where 35 MT of kelp were harvested near Whale Cove in 2000 (Stewart and Lockhart 2005).

Invertebrates

The invertebrate and urochordate fauna of the HB complex consists of freshwater, estuarine, and marine forms (Roff and Legendre 1986; Stewart and Lockhart 2005). Many of the species are widely distributed outside this region, generally in Arctic waters. Some may be relicts that survive in the warmer, less saline waters of James Bay but not elsewhere. Estuarine species are distributed throughout James Bay and southeast Hudson Bay but are present in the highest density in or near river mouths. Freshwater species do not survive far from the rivers, and Arctic marine species become dominant moving away from the large estuaries.

Few benthic species inhabit the intertidal zone on a permanent basis, likely due to ice scour that can extend well below the low tide mark (Dadswell 1974; Conlan *et al*. 1998; Conlan and Kvitek 2005) and to freezing (Dale *et al.* 1989). This zone is occupied during the open-water season by more mobile species. Central Hudson Bay supports a meagre benthic fauna with echinoderms--especially brittle stars, polychaetes, sea anemones and decapods being predominant (Grainger 1968; Barber *et al.* 1981). Along the west coast of James Bay, high densities of the clam *Macoma* and gastropod *Hydrobia* have been observed in sandy, sheltered flats or bays (Martini *et al.* 1980b). Nearby, coastal areas influenced by river mouths had very low densities of invertebrates. In estuaries, such as that of the Eastmain River, the marine zone has the most diverse benthic fauna, while the density of the benthic fauna in the brackish zone is very low compared with freshwater or marine areas (Grenon 1982).

The pelagic zone is characterized by comb jellies, arrow worms, copepods and amphipods, euphausids, and the pelagic sea butterflies. Zooplankton communities are strongly influenced by hydrodynamic features that create local differences in surface water temperature, salinity, stratification and mixing conditions (Harvey *et al.* 2001). Species assemblages offshore in Hudson Bay and to the north are characterized by typically Arctic species, such as the pteropod *Clione limacina*, amphipod *Themisto libellula* and copepod *Calanus hyperboreus*, with a greater abundance of the large, herbivorous copepod *C. glacialis/C. finmarchicus* and of euphasids in central Hudson Strait (Roff and Legendre 1986; Harvey *et al.* 2001). Species assemblages in James Bay and southeastern Hudson Bay reflect the massive seasonal freshwater inputs and estuarine character of the circulation (Grainger and McSween 1976). They are characterized by the presence of two **euryhaline** copepod species, *Acartia longiremis* and *Centropages hamatus* (Roff and Legendre 1986; Harvey *et al.* 2001).

The ice fauna is not as well known as the ice flora. In April 1983, offshore Grande rivière de la Baleine, invertebrates living in the lower 3 cm of the sea ice consisted largely of planktonic nematodes, rotifers, ciliates, and copepods--in order of abundance (Hsiao *et al.* 1984; Grainger 1988; Tourangeau 1989). The sea ice fauna was generally denser but less diverse than the zooplankton under the ice, both within and outside the river plume. The abundance was positively related to salinity, and to the presence of sea-ice microflora. Zooplankters beneath the ice are much more abundant below the brackish river plume than within it (Ponton and Fortier 1992). They are important foods for larval fishes. Marine species (e.g., Chaetognaths) are prevented from preying upon the fish and insect larvae in the overlying plume as long as stratified conditions prevail (Hudon 1994).

Secondary productivity in Hudson Bay may be of the same order as seasonally ice-free Arctic marine waters as a consequence of longer generation times in the colder water (Roff and Legendre 1986). During summer, the numbers and biomass of metazoan zooplankton in inshore and estuarine areas of Hudson Bay are similar to temperate oceans, while in offshore areas they are much lower--presumably as a consequence of low primary productivity. The biomass and abundance of total zooplankton along a north-south transect from the mouth of James Bay to Hudson Strait were low in the south (averaging 1.6 g dry wt/m^2 and 9432 ind/m^2) and increased sharply at the upper end of the bay and in Hudson Strait (averaging 6.0 g dry wt/m^2 and 40,583 ind/m^2) (Harvey *et al.* 2001). The catches of common species of decapods and fish in bottom trawls reveal a continuum of increasing species richness and abundance in an easterly direction through Hudson Strait, with the greatest species richness in Ungava Bay, where Arctic and Labrador Sea components of the fauna coexist (Hudon 1990). Within Hudson Strait there is a "hotspot" of invertebrate and fish biomass southwest of Resolution Island, where oceanographic conditions may create a persistent eddy-like structure that leads to the passive accumulation of zooplanktonic prey of shrimp (Hudon *et al.* 1993). Significant concentrations of northern shrimp *Pandalus borealis* and striped pink shrimp *P. montagui* have also been located within the strait west of 66°, and east of the strait in the Labrador Sea (DFO 2008).

Many invertebrate species are vital links in the food chain between primary producers and larger fish and marine mammals, but few are harvested for human consumption. The Iceland scallop (*Chlamys islandica*) has been harvested by exploratory commercial fisheries along the northeast coast of Hudson Bay and in Hudson Strait and Ungava Bay (Morin 1991; Lambert and Prefontaine 1995) but no large-scale commercial fishery has developed. Striped pink shrimp and northern shrimp have been harvested commercially near Resolution Island since 1979 (Orr *et al.* 2003). Prior to 1995, most fishing took place southwest of Resolution Island, and occasionally in northeastern Ungava Bay. Annual harvests from this area (SFA3) peaked in 1989 (*P. montagui* 1275.88 t; *P. borealis* 4.5 t) and since 2001 have not exceeded 26 t (T. Siferd, DFO Winnipeg, pers. comm. 2007). Since 1995, most fishing has been conducted southeast of Resolution Island. Shrimp west of 66° in Hudson Strait have not been fished commercially (DFO 2008). Their stock status is uncertain because the assessment is based on a single survey, but the fishable biomass index suggests that there may be potential for a directed *P. borealis* fishery in this area.

Inuit in the Belcher Islands have a stronger tradition of marine invertebrate harvesting than those in other coastal communities of the HB complex. They harvest the blue mussel (*Mytilus edulis*), green sea urchin (*Strongylocentrotus dreobachiensis*), six-rayed starfish (*Leptastarias polaris*), and brown sea cucumber (*Cucumaria frondosa*) for subsistence (Jamieson 1986; Giroux 1989). The green sea urchins and blue mussels are smaller as a rule than their temperate counterparts (Lubinsky 1980; Jamieson 1986). Inuit in other communities also harvest blue mussels and/or clams, typically from the intertidal zone at low tide (Doidge 1992a + b; Priest and Usher 2004; Stewart and Lockhart 2005).

Fish

Knowledge of fishes in the HB complex is scant except for harvested anadromous species, and in the vicinity of large estuaries. Lack of a proven, commercial offshore fisheries resource has limited offshore fisheries research, and ice conditions have limited seasonal research. At least 89 species of fish use the waters of Hudson Strait—more than are present in Hudson/James Bay (61), and fewer than along the Atlantic coast (Scott and Scott 1988; Stewart and Lockhart 2005). Very little is known of the fishes in Foxe Basin. Species richness and abundance increases in an easterly direction through Hudson Strait (Morin and Dodson 1986; Hudon 1990). The ability to exploit the extensive brackish zone is an important ecological adaptation for both the freshwater and Arctic marine species (Morin and Dodson 1986).

Many of the marine species in the HB complex are benthic non-specialists, characteristic of Arctic waters. In bottom trawls of eastern Hudson Strait, Arctic cod are dominant in terms of numbers and Greenland halibut in terms of weight; in western Hudson Strait they are replaced by lumpfish (*Cyclopeterus lumpus*) and seasnails (F. Liparidae) (Morin and Dodson 1986; Hudon 1990). Offshore, the relatively shallow depths in James Bay, Hudson Bay, and much of Foxe Basin likely exclude many of the deepwater fishes that occur in Hudson Strait, including commercially valuable species such as the Greenland halibut (turbot) (*Reinhardtius hippoglossoides*) and redfish (*Sebastes* spp.) (Morin and Dodson 1986; Stewart and Lockhart 2005). Mesopelagic species such as lanternfishes (F. Myctophidae) and redfish have only been reported from Hudson Strait and Ungava Bay. Greenland shark (*Somniosus microcephalus*), the only true top predator among the fish species, is common in Hudson Strait but has only been reported anecdotally from Hudson Bay and Foxe Basin (Stewart and Lockhart 2005). Small, shallower water species such as capelin (*Mallotus villosus*) and Arctic cod are vital links in the food chain of the HB complex between pelagic invertebrates and larger fish, marine mammals and birds. Large numbers of capelin spawn on beaches in the Belcher Islands and near the Nelson River in June (Comeau 1915; Dunbar 1988). Arctic cod are often associated with ice cracks or edges and move inshore in late summer, sometimes in very large schools. Larval Arctic cod are very common in the coastal waters of southeastern Hudson Bay (Ponton and Fortier 1992).

James Bay and southern Hudson Bay support characteristic and unusual estuarine fish communities that consist of a mixture of Arctic marine, estuarine, and freshwater species (Morin *et al.* 1980; Morin and Dodson 1986; Stewart and Lockhart 2005). Estuarine communities in the south include more freshwater and anadromous species and fewer Arctic and deepwater species than those to the north. Warm, shallow, dilute estuaries along the Quebec coast, from the Eastmain River north to Lac Guillaume Delisle (Richmond Gulf), attract typically freshwater species such as lake trout (*Salvelinus namaycush*), lake whitefish (*Coregonus clupeaformis*), lake cisco (*Coregonus artedi*), and burbot (*Lota lota*). Even species that seldom enter brackish water, such as the white sucker (*Catostomous commersoni*) and walleye (*Sander vitreum*) visit the estuaries of James Bay. Further north and moving offshore, where the salinity is higher and water colder, there are fewer freshwater species and more Arctic species such as Arctic charr (*Salvalinus alpinus*), Greenland cod (*Gadus ogac*) and shorthorn sculpin (*Myoxocephalus scorpius*).

The estuaries provide important seasonal foraging and nursery habitat for many species, spawning habitat for some, and year-round habitat for fourhorn sculpin (*Myoxocephalus quadricornis*) (Stewart and Lockhart 2005). Seasonal movements of these species are often complex and influenced by differences in biological requirements and variations in temperature and salinity. The timing and extent of the freshet, for example, influences the distribution of the marine larvae and determines when larvae of anadromous and freshwater species enter the estuary (Ponton *et al.*

1993). Before the spring freshet the larvae of marine species such as sand lance (*Ammodytes* spp.) and Arctic cod (*Boreogadus saida*) are marginally more abundant offshore, where porous sea ice supports the development of ice algae, than inshore where freshwater inhibits algal growth (Gilbert *et al.* 1992). Larval survival is closely coupled with the reproductive cycle of the copepods they prey upon (Fortier *et al.* 1995, 1996), so introductions that disrupt these cycles could reduce recruitment.

Inuit and Cree food fisheries harvest most fish taken from the HB complex. Neither group has a tradition of offshore marine fishing but both cultures have well-developed, open-water estuarine and coastal fisheries. These subsistence fisheries have considerable economic value and are important traditional social and cultural activities (Quigley and McBride 1987; Berkes *et al.* 1992; Fast and Berkes 1994; Wein *et al.* 1996). Commercially attractive marine fishes have not been found in sufficient quantity to support a viable commercial export fishery, but small fisheries have developed at most of the Inuit communities to supply anadromous Arctic charr to the local market (Stewart and Lockhart 2005). Some fish from the west coast of Hudson Bay are exported to Winnipeg.

Anadromous Arctic charr are the fishes most sought after for subsistence by Inuit in Nunavut (Priest and Usher 2004) and Nunavik (JBNQNHRC 1988). These fish are available at predictable times and locations each year (Stewart and Lockhart 2005). They are easy to catch using gillnets, grow relatively quickly and to a large size, and are relatively free of parasites that infect people. Subsistence fisheries for anadromous Arctic charr begin in coastal regions in late May and continue until late September--earlier than the commercial harvests, which avoid recent downstream migrants that are often in poor condition after winter starvation. Most harvesting takes place near the communities either along the coasts or at river mouths, or sometimes at inland lakes where they spawn and overwinter. Because these fish migrate long distances they may be vulnerable to harvest at various locations, complicating population management. They may also be widely vulnerable to the spread of any new parasites that cycle in introduced invertebrates. Anadromous brook trout (*Salvelinus fontinalis*) and Atlantic salmon (ouananiche, *Salmo salar*) are also harvested by Ungava Bay Inuit, either from fresh water or brackish coastal waters (JBNQNHRC 1988).

In the south, where anadromous Arctic charr are less abundant, or absent, other anadromous species dominate the coastal harvests. Inuit at Kuujjuarapik and Chisasibi harvest mostly anadromous whitefish (*Coregonus* spp., *Prosopium cylindraceum*) and brook trout (Schwartz 1976; Berkes and Freeman 1986; JBNQNHRC 1988). Cree along the James Bay and southern Hudson Bay coasts harvest anadromous lake cisco, lake whitefish, longnose sucker (*Catostomus catostomus*), and brook trout (Berkes 1979; JBNQNHRC 1982; Thompson and Hutchison 1989; Berkes *et al.* 1992).

Greenland cod, Arctic cod, and sculpins (*Myoxocephalus* spp.) are the only marine species commonly harvested by Inuit. Most of these fish are taken from Ungava Bay, the east coast of Hudson Bay, and the Belcher Islands (JBNQNHRC 1988; Priest and Usher 2004). Atlantic cod (*Gadus morhua*) are also harvested in Ungava Bay (Hildebrand 1948), and capelin in the Belchers (Hunter 1968; Fleming and Newton 2003).

Marine Mammals

Atlantic walrus (*Odobenus rosmarus*) and ringed (*Pusa hispida*), bearded (*Erignathus barbatus*), and harbour (*Phoca vitulina*) seals inhabit the waters of the HB complex year-round, while polar bears (*Ursus maritimus*) and Arctic foxes (*Vulpes lagopus*) frequent coastal areas in summer and ice habitats during other seasons (Stewart and Lockhart 2005). Harp (*Pagophilus groenlandicus*) and hooded (*Cystophora cristata*) seals and at least six species of whales including beluga (*Delphinapterus leucas*), bowhead (*Balaena mysticetus*), narwhal (*Monodon monoceros*), killer (*Orcinus orca*), minke (*Balaenoptera acutorostrata*), and humpback (*Megaptera novaeanglia*; S. Ferguson, DFO Winnipeg, pers. comm. 2007) whales are typically seasonal visitors to the region, although the first three species do overwinter in Hudson Strait and sometimes in leads and polynyas elsewhere. The whales, most seals, and perhaps walruses can dive to the bottom to feed throughout James Bay, and most, if not all, of Foxe Basin and Hudson Bay. The quality, extent and duration of the sea ice cover are vitally important determinants of their seasonal distributions, movements, reproductive success, and survival. The timing of seasonal movements can vary by a month or so from year to year depending upon ice conditions, and the offshore movements of most species are unknown. All of these species, with the exception of killer whales and other uncommon whales are harvested for food and materials, mostly by Inuit for subsistence.

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has designated bowhead as “Threatened”, and the eastern Hudson Bay and Ungava Bay beluga populations as “Endangered”; the Atlantic walrus, Lac des Loups Marins subspecies of harbour seal, polar bear, narwhal, and western Hudson Bay and eastern High Arctic/Baffin Bay beluga populations as “Special Concern (formerly Vulnerable)”; the ringed seal and hooded seal as “Not at Risk”; and bearded seal and Atlantic subspecies of the harbour seal as “Data Deficient” (http://www.cosewic.gc.ca/).

Introductions that affect the quantity or quality of prey available to marine mammals will impact their populations. They may also bring new diseases, parasites, or toxins. The impacts, positive or negative, will be greatest during periods when, and in areas where, these consumers are limited in their ability to forage elsewhere. Populations of species with large numbers and continuous distribution, such as the ringed seal, may be vulnerable to the spread of introduced disease and probably parasites (R. Stewart, DFO, pers. comm. 2008). Migratory species that are affected may have the potential to distribute any new diseases or parasites throughout their range.

Seals

The ringed seal (*Pusa hispida*) is the most common and abundant species of seal in the HB complex, where it is resident year-round (Smith 1975; Sergeant 1986; Priest and Usher 2004). Ringed seals occur in water of virtually any depth and their distributions likely are driven primarily by availability of predator-relief habitat, food availability and ice conditions (Reeves 2001). During the open water season seals of all ages are found nearshore (Frost and Lowry 1981). Adults live in these habitats year-round because they can maintain breathing holes through the landfast ice (McLaren 1958; Frost and Lowry 1981; Davis *et al.* 1980; Smith 1987; Smith *et al.* 1991), whereas non-breeders frequent the floe edge or moving pack ice during the winter and spring (Smith 1975; Lunn *et al.* 1997; Holst *et al.* 1999). There are significant numbers of ringed seals in the centre of Hudson Bay (Smith 1975; Miller and McLaren 1983; Miller

1984). While ringed seals are generally assumed to be sedentary, juveniles will undertake summer sojourns across Hudson Bay and back (S. Ferguson, DFO Winnipeg, pers. comm. 2007).

Ringed seals are adaptable in their feeding habits and eat a variety of pelagic, nectonic, and benthic invertebrates and fishes--particularly the amphipod *Themisto libellula* (synonym *Parathemisto libellula*), the mysid *Mysis oculata*, Arctic cod (*Boreogadus saida*), and sculpins (McLaren 1958; Smith 1987; Weslawski *et al.* 1994; Cleator 2001). Unlike bearded seals they seldom eat burrowing invertebrates, and like bearded seals they may avoid areas that are heavily used by walruses.

Bearded seals (*Erignathus barbatus*) are patchily distributed in the HB complex, typically at low densities relative to ringed seals (Stewart 2006). They frequent areas with moving sea ice and open water that are less than 150-200 m deep--especially areas in the 25-50 m depth range. They undertake local movements in response to ice conditions and avoid thick landfast ice unless it contains predictable leads. Bearded seals sometimes enter freshwater and have been seen 50 km inland from Hudson Bay in the Nelson River (W. Bernhardt, North/South Cons., Winnipeg, pers. comm. 2006). They typically occur alone or in small groups, and appear to avoid areas heavily used by walruses, which sometimes prey on them. Bearded seals eat a wide variety of foods, including pelagic fishes, but are primarily benthic feeders. The bulk of their diet usually consists of a few fish, crustacean, and mollusc species.

Small resident populations of harbour seals (*Phoca vitulina*) occur in areas where currents maintain open water year-round along the coasts of Hudson Bay and James Bay, typically in freshwater or estuarine rapids, small coastal polynyas, or at the ice edge (Doutt 1942; Mansfield 1967; Welland 1976). The species also occurs in Hudson Strait (Priest and Usher 2004). The adults tend to be solitary in the water but form small groups when hauled out on rocky shores. While the adults tend to be sedentary the young can undertake long migrations (Beck 1983). Harbour seals prey on a variety of fish, squids, and crustaceans (Beck *et al.* 1970; Bonner 1979; Bigg 1981).

Harp seals (*Pagophilus groenlandicus*) from the large population that winters in the North Atlantic are seasonal visitors to the HB complex (Mansfield 1967; Stewart and Lockhart 2005), and some may overwinter (Gamble 1987). They are common in Hudson Strait before the shore ice leaves in spring, rare in summer, and common again in autumn after the shore ice forms (Low 1906). Migrants arrive in Hudson Bay at ice break-up in early June and depart just before freeze-up in early October. This population may be increasing and re-occupying its former range within the HB complex (Stewart and Lockhart 2005). Harp seals feed opportunistically on small pelagic fish, especially capelin and Arctic cod, and on a variety of invertebrates, especially pelagic crustaceans (Hammill *et al*. 2005).

Hooded seals (*Cystophora cristata*) are also seasonal visitors to the HB complex. They migrate from wintering areas in the North Atlantic via Hudson Strait into northern Foxe Basin in July and return south in September (Koski 1980; T. Quillaq, pers. comm. 1985). This pelagic, deep-diving species is uncommon in Hudson Bay and James Bay. Elsewhere it feeds on a variety of pelagic and benthic fishes and invertebrates, including deepwater species such as Greenland halibut (Kovacs and Lavigne 1986).

The seal species most likely to be affected by the introduction of foreign biota into Hudson Strait and the HB complex in general is the ringed seal. It is resident year-round, widely distributed, and more numerous than the other seal species. The ringed seal is likely most vulnerable to changes that occur in the nearshore marine food web, in areas where landfast ice forms. Population level impacts are mitigated by the species' abundance, wide distribution, and varied diet. Bearded seals will be more susceptible than ringed seals to introductions that affect burrowing invertebrates, particularly molluscs, at depths greater than 25 m. The small harbour seal populations that overwinter in the open water of estuaries and small polynyas may be vulnerable to changes in pelagic and benthic fish and invertebrate populations in these areas. Harp and hooded seals are less likely to be affected by the introduction of coastal biota, as these seals forage widely and mostly on pelagic species.

Walrus

Atlantic walruses (*Odobenus rosmarus*) probably require large areas of shallow water (80 m or less) with bottom substrates that support a productive bivalve community, the reliable presence of open water over these feeding areas, and suitable ice or land nearby upon which to haul out (Davis *et al*. 1980). Walruses often gather in large herds, and are associated with moving pack ice for much of the year. When ice is lacking in summer and fall, they tend to congregate and haul out on low, rocky shores with steep or shelving subtidal zones that afford easy access to the water (Figure 18) (Mansfield 1959; Salter 1979a, b; Miller and Boness 1983).

The Northern Hudson Bay–Davis Strait population is distributed from Arviat on the west coast of Hudson Bay north and east throughout Hudson Strait (Richard and Campbell 1988). Some animals remain in local areas year-round, apparently moving inshore and offshore in response to changes in the ice; others appear to undertake significant seasonal migrations. There is a general westward movement of walruses through Ungava Bay and Hudson Strait in summer to Nottingham and Salisbury Islands, with a return movement in the fall (Degerbøl and Freuchen 1935; Loughrey 1959). Concentrations occur in the fall at or near haulouts on Bencas, Walrus, Coats, Mills, Nottingham and Salisbury Islands, and on western Foxe Peninsula (Orr and Rebizant 1987) (Figure 19). Some walruses live year-round near Nottingham and Salisbury Islands and in Roes Welcome Sound, where strong currents maintain polynyas through the winter (Kemp 1976; Orr and Rebizant 1987; Fleming and Newton 2003). The Foxe Basin walrus population is widely distributed, year-round in the relatively shallow waters of northern Foxe Basin, and the small South and East Hudson Bay population inhabits the area from the Ottawa Islands south to the Ekwan Point area of western James Bay (COSEWIC 2006).

Walrus may be more vulnerable to damage from species introductions than other marine mammals in the region. Their use of coastal habitat puts them in areas where introduced species are most likely to establish, and the benthic molluscs they eat could be affected by a wide variety of introductions. Degradation or contamination of bivalve beds in the vicinity of wintering areas, especially when animals cannot move elsewhere to feed, and near haulouts that provide important summer resting habitat could damage local populations. Clumped behaviour facilitates the spread of disease and perhaps parasites among walrus (R. Stewart, DFO, pers. comm. 2008).

Whales

Belugas (*Delphinapterus leucas*) use most of the HB complex while foraging or during migration (COSEWIC 2004a; Stewart and Lockhart 2005). In the spring, many belugas migrate from wintering areas in Hudson Strait following ice leads into the HB complex (Stewart *et al.* 1995; Stewart and Lockhart 2005). The largest summering concentration of belugas in the world occurs in the Nelson River estuary area, and there are smaller concentrations at the estuaries of the Seal, Churchill, Winisk, Severn, and Nastapoka rivers (Figure 18) (Richard *et al.* 1990). Use of these estuaries by belugas may be related to neonate survival and/or moulting. Some individuals move extensively along these shallow coasts in summer (Richard and Orr 2003), presumably to feed on fish and invertebrates. Most belugas leave Hudson Bay in October or November ahead of the forming ice, moving along the coasts or offshore across the middle of the bay to overwinter in the pack ice of Ungava Bay or eastern Hudson Strait (Figure 19). Some animals overwinter in James Bay (Jonkel 1969), but the extent of overwintering there is unknown. The seasonal movements of belugas in northern Foxe Basin are poorly known, but some remain there year-round (Stewart *et al.* 1995).

Capelin, estuarine fishes, squid, decapod crustaceans, and annelid worms (*Nereis* sp.) are important foods for adult belugas summering in Hudson Bay (Sprules 1952; Doan and Douglas 1953; Breton-Provencher 1979; Simard *et al*. 1980; Watts and Draper 1986; McDonald *et al*. 1997). Young whales that are cutting their teeth will also eat *Nereis* sp. (Doan and Douglas 1953).

Narwhals from the Hudson Bay population that winter in Hudson Strait migrate westward in the spring, traveling offshore through Hudson Strait and Foxe Channel until they reach the floe edge east of Repulse Bay (Sutton and Hamilton 1932; Richard 1991; Koski and Davis 1994; Gonzalez 2001). They move into their main summering grounds in western Foxe Channel, Frozen Strait, Lyon Inlet and Repulse Bay as ice conditions permit and typically remain until late August or early September, when they travel southeastward out of the area following the east coast of Southampton Island (Richard 1991; Gonzalez 2001; COSEWIC 2004b). There is no evidence of movement northward into Foxe Basin or of large summer aggregations elsewhere in the HB complex. Narwhals that sometimes visit northern Foxe Basin in summer may belong to the larger Baffin Bay population and enter the region via Fury and Hecla Strait (Stewart *et al.* 1995). Their route to wintering grounds is unknown.

In summer, narwhals prefer coastal habitats that offer deep water and shelter from the wind (Finley 1976; Kingsley *et al*. 1994; Richard *et al*. 1994). Their primary summer foods in the Canadian Arctic are Arctic cod (*Boreogadus saida*), Greenland halibut (*Reinhardtius hippoglossoides*), squid (*Gonatus fabricii*), and decapod crustaceans (Finley and Gibb 1982; Hay 1984). While wintering in the pack ice, narwhals prefer areas of fjords and the continental shelf where depths range from 1000 to 1500 m and upwellings may increase biological productivity (Dietz and Heide-Jørgensen 1995; Dietz *et al*. 2001).

The only baleen whale that occurs commonly in the HB complex is the bowhead (*Balaena mysticetus*), and it is seldom seen in southern Hudson Bay and James Bay (Stewart and Lockhart 2005). These large, ice-adapted whales are present during the winter in Hudson Strait (Dueck *et al.* 2006; DFO 2009) and sometimes in Hudson Bay (Low 1906; S. Ferguson, DFO Winnipeg, pers. comm. 2007). During periods of ice cover they are typically associated with the floe edge. Most of the bowheads that summer in the HB complex likely enter from Hudson Strait in the spring, following the receding pack ice to seek out the most productive feeding areas (Wakeham 1898; Low 1906; NWMB 2000; Reeves and Cosens 2003; Dueck *et al.* 2006) These areas often correspond to oceanic fronts where mixing occurs and planktonic crustaceans are abundant (Finley *et al.* 1983; Borstad 1985). During the summer bowheads are concentrated in northern Foxe Basin and in the Repulse Bay - Roes Welcome Sound - Chesterfield Inlet area of Hudson Bay, which may serve as nursery areas (Cosens and Blouw 2003). They are present in western Foxe Basin from July until November. Some move south ahead of the forming ice edge, while others that pass through Fury and Hecla Strait may return south via Lancaster Sound (NWMB 2000; Dueck *et al.* 2006). Whales in western Hudson Bay may move north into the Repulse Bay area as summer progresses and likely move east into Hudson Strait in late fall. Whales from the HB complex and Baffin Bay share common summer and winter ranges, suggesting that they belong to a single, wide-ranging population (Dueck *et al.* 2006; Heide-Jørgensen *et al.* 2006). Indeed, tagged individuals have circumnavigated Baffin Island.

Bowheads feed mainly by "skimming" small planktonic and benthic crustaceans from the water with their baleen (Lowry *et al*. 1978; Wursig *et al*. 1985), and often occur in areas where zooplankters, particularly calanoid copepods, are abundant relative to the surrounding waters (Scoresby 1820; Griffiths 1981). Feeding areas often correspond to oceanic fronts where temperature, turbidity, or current patterns suggest there is discontinuity or mixing (Finley *et al*. 1983; Borstad 1985).

Several other whale species are occasional seasonal visitors to the HB complex, arriving later in the season than the ice-adapted Arctic whales and leaving earlier (Stewart and Lockhart 2005). Killer whales migrate into Hudson Strait, Hudson Bay, and Foxe Basin to prey on other marine mammals (Milani 1986; Reeves and Mitchell 1988). Sightings are infrequent and the species may be rare in James Bay and southern Hudson Bay. The minke whale is a rare summer visitor to Hudson Bay. A single humpback whale was seen near Repulse Bay in the summer of 2007 (S. Ferguson, DFO Winnipeg, pers. comm. 2007). There are also reports of sperm whales and northern bottlenose whales in Hudson Bay but their occurrence has not been confirmed and at best they are rare.

Beluga whales may be more vulnerable to species introductions than other whales. Very large concentrations of belugas moult and feed during the summer in and near the large estuaries of Hudson Bay (e.g., Seal, Churchill, Nelson, Winisk, Severn, Nastapoka), particularly the Nelson Estuary (23,000 animals; Richard *et al.* 1990). Summer occupancy of these estuaries may be very important for neonate survival and moulting, as these populations historically braved intense harvesting pressure to continue using these habitats (Reeves and Mitchell 1987, 1989a, 1989b). Coastal estuaries are often favourable environments for the establishment of introduced species. Introductions that altered or contaminated the food web in these areas might harm affect beluga summering in these estuaries. Narwhals and bowhead, the only other common species of whales in the HB complex, frequent deeper water and are less likely to be affected by the introduction of coastal species. While the potential for introductions that alter the pelagic food web and affect production of crustacean macroplankton (e.g., krill) at oceanic “hot spots” seems low, it might impact bowhead populations if it occurred.

Polar bear

Polar bears (*Ursus maritimus*) that summer along coasts of the HB complex move onto the ice when it forms in the fall, and travel widely until melting forces them ashore to fast until freeze-up (Urquhart and Schweinsburg 1984; Stirling and Ramsay 1986; Kolenosky *et al.* 1992; Stirling *et al.* 2004; Lunn *et al.* 2005). While on the ice, they hunt ringed and bearded seals to build up the fat stores they require to survive their summer fast (see also Iverson *et al.* 2006). Arctic fox (*Vulpes lagopus*) also venture onto the sea-ice, where they follow polar bears to scavenge their kills and dig into nearshore snow lairs of ringed seals to prey on pups (Degerbøl and Freuchen 1935; Smith 1976; Stirling and Archibald 1977; Roth 2003).

Because polar bears are the apex predator of the Arctic ecosystem they may be very susceptible to the food chain effects of introduced species. They will be particularly vulnerable to introductions that cause ringed or bearded seal populations to decline. They may also be more susceptible than other species to changes in the food chain that increase the biomagnifications of contaminants.

Birds

The HB complex provides resources of critical national and international importance to migratory seabirds, waterfowl, and shorebirds. Their distributions are determined largely by habitat availability and climatic factors, especially temperature (Morrison and Gaston 1986; Stewart and Lockhart 2005). Coastal cliffs, low-lying rocky islands, wide tidal flats--often associated with wet lowland tundra, salt marshes, eelgrass beds, and open water (e.g., polynyas and leads) are particularly important habitats. Biological oceanography is also important as it determines the local abundance of food for offshore and nearshore feeders. Few species remain year-round due to the near complete ice cover. The seabirds migrate into the region mostly from the east via Hudson Strait, while waterfowl and shorebirds typically enter from the south via James Bay or southern Hudson Bay. The geese and ducks, in particular, and loons, murres and guillemots sustain important subsistence harvests by Inuit and Cree, who also harvest duck eggs and eider down. Large gaps remain in knowledge of this region's bird fauna, particularly with respect to the use of offshore waters.

Introductions that affect the quantity or quality of prey available to marine birds will impact bird populations. The impacts, positive or negative, will be greatest during periods when, and in areas where, the birds are limited in their ability to forage elsewhere. Introduced species may also carry disease, parasites, or toxins that affect bird populations. Habitats in Hudson Strait are particularly important to two colonial nesting bird species, the thick-billed murre (*Uria lomvia*) (aka Brünnich's guillemot) and the common eider (*Somateria mollissima*).

Thick-billed murres constitute 90% of the summer seabird biomass in northern Hudson Bay and Hudson Strait (Gaston and Hipfner 1998). They migrate into the HB complex from the Atlantic coast in May and June as the ice breaks up (Gaston and Hipfner 1998; Gaston 2002; Mallory and Fontaine 2004). Over 670,000 pairs breed in the HB complex (Gaston 2002). Large breeding colonies are located on vertical cliffs near oceanographic "hotspots" where prey species are concentrated (Cairns and Schneider 1990) (Figure 18). Persistent spring ice cover will delay murre breeding and alters their diet (Gaston and Hipfner 1998). Adult murres forage over a wide area during the breeding season, and cover a much larger area later in the summer and fall when juveniles are floating flightless at sea during their sea-rearing period (Minerals Management Service 2007). Some forage up to 200 km from their colony, pursuing small pelagic and benthic fish, crustacean zooplankton, squid (*Gonatus* sp.), and annelids (*Nereis* sp.) under water to a depth of 100 m or more (Tuck 1961; Gaston and Noble 1985; Gaston and Bradstreet 1993). In late August and early September, most of the murres from Digges Sound return eastward through Hudson Strait on a swimming migration that takes them to Labrador by October (Gaston 1982b, Orr and Ward 1982). Birds at Akpatok Island depart in late August (Mallory and Fontaine 2004). Introductions that reduce the quantity or quality of small pelagic and benthic fishes and invertebrates, change the seasonal availability of these prey species, or reduce water clarity or quality in foraging areas could put the breeding success of murres at the large colonies in Hudson Strait at risk.

Large breeding colonies of common eider (*Somateria mollissima*) are distributed on low-lying rocky coasts and islands of the HB complex, especially where mussel beds and reefs provide feeding grounds (Abraham and Finney 1986) (Figure 18). Colonies of the migratory northern subspecies (*S. m. borealis*) in Ungava Bay and Hudson Strait are more likely to be impacted by introductions than eiders elsewhere in the HB complex. Large *S. m. borealis* colonies are located in Ungava Bay on the Eider Islands (4,100 pairs), Plover and Payne islands (3,500 pairs), Gyrfalcon Island 3,600 pairs, and on islands in northeast (6,700 pairs) (Mallory and Fontaine 2004). The subspecies is also concentrated in the Markham Bay area of Hudson Strait from April through October (45,000 birds, 8,000 nests; Gilchrist *et al*. 1998, 1999 cited in Mallory and Fontaine 2004). In April, the ice edge south of Baffin Island, between Cape Dorset and Markham Bay, is an important staging area for birds moving into the HB complex (Gaston and Cooch 1986). In the fall, the low arctic population migrates eastward through Hudson Strait enroute to Atlantic Canada and west Greenland (Labrador and Baffin Bay LMEs respectively) (Mosbech *et al.* 2006).

The Hudson Bay subspecies of the common eider, *S. m. mollissima*, is one of the few bird species that lives year-round in Hudson Bay and James Bay (Abraham and Finney 1986; Nakashima 1988). In winter, the entire Hudson Bay eider population of 100,000 birds is concentrated in small polynyas and leads where open water and shallow depth coincide (Nakashima and Murray 1988, CWS Waterfowl Committee 2006). Inuit report their presence, sometimes in quantity, at almost every ice edge that is accessible from Sanikiluaq in winter and in a number of polynyas (Nakashima 1988).

Both eider subspecies forage in intertidal and subtidal waters, primarily for invertebrates (Abraham and Finney 1986; Nakashima and Murray 1988; Goudie *et al.* 2000; Heath *et al*. 2006). They feed mainly on blue mussel and green sea urchin but also eat other molluscs, crustaceans, annelids (*Nereis* spp.), and sometimes fish eggs. Introductions that reduce the quantity or quality of these benthic macroinvertebrates or reduce water clarity or quality in foraging areas could adversely affect eiders. The populations most likely to be affected by introductions are probably those in Hudson Strait and Ungava Bay, while the most vulnerable eiders are likely those that winter in the leads and small polynyas of southeastern Hudson Bay. Changes to the food webs in these restricted winter habitats, particularly those affecting the blue mussel and green sea urchin could seriously threaten local eider populations and impact local Inuit who harvest these birds, their eggs, and feathers.

Seabirds that feed offshore are common during the open water season in Hudson Strait and northeast Hudson Bay, but less so elsewhere in the HB complex (Miller and McLaren 1983; Miller 1984; Brown 1986; Morrison and Gaston 1986). Juvenile and non-breeding northern fulmar (*Fulmarus glacialis*) and black-legged kittiwake (*Rissa tridactyla*) move westward into Hudson Strait in large numbers in July to feed, reaching the western part of the Strait by September (Brown 1986; Morrison and Gaston 1986). Thousands of northern fulmars and hundreds of black-legged kittiwakes forage near the Button Islands in August and September (MacLaren Atlantic Ltd. 1978a+b). Small fish, crustaceans, molluscs—including squid, and marine worms are important prey items (Alsop 2002). While Hudson Strait does not support the wealth of shorebirds found elsewhere in the HB complex (Mallory and Fontaine 2004). These birds are presumably enroute to breeding habitat in Foxe Basin. During their spring migration they frequent ice edges, where they likely feed on ice-associated crustacean zooplankton (Orr *et al*. 1982). The pelagic feeding habits and mobility of these seabirds, and of the red phalarope, should limit their vulnerability to the introduction of non-indigenous coastal biota.

Guillemots, gulls and terns are the only seabirds common in Foxe Basin, Hudson Bay, and James Bay (Morrison and Gaston 1986). Their breeding colonies are typically further from the ABWEZ, and often smaller than those of the thick-billed murre and common eiders; gulls also eat a wider range of taxa. Consequently, these seabirds may be less vulnerable to the introduction of coastal species than the murres and eiders.

Coastal habitats in Foxe Basin, Hudson Bay, and James Bay support enormous populations of breeding and migrating waterfowl and shorebirds. The shallow, low-lying coasts with rich saltmarshes and broad tidal flats support the entire eastern Arctic breeding population of the lesser snow goose, *Chen caerulescens caerulescens* (Morrison and Gaston 1986; CWS Waterfowl Committee 2006). The largest snow goose colony in the world is located along the east coast of Foxe Basin on the Great Plain of the Koukdjuak (1997 estimate 1,770,000 birds; CWS Waterfowl Committee 2006). Other large colonies are scattered around the coasts of Hudson and James bays (Figure 18). During migration, the entire Foxe Basin population stops to rest and feed at marshes on the west coast of James Bay (Gillespie *et al.* 1991). Goose overgrazing of the intertidal saltmarshes is degrading their prime habitats at La Pèrouse Bay, in the McConnell River Migratory Bird Sanctuary, and elsewhere (Jefferies *et al.* 2006).

Tidal flats in western James Bay, particularly north and south of the Albany River, provide resources of critical international importance for migrating Hudsonian godwit (*Limosa haemastica*) and red knot (*Calidris canutus*) (Morrison 1983) (Figure 18). Globally significant populations of red phalaropes (120,000 pairs), and other shorebirds summer on Prince Charles and Airforce islands in northern Foxe Basin (Mallory and Fontaine 2004). In the fall, the knots and other species of shorebirds make a direct flight from James Bay to the Atlantic seaboard or, in the case of Hudsonian godwit, to South America. They require fat built up from feeding on along the James Bay coast to fuel them on the flight (Martini *et al.* 1980b). During migration, small intertidal molluscs, crustaceans, and polychaetes are important foods for many of these shorebirds (Harrington 2001; Alsop 2002).

Any introduction that reduced the quantity or quality of the intertidal saltmarsh vegetation would adversely impact the large snow goose populations, and might also affect shorebirds. Introductions that affected the quality or quantity of intertidal invertebrates available during the open water period could impact a wide variety of shorebirds and waterfowl. Because these birds are migratory, the effects of these impacts could be felt as far away as South America.

Large numbers of waterfowl congregate in flocks along the coasts. In late July of 1977, 88,700 moulting male black scoters (*Melanitta nigra*) were observed off the James Bay coast of Ontario (Ross 1983). The total number of moulting scoters along this coast in summer is likely much higher, perhaps 320,000 birds (Ross 1994). There is also important moulting or migration habitat along the east coast of James Bay (Benoit *et al.* 1991), with smaller numbers along the southeast coast of Hudson Bay (Savard and Lamothe 1991). These birds feed primarily on pelecypod molluscus (e.g., blue mussel, softshelled clam *Mya arenaria*, northern Astarte *Astarte borealis*), crustaceans, nematodes, and dipterans (Ross 1994; Bordage and Savard 1995). They would be vulnerable to introductions that affected the quantity or quality of these invertebrates, particularly the blue mussel.

Rich and extensive beds of eelgrass along the northeast coast of James Bay form the base of major food chains (Curtis 1974/5). Brant (*Branta bernicla*) and other waterfowl graze on the leaves, seeds, and rhizomes during their northward spring migration and southward fall migration (Curtis 1974/5; Curtis and Allen 1976; Dignard *et al*. 1991; Lalumière *et al*. 1994; Ettinger *et al*. 1995; Reed *et al.* 1996, 1998). During the fall migration over 50% of the Atlantic brant population may use these habitats (Thomas and Prevett 1982). The area of south of Roggan River attracts up to 60,000 brant (near Chisasibi; Bellrose 1980), over 100,000 Canada geese (*B. canadensis*), and numerous ducks--principally black duck (*Anas rubripes*) (Curtis and Allen 1976). Species introductions that damage these beds could have serious ecological consequences, particularly for brant and other waterfowl.

Large estuaries are also important habitat for migratory water birds. Red throated (*Gavia stellata*) and Pacific (*G. pacifica*) loons congregate at the mouth of the Churchill River, Manitoba in May and June on their way north (Jehl and Smith 1970; MARC 2003). On 8 June 1980, an estimated 10,000 Pacific loons passed northward near Churchill. Whether these migrants would be affected significantly by changes in estuarine ecology related to invasive species is unknown.

Parks and Protected Areas

Marine parks or protected areas have not been established in Hudson Strait, James Bay, or Hudson Bay, although studies have been conducted to recommend areas for consideration (Mercier 1991; Stewart *et al.* 1991, 1993). Protection is afforded to coastal habitats and wildlife, such as the polar bear, by Wapusk National Park in northern Manitoba and Ukkusiksalik National Park in the Wager Bay area of Nunavut; Polar Bear, Kesagami Tidewater, and Winisk River provincial parks in Ontario; and Ijiraliq Territorial Park near Rankin Inlet in Nunavut (Stewart and Lockhart 2005). Migratory birds, particularly waterfowl and shorebirds, are protected in the James Bay area by the Boatswain Bay, Hannah Bay, Moose River and Akimiski Island migratory bird sanctuaries (MBS), along the Kivalliq coast by the McConnell River MBS, on Southampton Island by the Harry Gibbons MBS and East Bay MBS, and on Baffin Island by the Cape Dorset MBS and Dewey Soper MBS. The Twin Islands in northern James Bay are a Territorial Game Sanctuary. The Moose River, Hannah Bay, McConnell River, and Dewey Soper MBSs, and Polar Bear Provincial Park, have been designated Ramsar sites under the Convention on Wetlands of International Importance as Waterfowl Habitat (The Ramsar Convention) (Gillespie *et al.* 1991). A number of key terrestrial and marine habitats for migratory birds and the indigenous Hudson Bay eider are not protected.

ECOLOGICALLY SENSITIVE AREAS

The information base from which to identify ecologically sensitive areas within Hudson Strait and throughout the HB complex is weak. Important information on spatial and seasonal changes in oceanography and on species' ecology is lacking. The available information is strongly weighted towards large edible species that are accessible near shore during the summer. Concentrations of walrus and eiders provide indicators of productive benthic habitats, seabird colonies of rich pelagic habitats, and waterfowl of productive tidal marshes and eelgrass beds (Figure 18). However, similarly rich habitats may exist in other areas that otherwise provide less attractive habitats for these large species. Chlorophyll and trawl data suggest that the area west of Resolution Island may be biologically richer and more productive than other areas of the Strait. But this has not been confirmed. The ecological sensitivity of these areas to species invasions is likewise unknown.

Large estuaries are likely among the most ecologically sensitive areas, as they offer a wide variety of habitats, serve many important biological functions, and may be more vulnerable to colonization by invasive coastal species. The largest estuaries are located in James Bay, Hudson Bay, and southern Ungava Bay. Of these, the more southerly the estuaries are likely most sensitive, as they are larger and warmer. The largest estuaries in Ungava Bay are all located at least 200 km from the ABWEZ.

CONSIDERATION OF ALTERNATIVES TO BALLAST WATER EXCHANGE IN HUDSON STRAIT

All in all, very little is known of the oceanography and ecology of Hudson Strait and the HB complex in general. Even less is known of potentially invasive biota being carried there in ballast water. Based on the information that is available, there are a few physical parameters that can be used to consider where best to locate an alternative ballast water exchange zone for the region. These include depth, temperature, salinity, distance from shore, current, tidal range, and ice cover (Table 2). Within Hudson Strait, each of these parameters offers a range of possibilities that can make it easier or harder for invasive species from warmer coastal waters to establish.

- **Depths** range up to about 1000 m but rise to less than 300 m at sills along the 70°W longitude, and in the west. Because the most recent ballast water exchange is likely to have been conducted during unloading at ports, the objective is to release these organisms, which will tend to be best adapted to shallow coastal waters, in the deepest area possible. This area is in eastern Hudson Strait (Figure 3).
- **Surface temperature** (mean annual) is lower in Hudson Strait than in Hudson Bay or the Labrador Sea, the mean annual temperature in the strait varies with location from about 0 to 2°C. Both the range and maxima are small relative to most potential sources, and they pose an important barrier to the establishment of introduced species (North/South Consultants Inc. 2006).The objective then is to exchange in the coldest possible area to limit the likelihood of subarctic,

temperate, and tropical species from becoming established. Eastern and northern Hudson Strait are about 1°C colder on average than central Hudson Strait (Figure 20). Exchange in eastern Hudson Strait would be preferred as it can be completed further from shore, in deeper water.

- **Surface salinity** is typically 30 to 33.5 mg/L, with lower values along the south shore. Many euryhaline species can survive in waters with salinity gradients between 0‰ and 30‰ (NRC 1996). The objective then is to exchange in an area where salinity is >30 mg/L thereby reducing the likelihood that euryhaline coastal species may become established, keeping at least 20 km off the south shore limits exposure to lower salinity (Figure 6, Figure 7).
- **Maximum Distance from shore** ranges from about 32 to 85 km down the length of the strait. The objective is to exchange in an area that is as far from the coast as possible, to reduce the likelihood of coastal and euryhaline biota from becoming established (Levings *et al*. 2004). The strait is widest in the east, except at the mouth (Figure 3).
- **Currents** that carry foreign biota away from the coasts and out of the HB complex are desirable. These are perhaps best developed in eastern Hudson Strait (Drinkwater 1986; Saucier *et al*. 2004), although there is some risk that biota may be carried into Ungava Bay (Figure 4).
- **Tidal ranges** vary along the strait and are very high in Ungava Bay and central Hudson Strait relative to most areas. The objective is to exchange in an area where benthic biota that do reach the coast are likely to have the greatest possible exposure to drying conditions and cold air temperatures, thereby limiting their ability to establish. Tidal ranges are generally greatest in central and eastern Hudson Strait and in Ungava Bay (Drinkwater 1986).
- **Sea ice** can limit the ability of biota to establish by creating a barrier to the surface that limits seasonal light penetration, and by physical scouring of coastal habitats. The ice thickness and coverage tend to be lower in eastern Hudson Strait than to the west. This could facilitate species establishment but it is likely offset by ice scour, which will be greater due to the higher tidal range (Figure 9).

Taken together these characteristics support the use of the existing ABWEZ in eastern Hudson Strait for ballast water exchange, albeit with a proviso that **exchange take place as far from shore as possible**. The area east of 69°W that is at least 300 m deep and 25 km offshore offers what may be the best option available (Figure 21). The characteristics that recommend this area for receiving foreign ballast water, namely deep, cold, relatively saline and largely ice-covered waters that are removed from shore and subject to strong eastward currents, also mean that the biota taken up during the exchange may be less likely to establish in the shallower, warmer, less saline coastal waters near Churchill (Table 2). The differences in these parameters, while not as great as those between foreign ports and Hudson Strait, are as large as is possible for biota taken from the Hudson Strait region. The use of central Hudson Bay for ballast water exchange should be discouraged as exchange in this region would bypass the natural barrier posed to species invasions by Hudson Strait.

Ecologically sensitive areas that have been identified in Hudson Strait are located near the coasts and unlikely to receive ballast water directly, with the possible exception of productive waters west of Resolution Island (Figure 16). This biological hotspot appears to be rich in a broad range of pelagic taxa. It will be influenced somewhat by water from the Baffin and Labrador LMEs and residence time of this water may be limited by currents that flow east out of the strait.

Exchanging ballast water in the Hudson Strait ABWEZ may offer advantages to conducting the exchange outside the ABWEZ. The ABWEZ offers the greatest possible temperature differentials, both between the source and exchange zones and the exchange zone and Port of Churchill. This is accomplished at the expense of slightly lower differentials in salinity and closer proximity to coastal environments in the exchange zone. Given that most of the source harbours are in much warmer water this may be more important for eradicating unwanted invaders than salinity, which may be quite variable in the source environments. Ballast water picked up in the surface waters of Hudson Strait should carry biota that are largely Arctic in origin, with some subarctic biota from Davis Strait or the Labrador Sea, depending upon where the exchange begins and ends. Currents entering Foxe Basin and Hudson Bay from the north and east already carry many of these species in the Hudson Bay complex naturally. Depending upon where the exchange occurs, open ocean exchanges of ballast water outside the EEZ may entrain temperate or subarctic marine species that are not indigenous to Hudson Bay. The likelihood of them establishing in the ice covered waters of Hudson Bay should be low but it might change if the climate ameliorates.

To use the existing ABWEZ, vessels traveling west through Hudson Strait may have to alter course from the recommended route, which is as follows:

> "Vessels enter the strait about midway between the Button Islands and Resolution Island, and from a position 20.5 miles S of Resolution Island they make good a course of 293° for about 300 miles to a position with the light at the W end of Charles Island bearing 235°, distant 14 miles. They next make good a course of 266° for 106 miles to a position with Digges Island Light bearing 180°, distant 8 miles and the light on Nottingham Island bearing 008°, distant 23 miles. The description of this track as far as a position off Churchill Harbor is continued in Sector 16. 13.7 **Note.—**After entering Hudson Strait, if it is desired to pick up the S shore W of Ungava Bay, it will be better to make Wales Island rather than to attempt to make the land to the E. Wales Island is bold and easily identified." National Geospatial-Intelligence Agency (2008: p. 242)

This course (Figure 21) may be adjusted in response to ice and ocean conditions. Ships that follow the track will pass north of the 300 m depth contour in much of eastern Hudson Strait, and south of this contour in the vicinity of Charles Island. They will pass at least 20 km offshore except in the Digges Island area, where the track takes them within 12.6 km of the coast.

Mid-ocean exchange of ballast water by ships enroute to Vancouver took about 400 km on average (Levings *et al*. 2004). If vessels entering Hudson Strait require a similar distance they will have to begin their exchange about 150 km east of the east entrance to Hudson Strait in order to complete ballast water exchange before reaching 70°W. Otherwise, depending upon their exchange method (typically empty-refill or flow-through), they might have to alter their rate or route of passage within Hudson Strait. **To achieve depths of over 300 m while inside the strait they also have to follow a more southerly course.**

UNCERTAINTIES

There really are fewer certainties than uncertainties with respect to ballast water exchange in Hudson Strait. Predictive ability is severely constrained by:

1. limited knowledge of the physical, chemical, and biological oceanography
2. information gaps related to shipping and ballast water exchange in the HB complex
3. lack of knowledge regarding current and future risks of species introductions associated with shipping and ballast exchange in the Arctic, and
4. limited understanding of how global climate change may affect the oceanography, shipping patterns, and risks of introductions.

The first three points have already been discussed in some detail. The latter has not.

Climate change may alter the environmental conditions in the HB complex and in Hudson Strait. Warming has the potential to increase the mean annual water temperature, increase salinity, reduce or eliminate ice cover, and alter density-driven currents. The extents of these changes are likely to vary geographically, and they could alter the effectiveness of Hudson Strait as a barrier to the entry of subarctic species into Hudson Bay and Foxe Basin. A moderate warming of climate could, for example, substantially reduce the effectiveness of low maximum temperatures as a barrier to species invasions (North/South Consultants Inc. 2006). These changes could also make some environments easier for foreign biota carried in ballast water to colonize, both by ameliorating the harsh environmental conditions and by weakening existing biota that are better adapted to life in the harsher conditions. Consequently the location of the ABWEZ should be reassessed periodically to ensure that it continues to provide the best possible protection for the region.

Ballast water is just one vector for non indigenous species on a ship (NRC 1996; Minchin and Gollasch 2003). Hull fouling and sediment in tanks and on anchors are other potential vectors of invasive species to be considered.

RECOMMENDATIONS

1) The ABWEZ in Hudson Strait should remain in force but its location should be specified more precisely to ensure that exchange takes place over water deeper than 300 m and as far as possible from the coasts. The zone bounded in the east by 63°W; to the north by a line from 61°05'N, 63°00'W to 61°05'N, 67°00'W to 61°30'N, 69°00'W; in the west by 69°W; and to the south by a line from 61°20'N, 69°00'W to 60°55'N, 67°00'W to 60°55'N, 63°00'W is recommended (Figure 22).
2) All vessels entering the Canadian Eastern Arctic via Hudson Strait should be required to exchange their ballast, if they have ballast on board, or to flush their ballast tanks, if they do not have ballast on board. International vessels should have conducted these measures outside the EEZ and use the ABWEZ only as a last resort in case of emergency. Until ballast water treatment is implemented or research demonstrates that the risk is acceptable a precautionary approach should also be adopted with respect to domestic vessels, whereby they are required to exchange their ballast water or flush their tanks either before

reaching the ABWEZ in an area at least 50 nautical miles offshore where the water is at least 500 m deep, or in the ABWEZ. Otherwise the potential spread of non-indigenous species from domestic coastal waters is uncontrolled.

3) The ABWEZ should be reassessed periodically to ensure that it remains the best choice. Considerations should be given to including the Labrador Sea in any future reassessment.
4) An accessible record of ballast water exchanges by all vessels, foreign and domestic, that enter the HB complex should be developed and maintained. This record should also include data on all releases of ballast water within the HB complex by these vessels, and by local vessels, so that the risk of their introducing and/or spreading non-indigenous taxa within the region can be assessed.
5) Biological sampling should be undertaken to quantify the risks of non-indigenous species introductions associated with ships entering the HB complex from international and domestic waters.

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GLOSSARY

Deadweight (often abbreviated as **DWT** for deadweight tonnes) is the displacement at any loaded condition minus the lightship weight. It includes the crew, passengers, cargo, fuel, water, and stores.

Euryhaline species tolerate a wide range of salinities.

Invasive species spread rapidly when introduced and once established have the potential to cause environmental or economic harm. Not all introduced species are invasive.

Nektonic organisms are free-swimming, pelagic animals.

Net tonnage is a calculation of a ship's cargo capacity found by measuring the space of the ship's hull under the upper deck but excluding the space taken up by machinery, accommodation and navigation.

Non-indigenous species are not native to the ecosystem under consideration. They are not necessarily capable of establishing viable populations or becoming invasive.

Planktonic organisms are the small plants and animals that float or drift in water.

Propagule pressure is the number and quality of propagules (i.e., any viable life history stage of an organism) that is being delivered to an ecosystem.

ACRONYMS

ABWEZ = alternate ballast exchange zone

BOB = a ship carrying ballast water in its ballast tanks (i.e., “Ballast-On-Board”). A vessel that is not carrying cargo and that has water in its ballast tanks is described as being “in ballast”, while a vessel with some cargo and some ballast is described as being “with ballast”.

BWE = ballast water exchange

EEZ = exclusive economic zone, Canada’s 370 km or 200 mile limit

LME = large marine ecosystem, one of a system of such areas that have been identified worldwide. The Hudson Bay Complex LME includes Hudson Strait, Ungava Bay, Foxe Basin, Hudson Bay, and James Bay.

MOE = mid-ocean exchange

NMR = Nunavik Marine Region

NSA = Nunavut Settlement Area

NOBOB = a ship carrying no pumpable ballast water in its ballast tanks (i.e., "No-Ballast-On-Board").

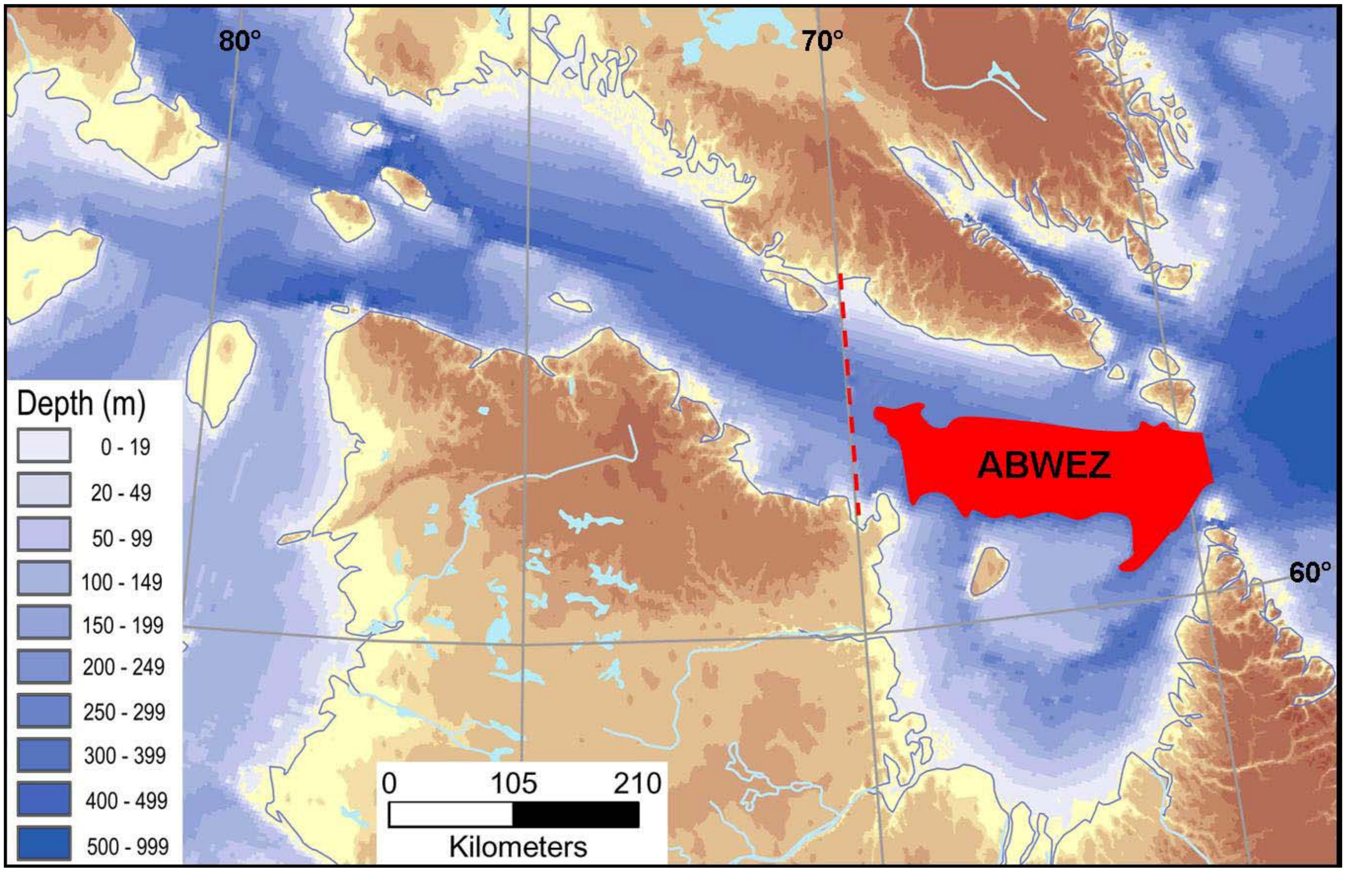

Figure 1. Under the *Canada Shipping Act* (P.C. 2006-495 June 8, 2006) Ballast Water Control and Management Regulations, the Alternate Ballast Water Exchange Zone (ABWEZ) in Hudson Strait is located east of 70°W longitude where the water is at least 300 m deep.

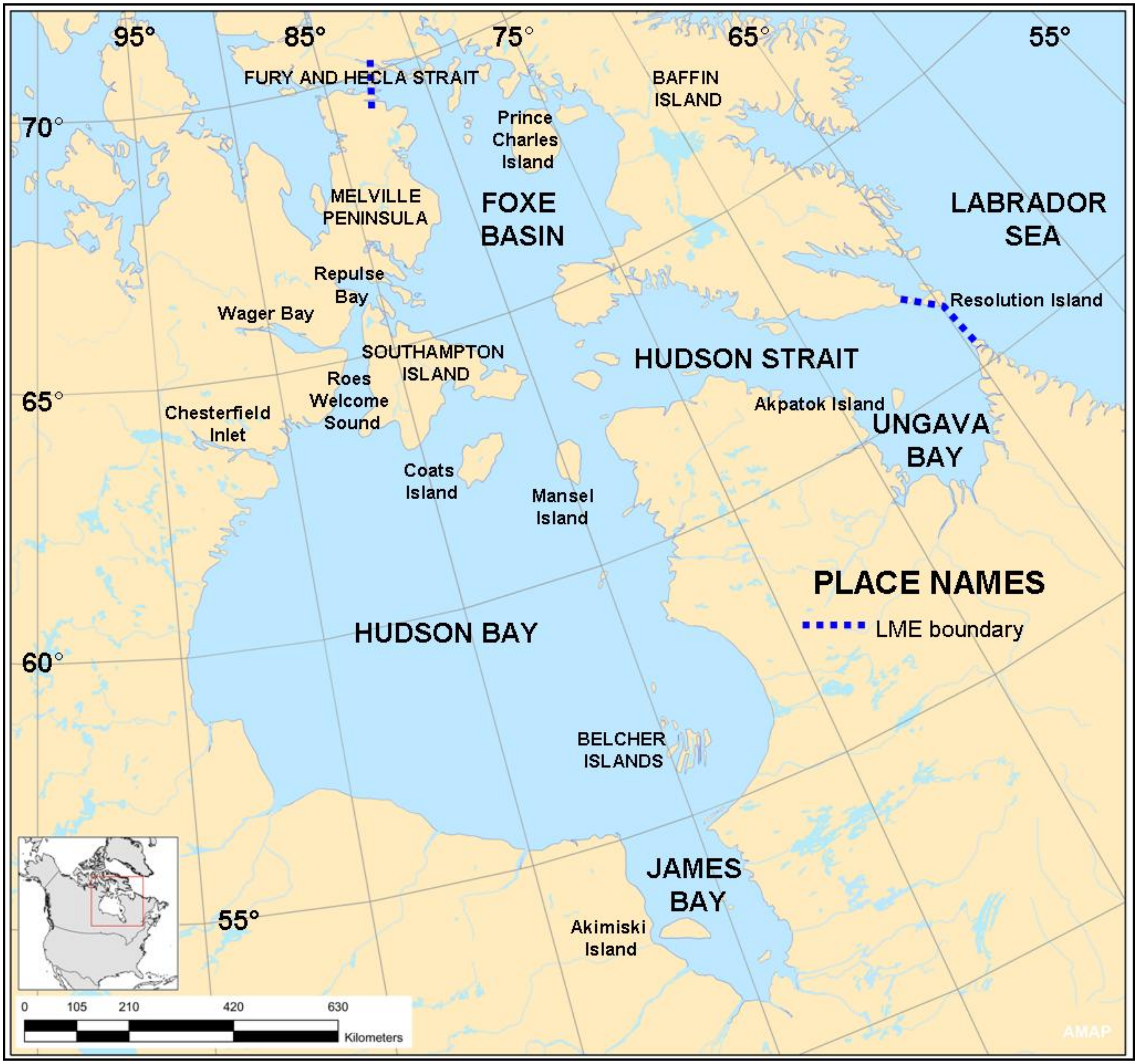

Figure 2. Key place names in the Hudson Bay complex LME (Large Marine Ecosystem) (base map from Arctic Monitoring and Assessment Programme).

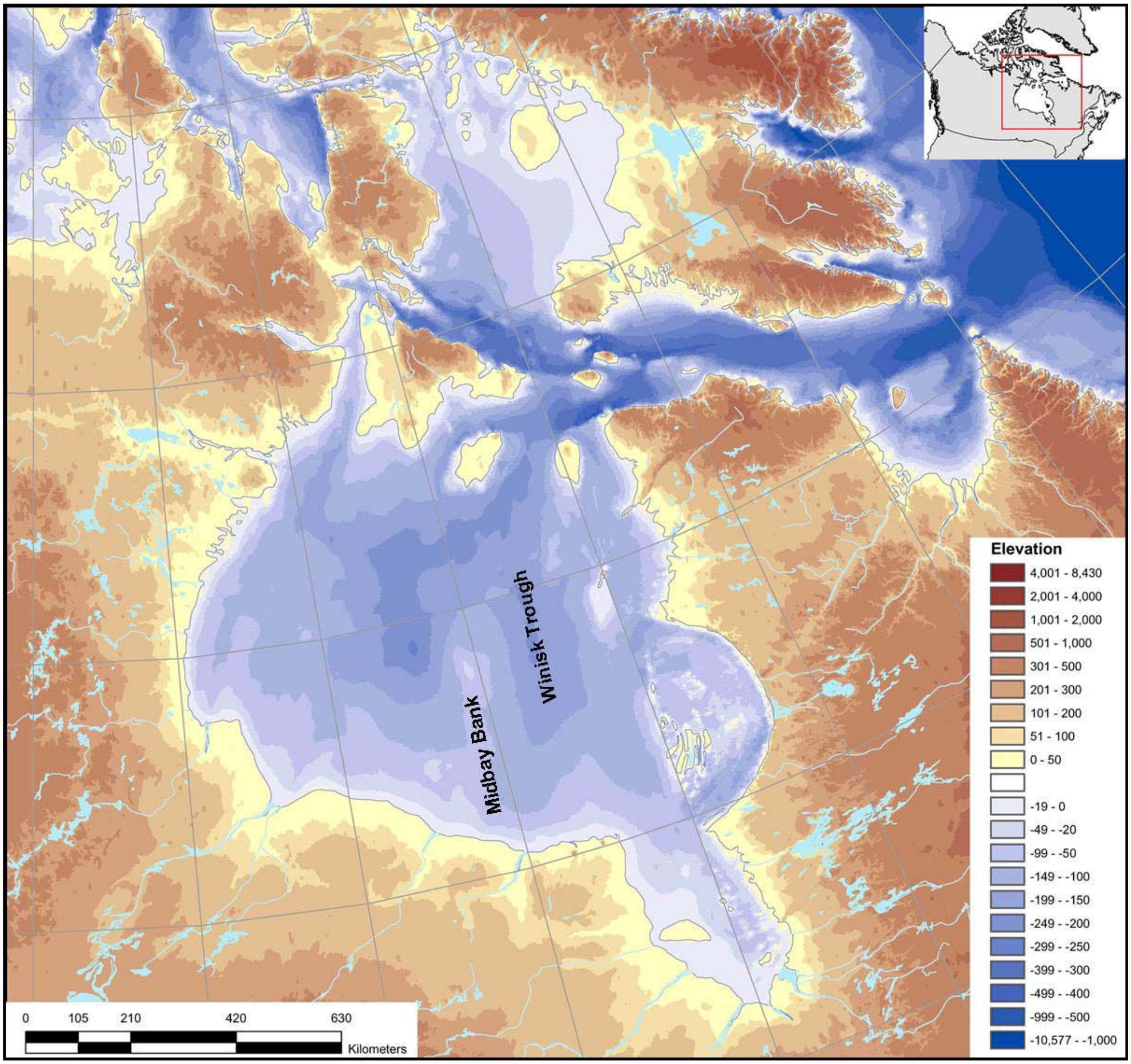

Figure 3. Topography and bathymetry (m) of the Hudson Bay complex LME (Adapted from Arctic Monitoring and Assessment Programme).

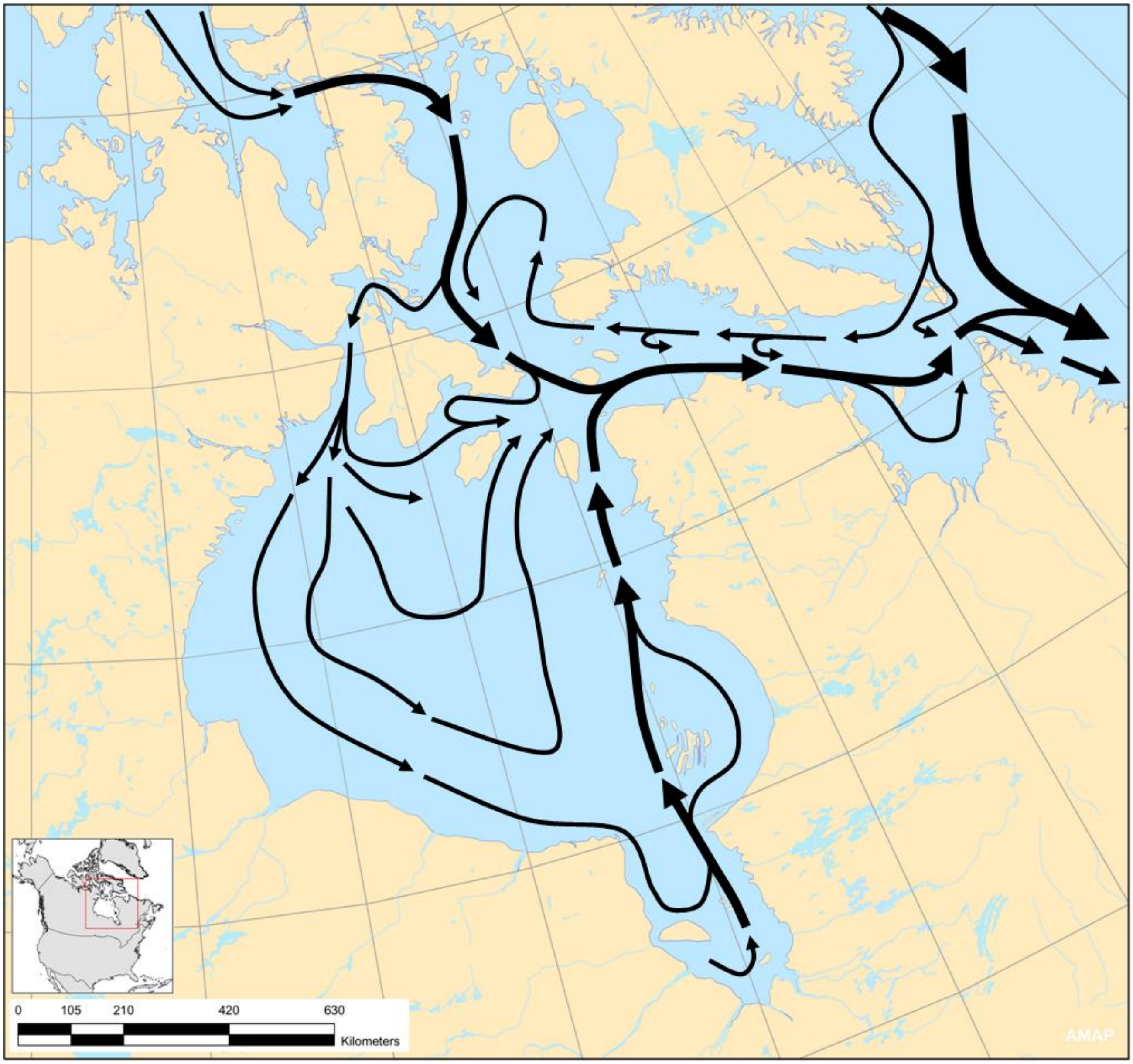

Figure 4. Summer circulation of water in the Hudson Bay complex (after Fisheries and Oceans Canada poster 8: Eastern Canadian Arctic) (Base map courtesy of the Arctic Monitoring and Assessment Programme).

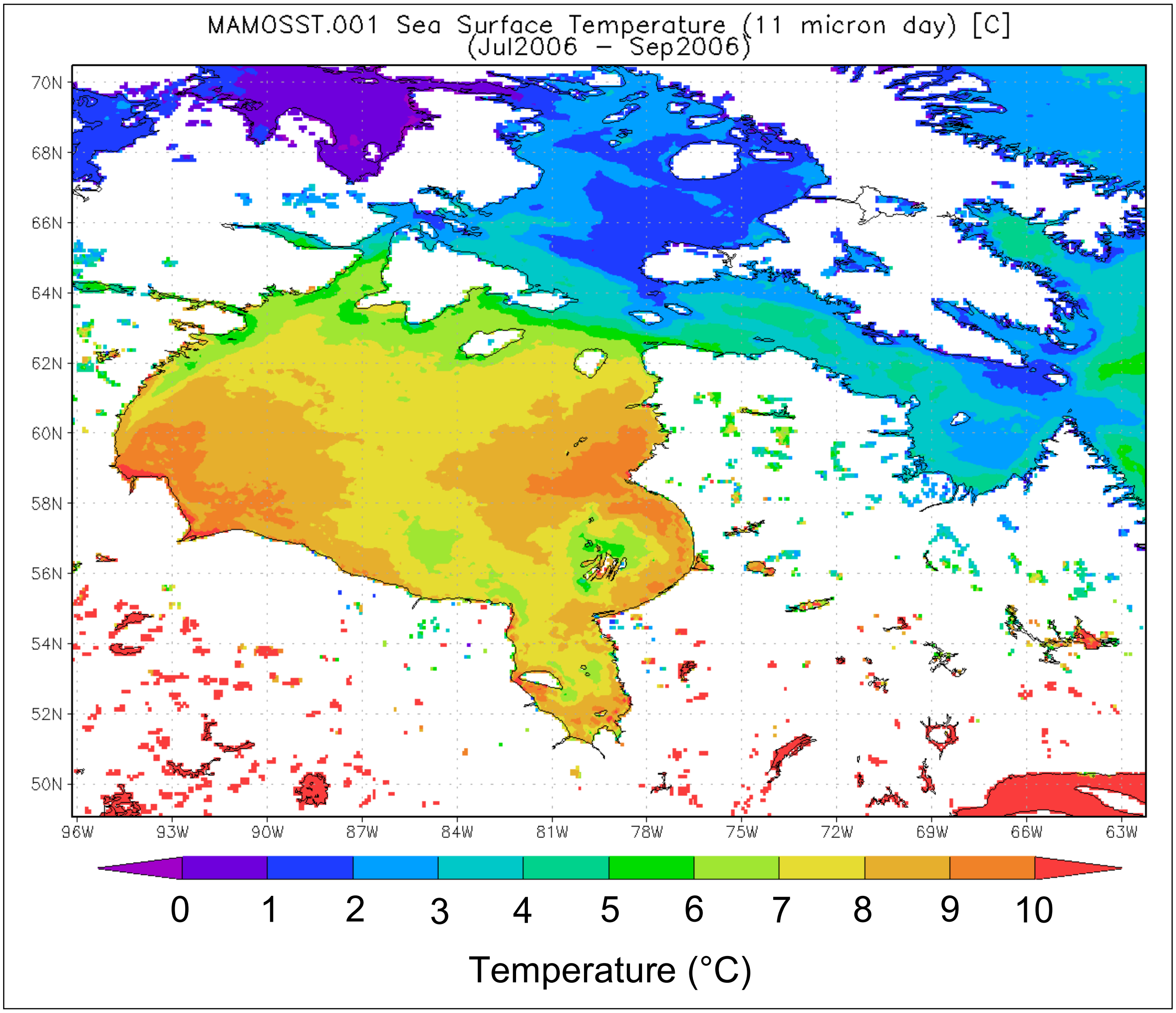

Figure 5. Summer (July-September) sea surface temperature in 2006 (Prepared using the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

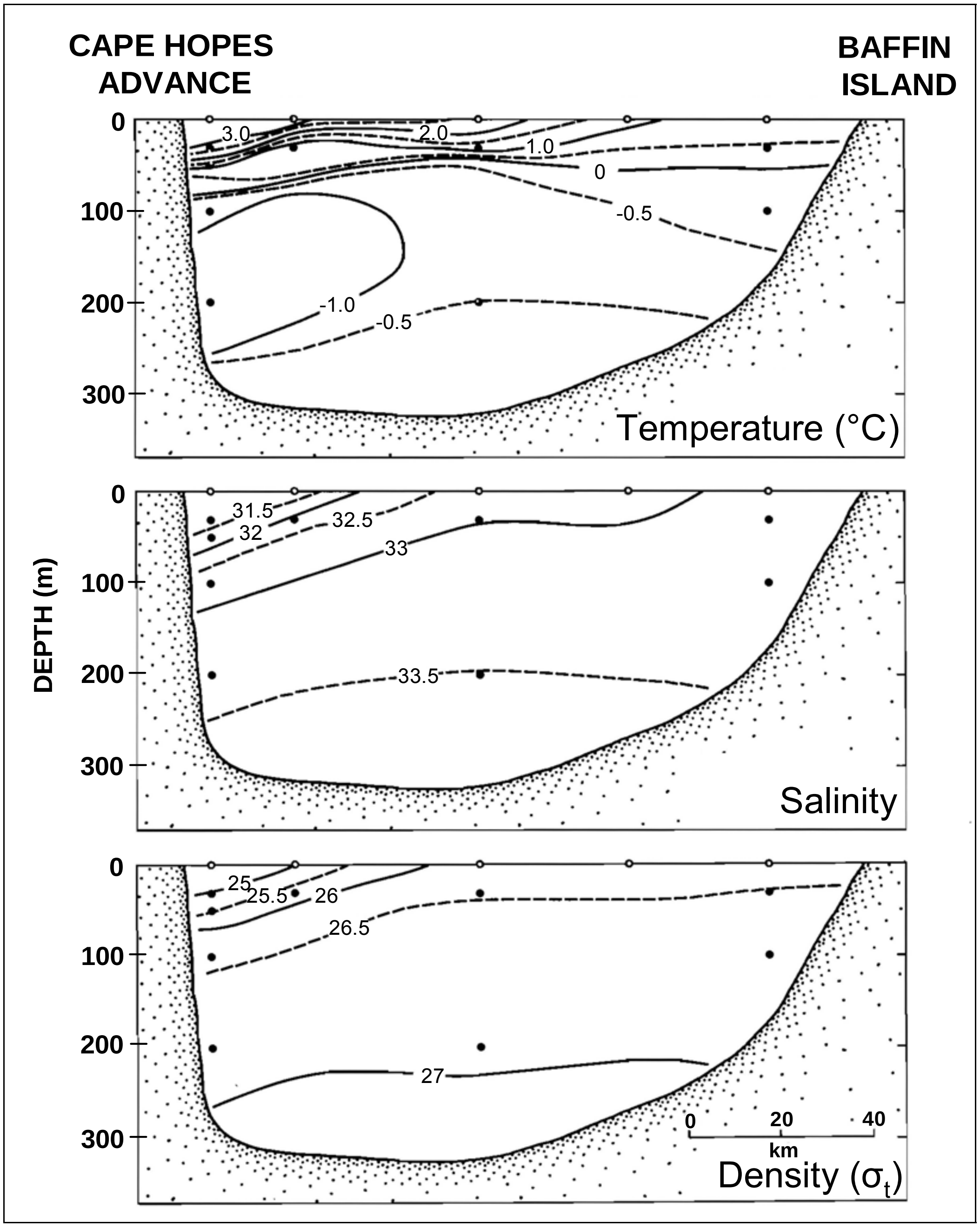

Figure 6. Summer temperature, salinity, and density across Hudson Strait from Cape Hopes Advance to Baffin Island (modified from Drinkwater 1988). See Figure 7 for location of cape.

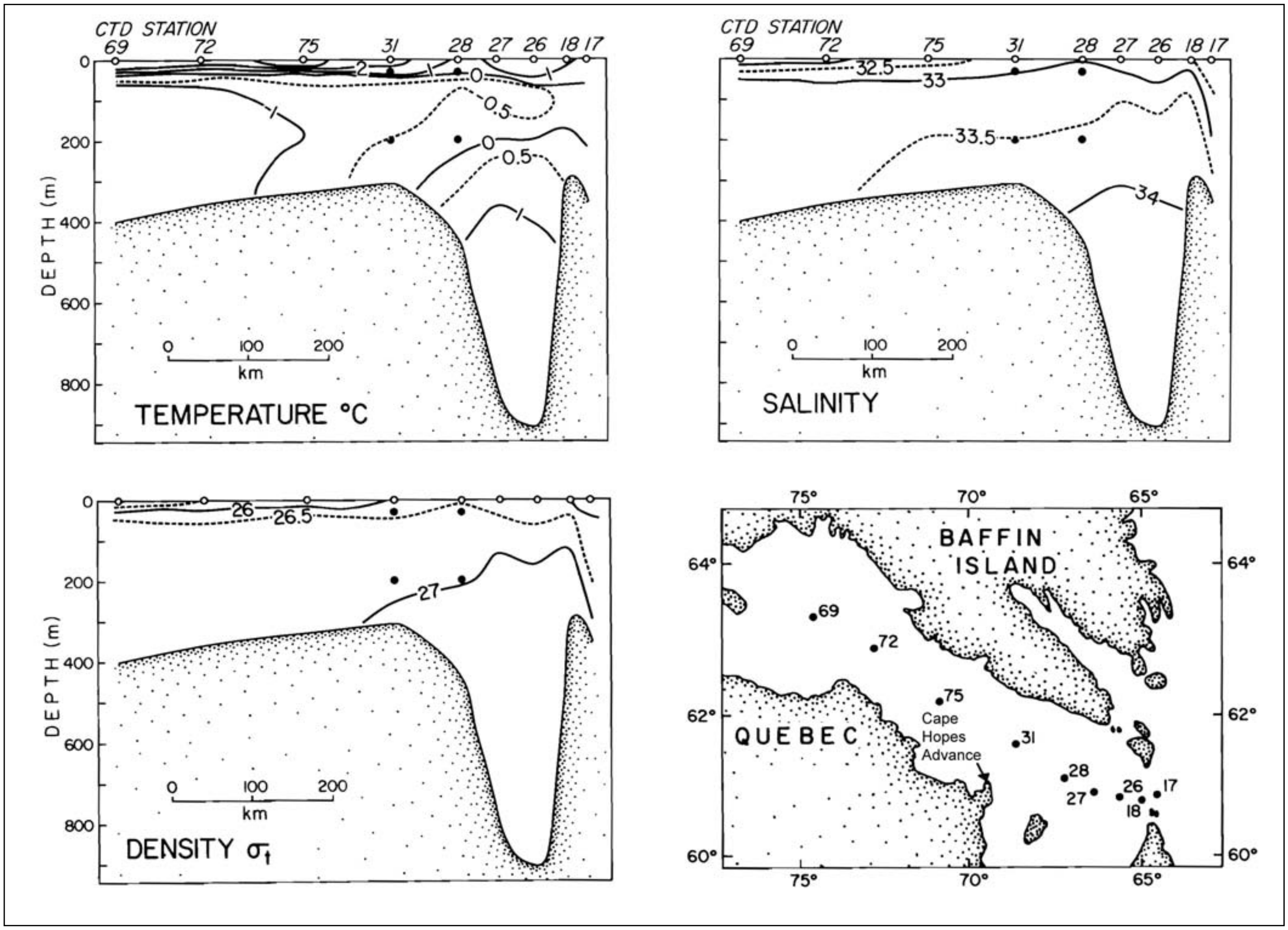

Figure 7. Summer temperature, salinity and density along a transect parallel to the axis of Hudson Strait (from Drinkwater 1988, p. 258).

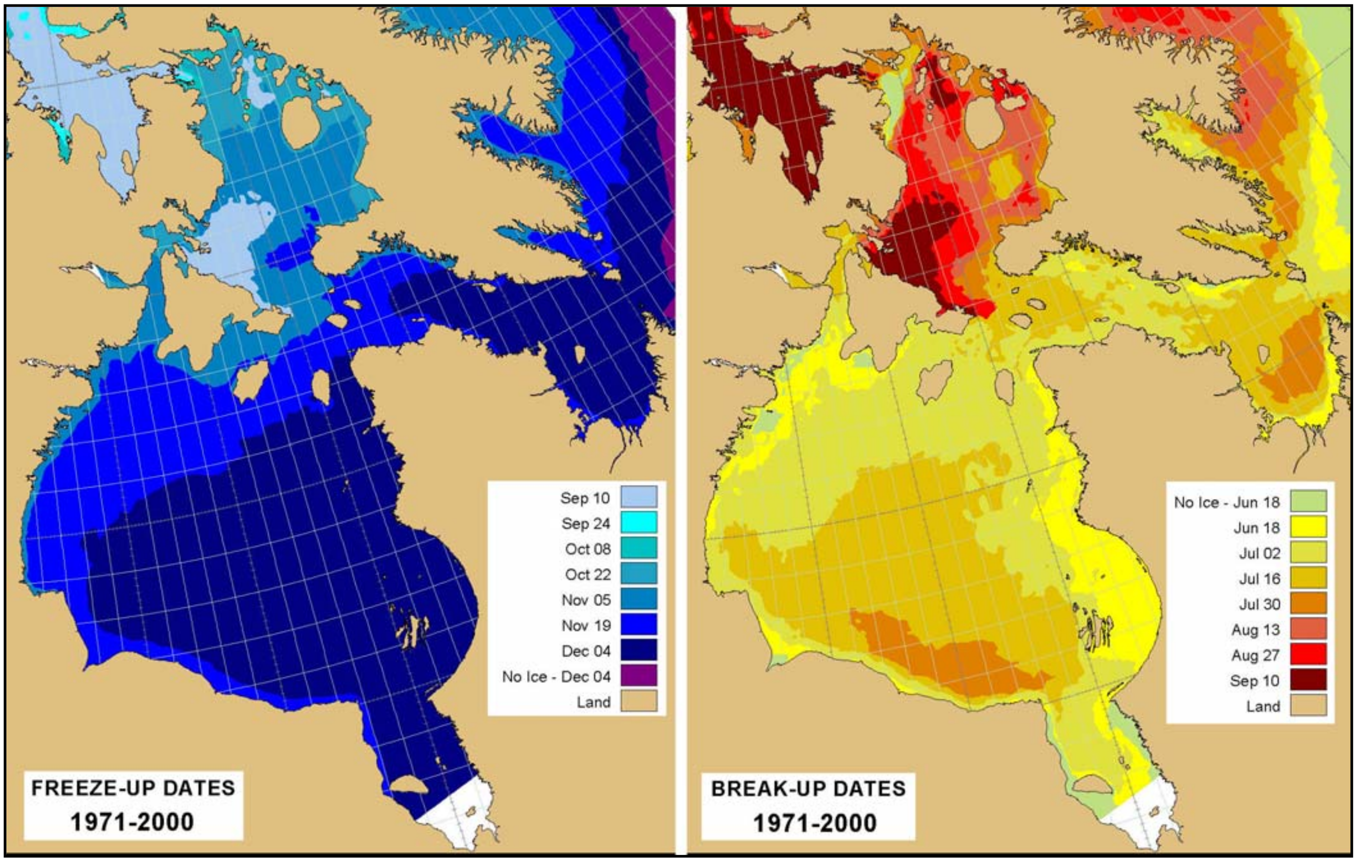

Figure 8. Ice formation and breakup in the Hudson Bay complex over the 21 year period 1971 to 2000 (from http://www.ice.ec.gc.ca/IA_NWCA_SM/ar_freezeup.gif ; http://www.ice.ec.gc.ca/IA_NWCA_SM/ar_breakup.gif).

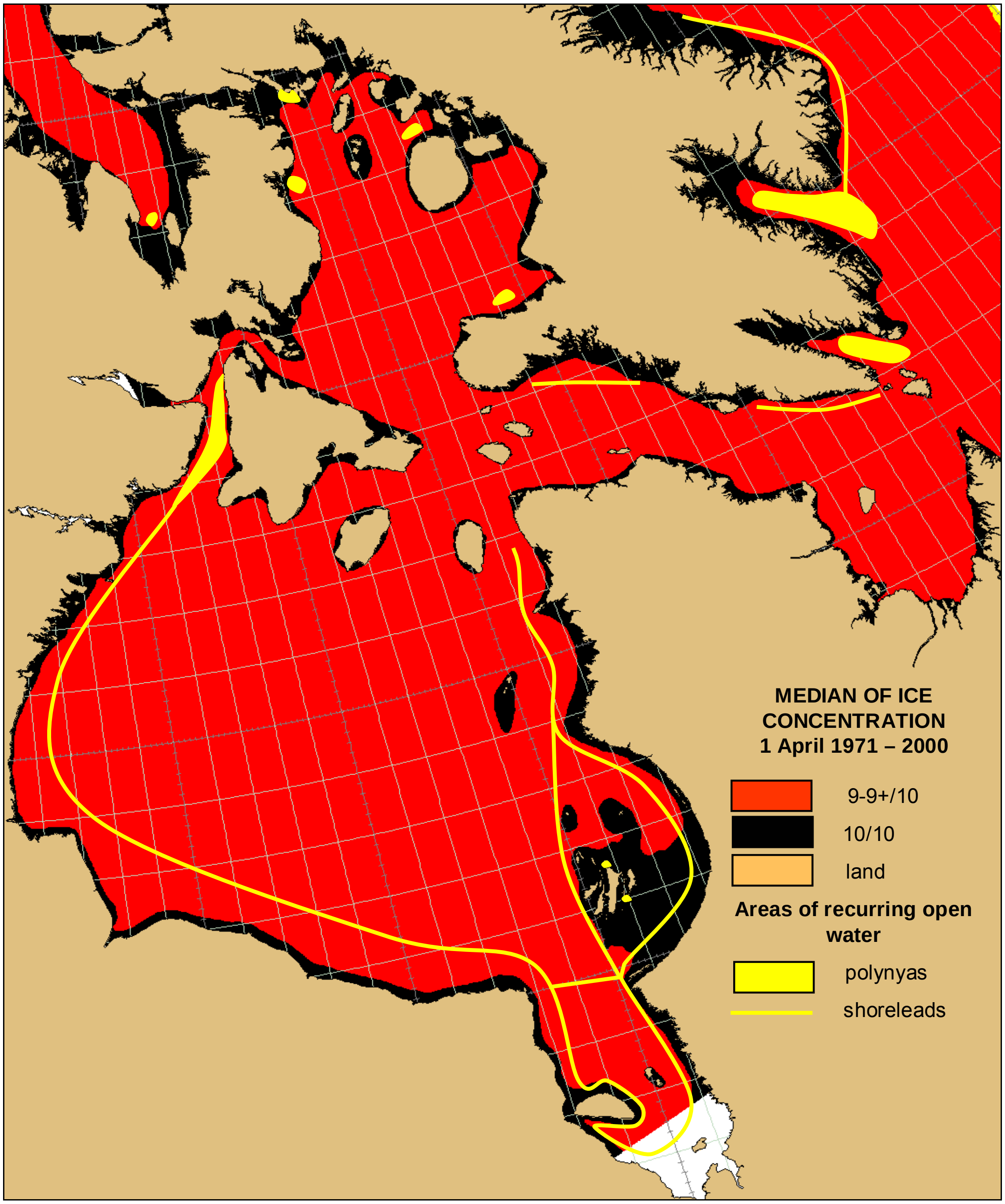

Figure 9. Median of sea ice concentration in the Hudson Bay LME on 1 April over the 21 year period 1971 to 2000 (from http://www.ice.ec.gc.ca/IA_NWCA_MCSI/ar_ctmed0401.gif), overlain by a schematic depicting areas of recurring open water (Stirling and Cleator 1981).

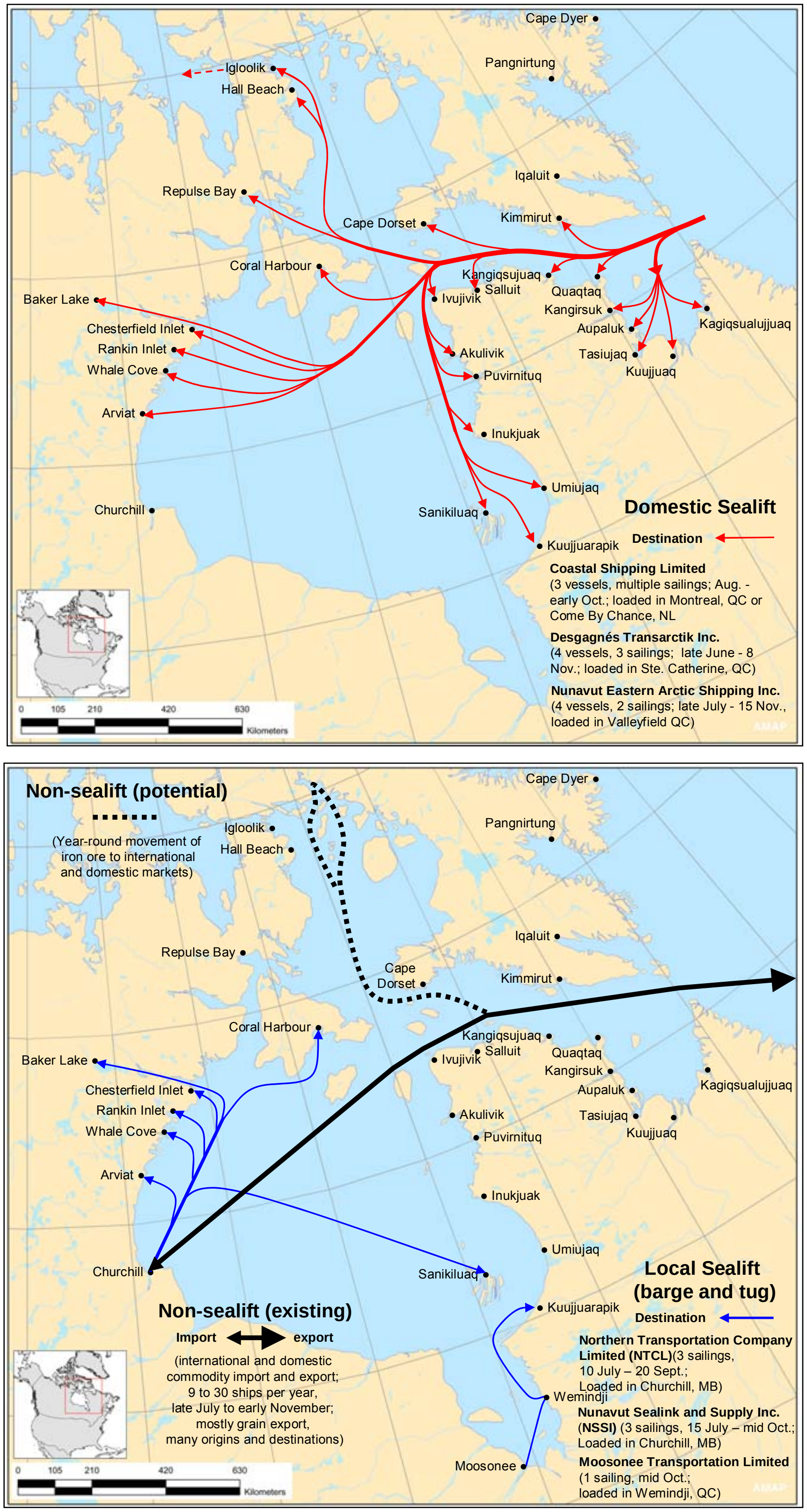

Figure 10. Annual shipping activity in the Hudson Bay LME related to the sealift (domestic top and local bottom) and to non-sealift import and export (bottom). Sources cited in text.

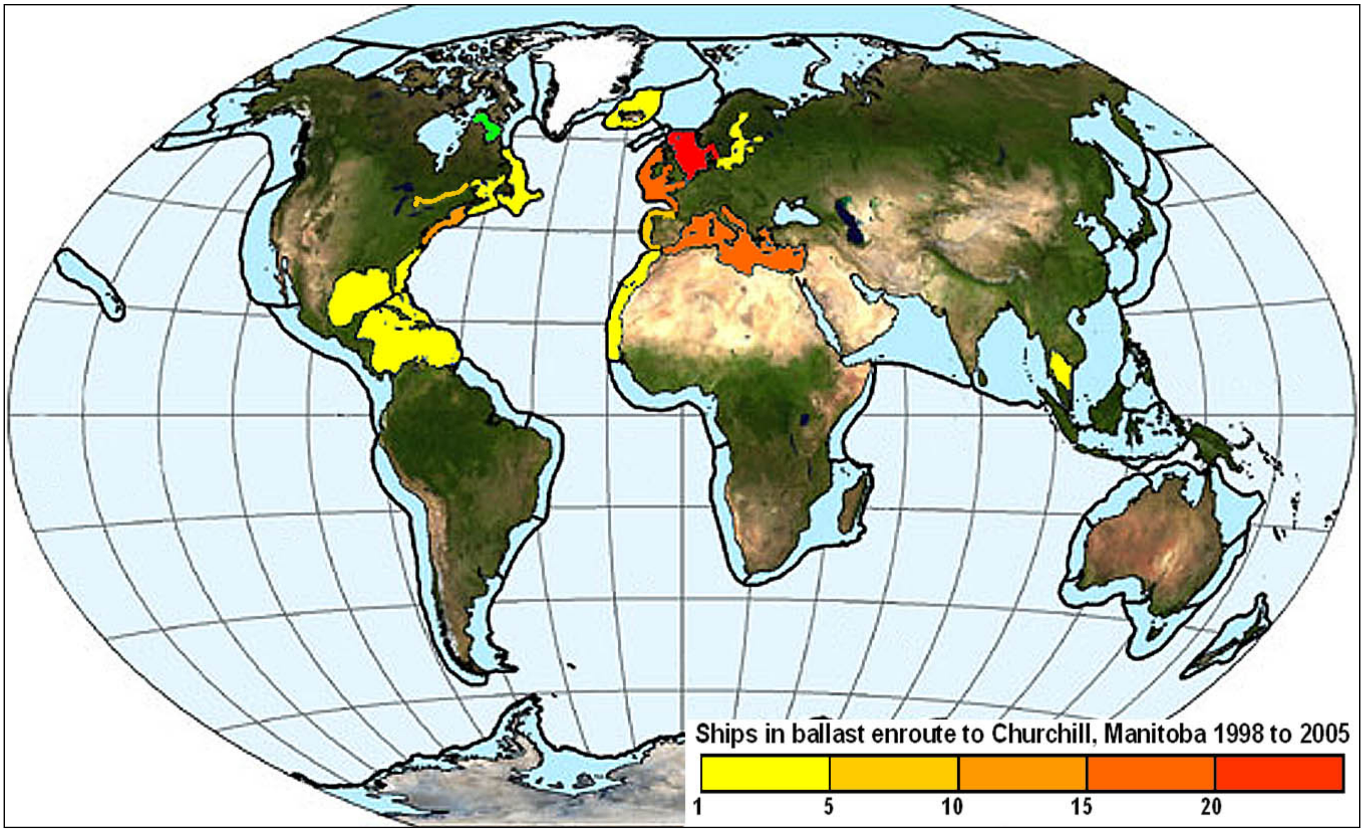

Figure 11. Large Marine Ecosystems (LMEs) used as the last port of call for ships in ballast enroute to Churchill, Manitoba from 1998 through 2005. Hudson Strait is coloured bright green. The LME base map is from http://www.lme.noaa.gov/Portal/ptk.

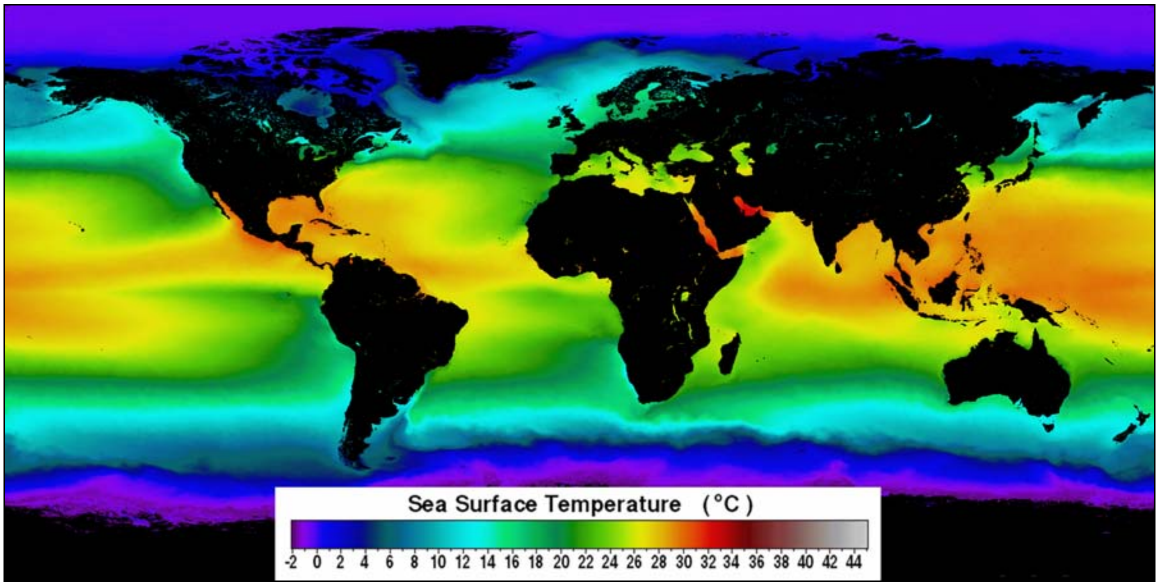

Figure 12. Composite of summer sea surface temperatures (21 June—20 September) integrated over the period 2002 to 2008. Data were collected by the U.S. National Aeronautics and Space Administration's (NASA) Aqua (EOS-PM) satellite, using its Moderate Resolution Imaging Spectroradiometer (MODIS). (From http://oceancolor.gsfc.nasa.gov/cgi/l3/A20021722008264.L3m_SCSU_SST_4.png?sub=img)

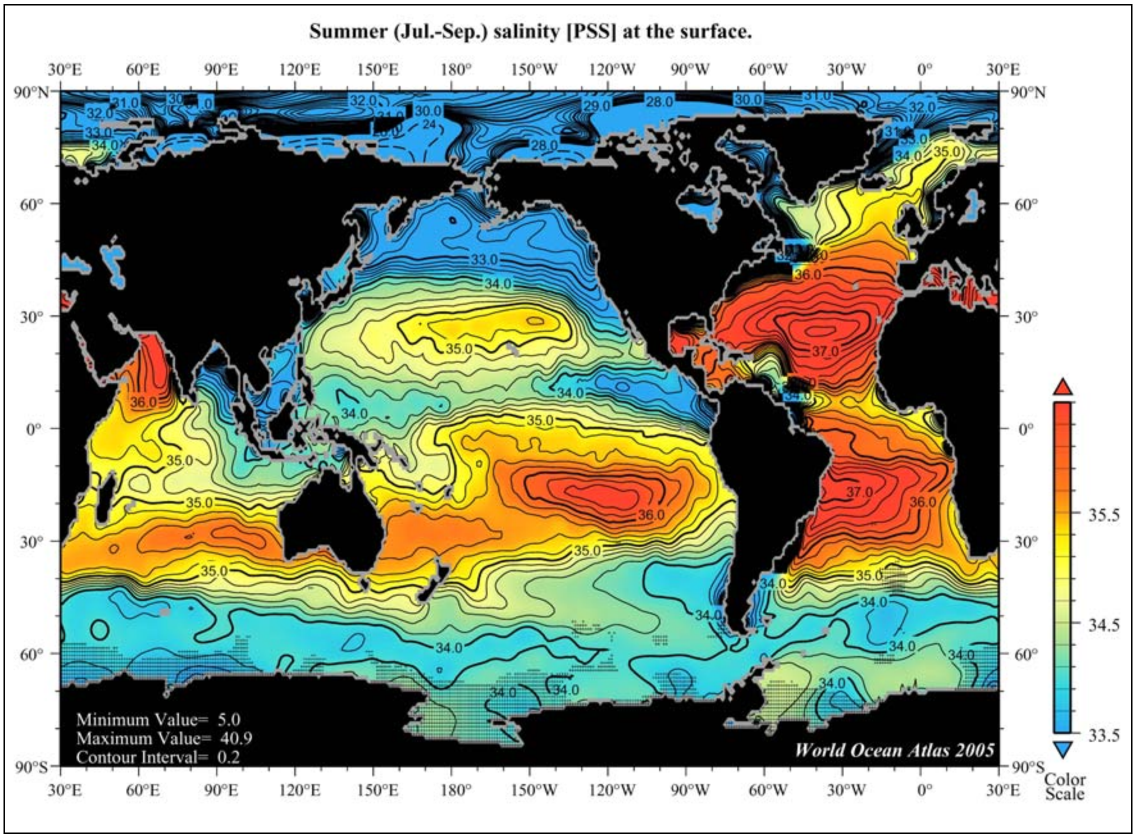

Figure 13. Summer salinity at the surface (practical salinity scale=pss) (Antonov *et al*. 2006).

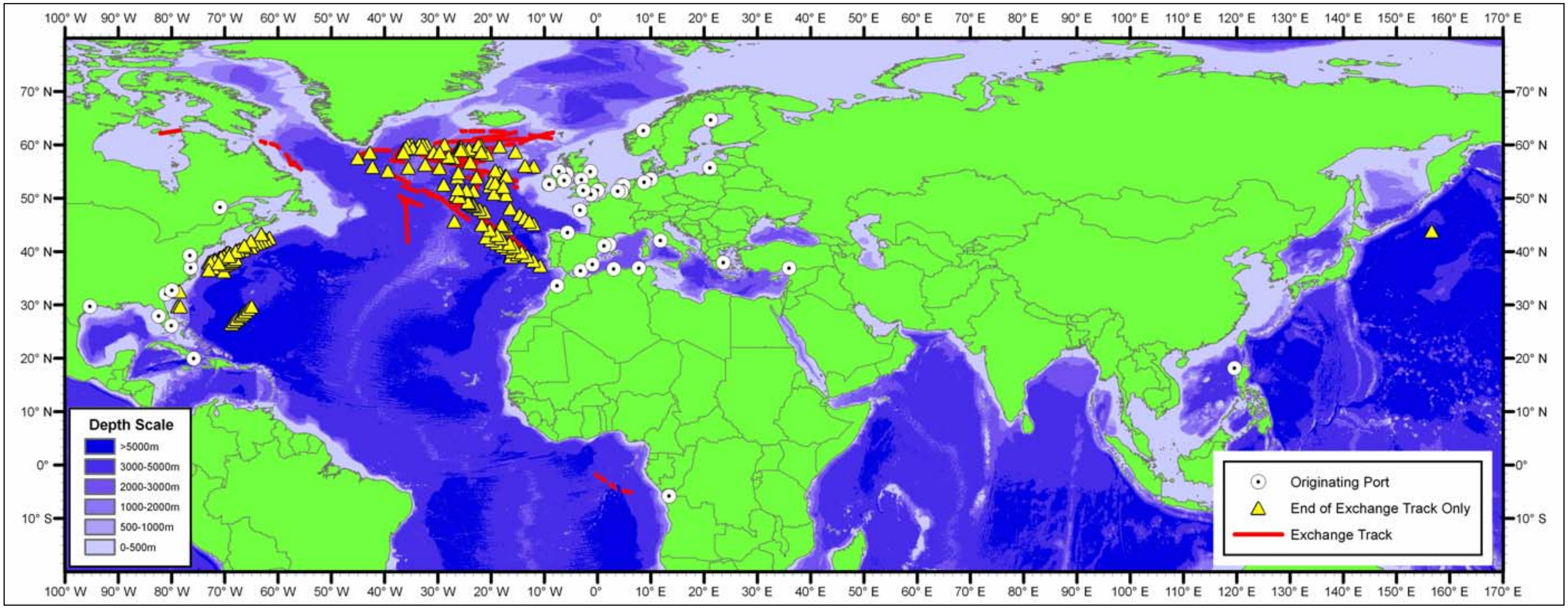

Figure 14. Ballast water exchange by vessels enroute to Churchill, Manitoba in 2005 to 2008 (Data from the INNAV database courtesy of C. Wiley, DFO/TC, Sarnia, ON ; Figure prepared by T. Siferd, DFO, Winnipeg, MB).

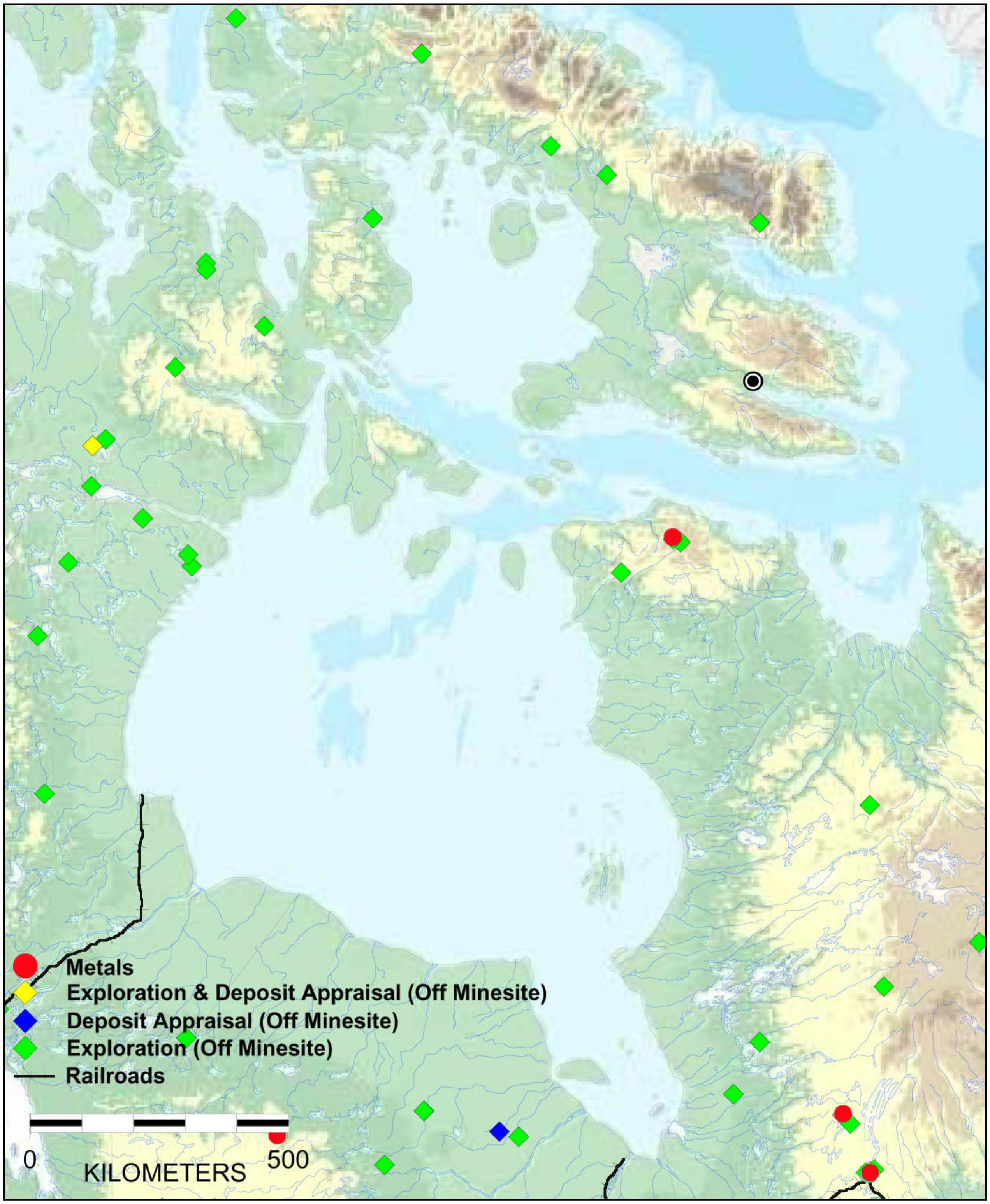

Figure 15. Active metal mines and mineral exploration and deposit appraisals near the HB complex coasts (from http://mmsd.mms.nrcan.gc.ca/maps/MiningMap/min-min-eng.aspx)

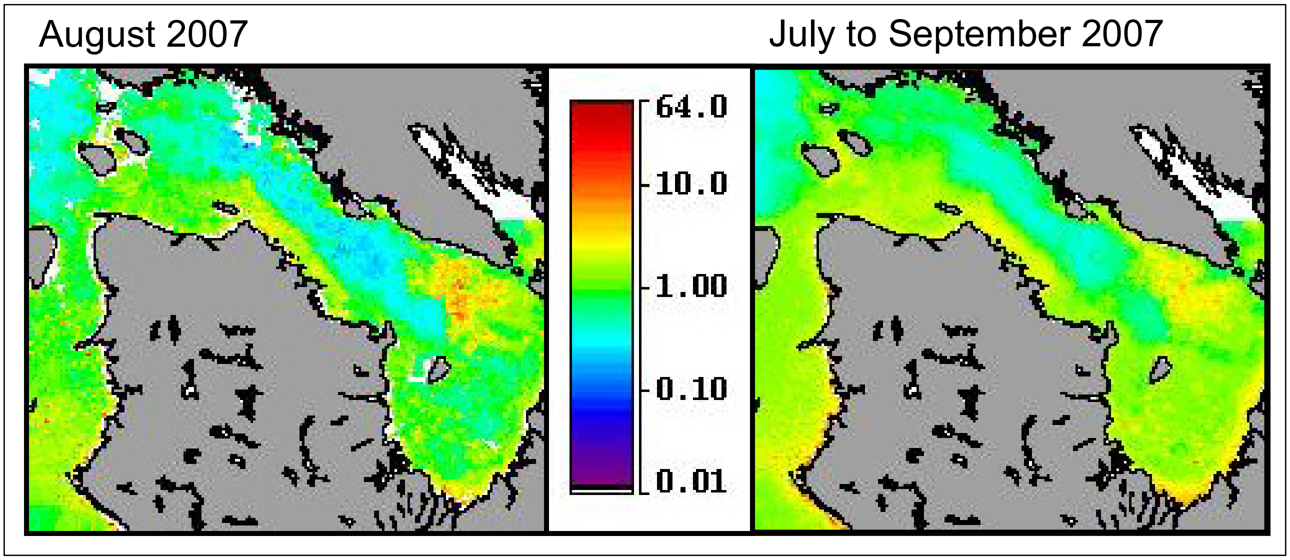

Figure 16. Surface chlorophyll-a concentration (mg/m³) in Hudson Strait during August 2007 and over the summer period (July through September) of 2007 from SeaWiFS data collected on the Orbview-2 satellite (courtesy H. Maass, DFO Dartmouth, NS).

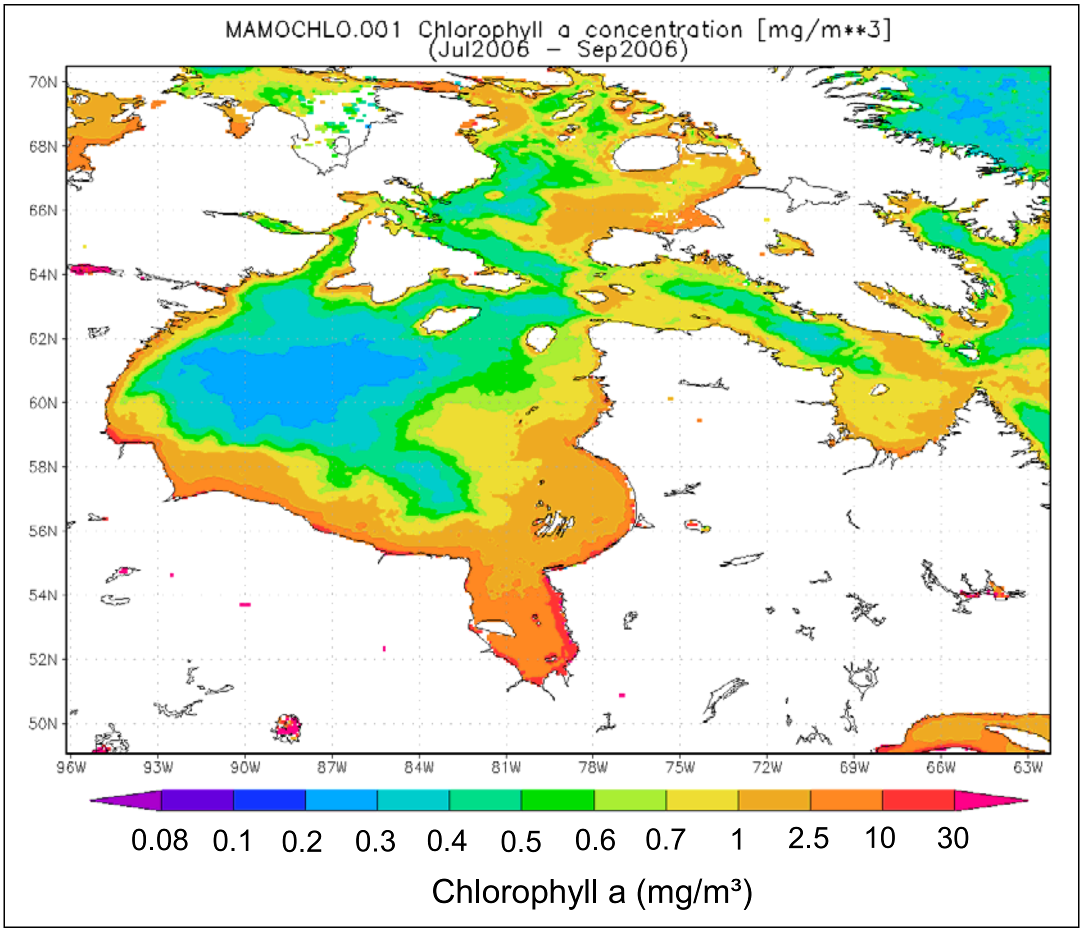

Figure 17. Chlorophyll-a concentration in the summer of 2006 (July through September) (Prepared using the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

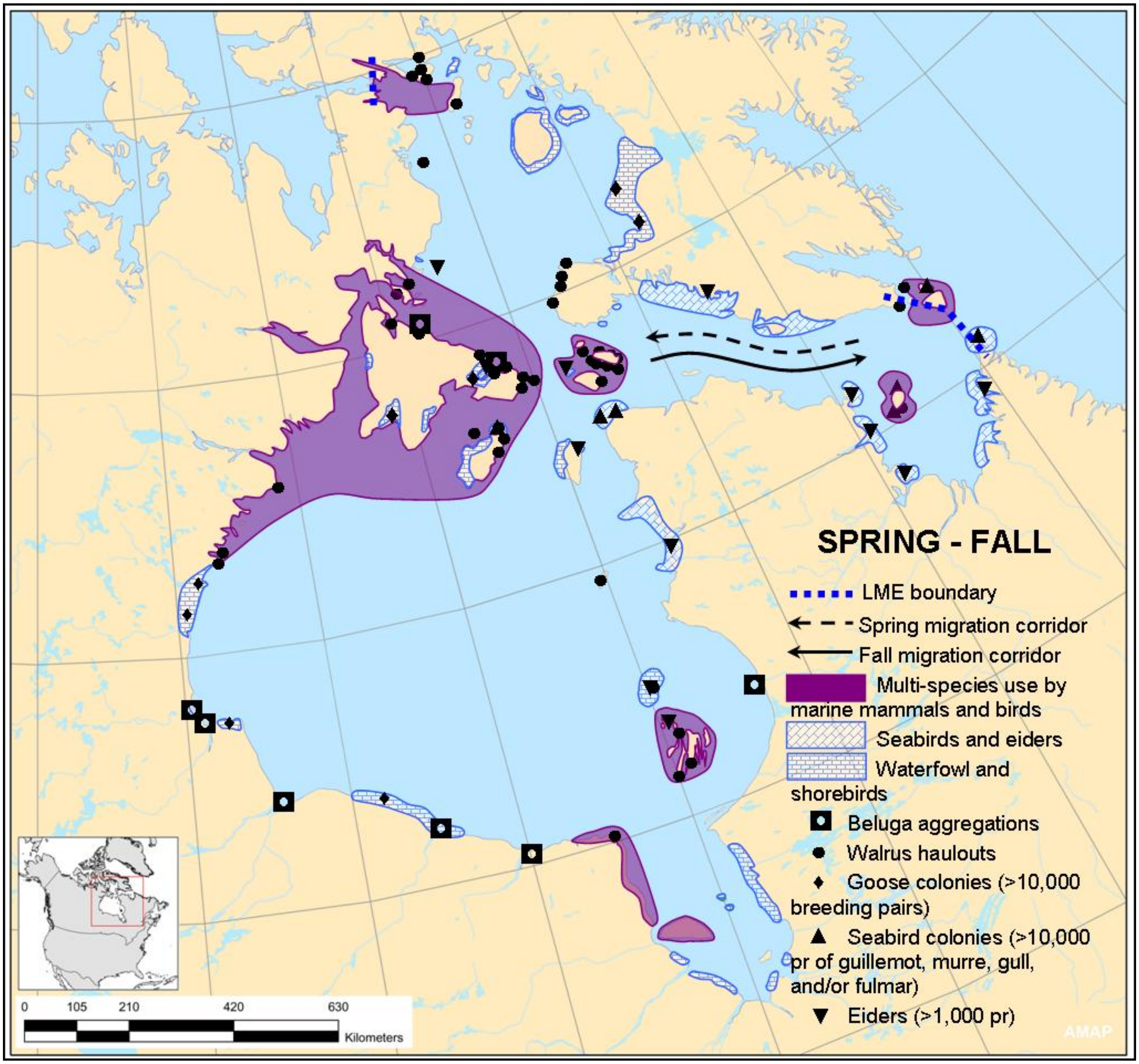

Figure 18. Important concentrations of marine mammals and birds within the Hudson Bay LME and along its coasts during spring through fall (roughly March to mid-November in the south, late May to late October in the north) (Base map courtesy of the Arctic Monitoring and Assessment Programme).

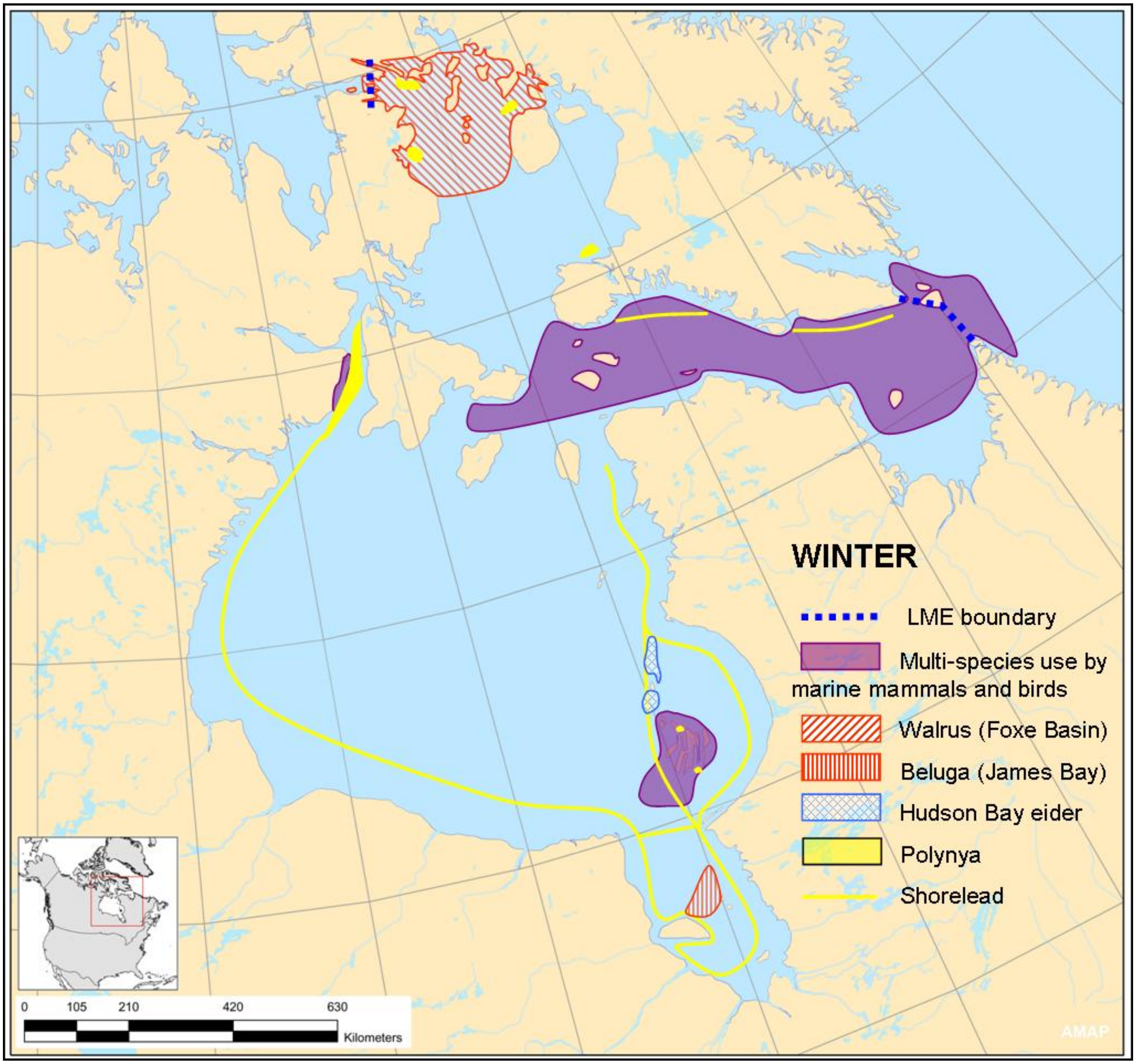

Figure 19. Important concentrations of marine mammals and birds within the Hudson Bay LME and along its coasts during winter (roughly mid-November to March in the south, late October to late May in the north) (Base map courtesy of the Arctic Monitoring and Assessment Programme).

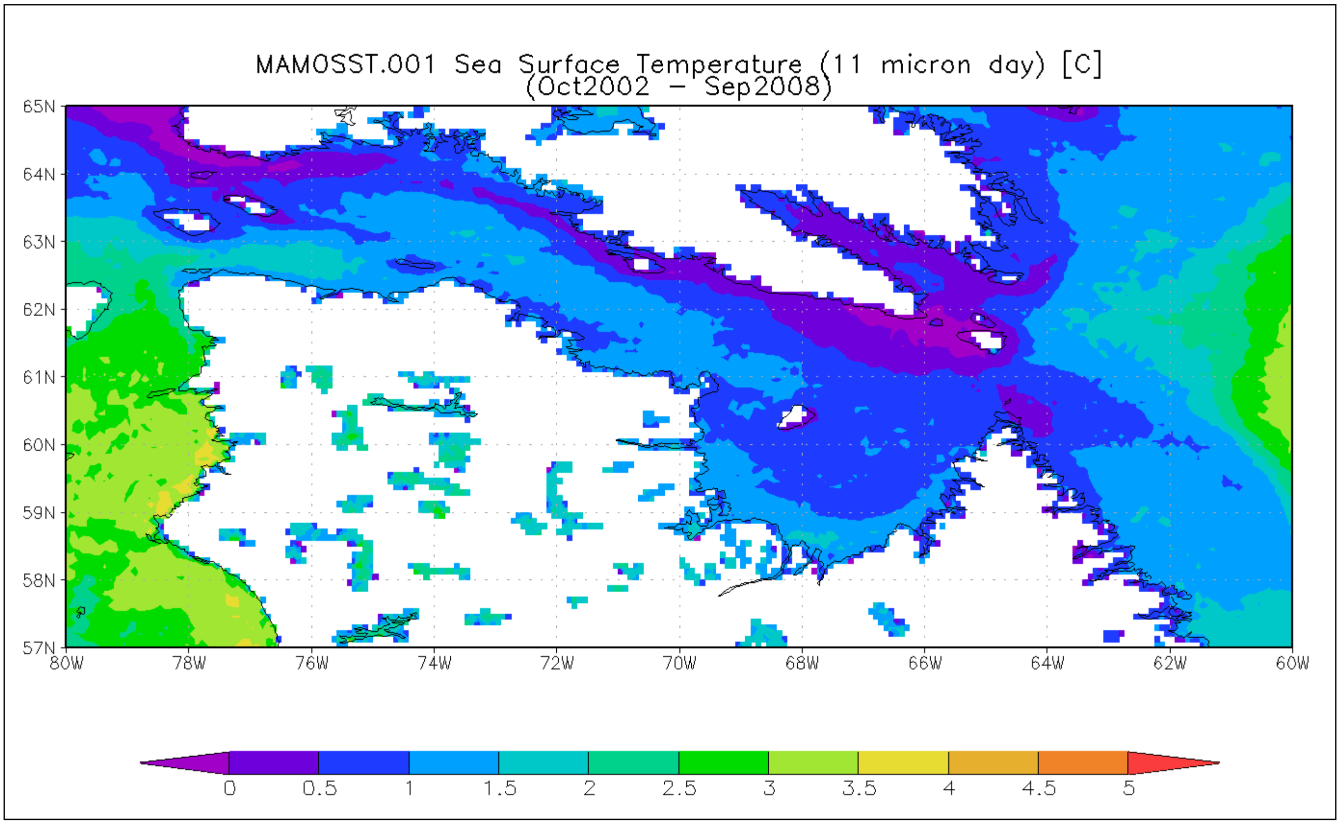

Figure 20. Composite of surface water temperature (°C) in Hudson Strait over the 6-year period from October 2002 through September 2008 (Prepared using the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences Data and Information Services Center).

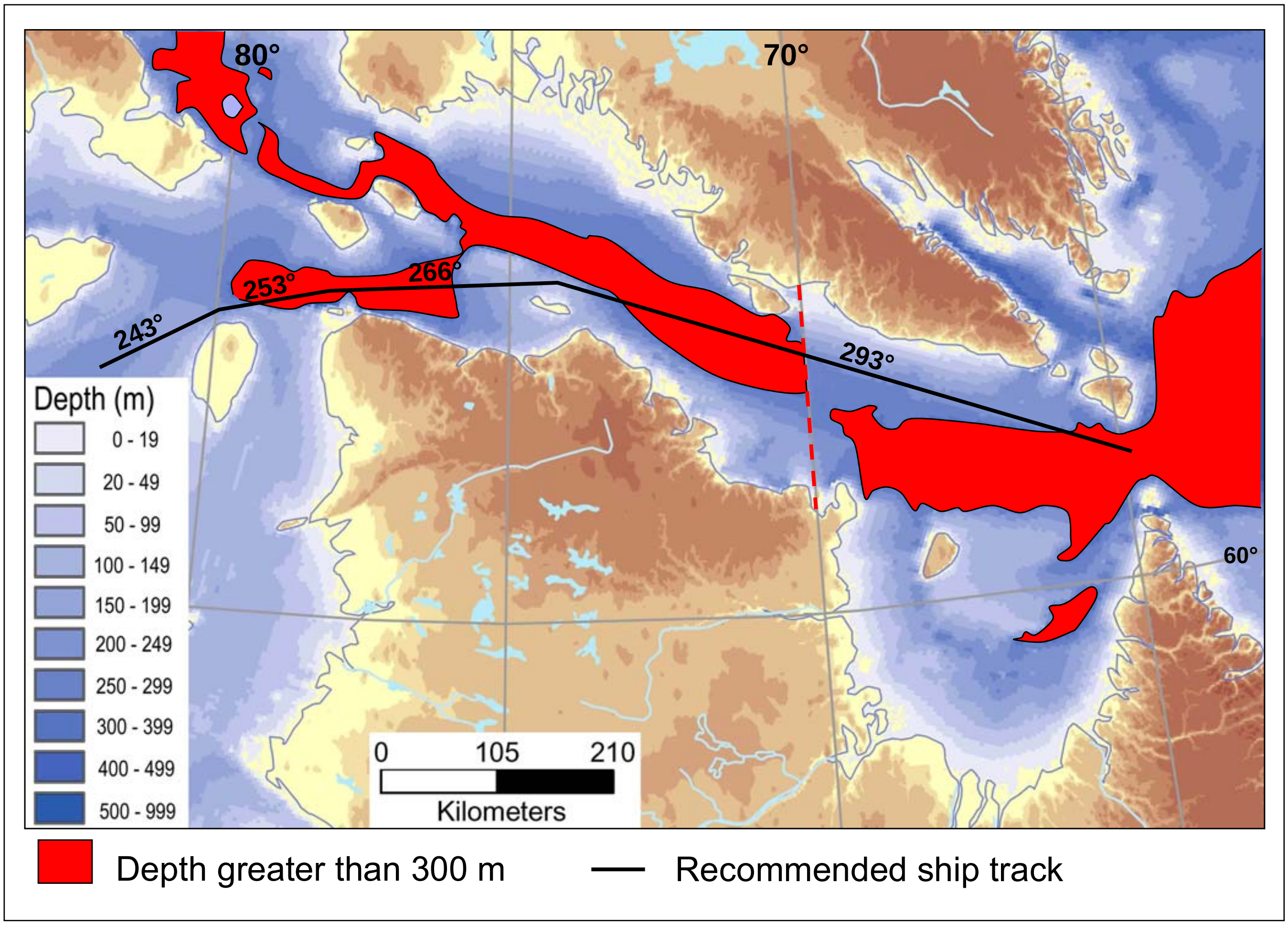

Figure 21. Recommended ship track through Hudson Strait plotted over depths greater than 300 m. Ship track from National Geospatial-Intelligence Agency (2008). (Base map courtesy of the Arctic Monitoring and Assessment Programme)

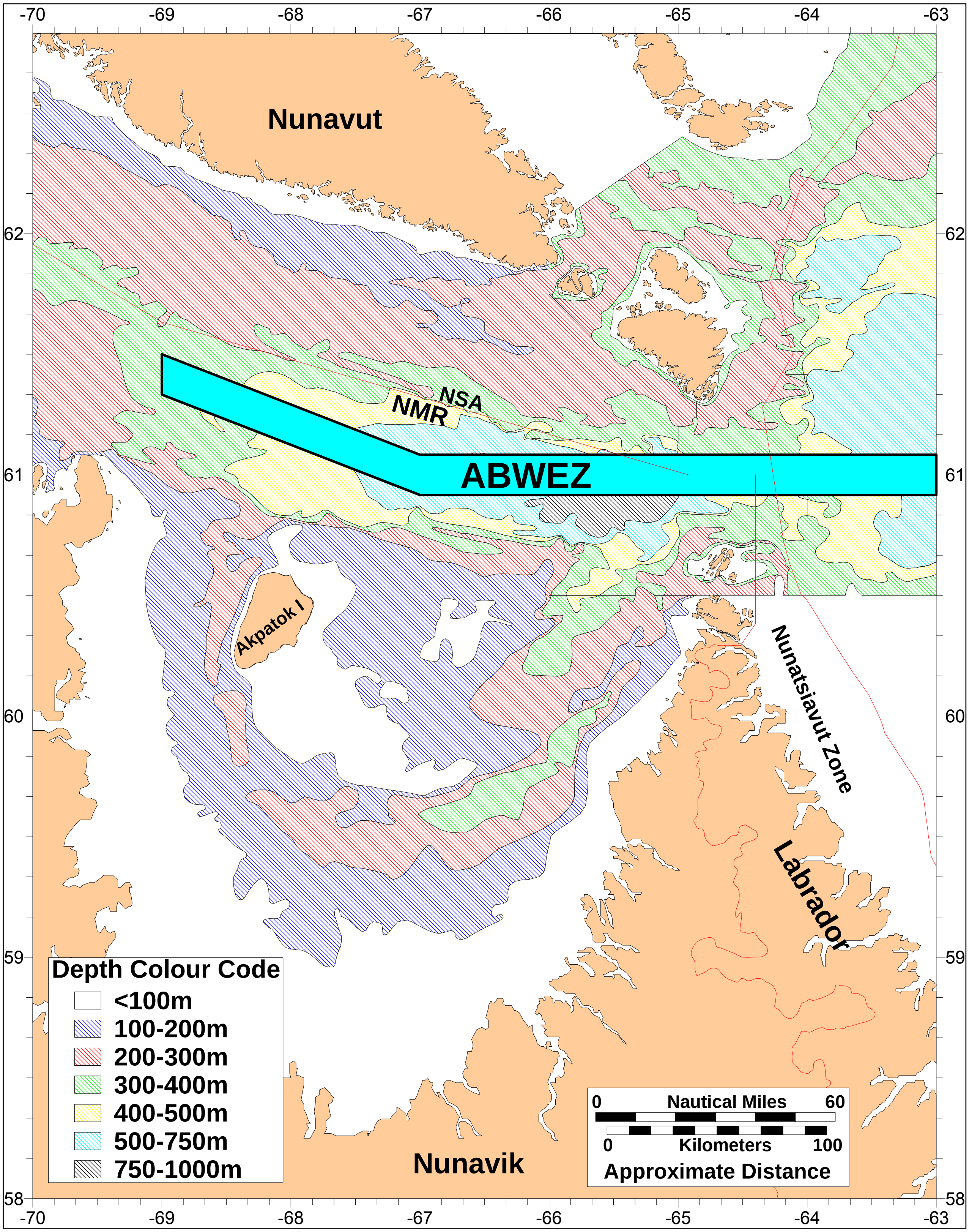

Figure 22. Adjusted Alternate Ballast Water Exchange Zone (ABWEZ) in Hudson Strait, showing depth contours, and the bounds of the Nunavut Settlement Area (NSA), Nunavik Marine Region (NMR), and Nunatsiavut Zone. (Map prepared by T. Siferd, DFO, Winnipeg).

Table 1. Large marine ecosystem (LME) of last port of call for ships arriving in ballast at the Port of Churchill in 1998 to 2005. Ship data are from I. Sawatzky (Hudson Bay Port Company, Churchill, MB, pers. comm. 2008), LME designations from http://www.lme.noaa.gov/, and water temperatures from http://oceancolor.gsfc.nasa.gov/cgi/l3/A20021722008264.L3m_SCSU_SST_4.png?sub=img .

Large Marine Ecosystem of last Port of Call	**Number of Ships**	**Oceanic Region**	**Number of Ships**			**Range of average summer surface water temperature (°C) over the LME**
			Tropical	**Temperate**	**Sub-arctic**	
Baltic Sea	1	Atlantic Ocean (eastern)		1		14-19
Gulf of Mexico	1	Atlantic Ocean (western)	1			27-31
Newfoundland-Labrador Shelf	1	Atlantic Ocean (western)			1	1-16
Gulf of Thailand	1	Pacific Ocean (western)	1			29-31
Caribbean Sea	3	Atlantic Ocean (western)	3			26-31
Scotian Shelf	4	Atlantic Ocean (western)		4		14-17
Canary Current	5	Atlantic Ocean (eastern)		5		17-28
Southeast US Continental Shelf	5	Atlantic Ocean (western)		5		27-31
Iceland Shelf	5	Polar Oceans			5	6-13
Iberian Coastal	8	Atlantic Ocean (eastern)		8		17-22
Great Lakes/St. Lawrence River	10	Continental North America (freshwater)		10		11-23
Northeast US Continental Shelf	12	Atlantic Ocean (western)		12		13-30
Celtic-Biscay Shelf	16	Atlantic Ocean (eastern)		16		14-21
Mediterranean	17	Atlantic Ocean (eastern)		17		21-30
North Sea	27	Atlantic Ocean (eastern)		27		12-18
Total	116		5	105	6	
Hudson Strait						0.5-3.5
Foxe Basin						0.5-1.5
Hudson Bay						4-9
Churchill						9

Table 2. Comparison of physical and chemical parameters between source ports, the ABWEZ in Hudson Strait, and the Port of Churchill. Sources cited in text unless otherwise noted.

Parameter/Location	**Source Ports (Tropical, Temperate, Subarctic)**	**ABWEZ Exchange Zone (Hudson Strait)**	**Loading Port (Churchill)**
Sea surface temperature (mean summer daylight) [(1)]	12-31°C	0.5-3.5°C	9°C
Salinity (surface)	0->34 ‰ [(2)]	~25-33.5 ‰ [(3)]	< 28 ‰ [(4)]
Depth	likely < 50 m	> 300 m	8.5 m [(5)]
Distance from shore	< 1 km	~20-50 km	< 1 km
Seasonal ice cover	none	9-9+/10ths [(6)]	10/10ths [(6)]
Spring tidal range	variable	4.9 – 12.5 m [(7)]	~4 m [(8)]

[(1)] mean summer daylight sea surface temperature (June 21-Sept 20) over the period 2002 to 2008 (source: oceancolor.gsfc.nasa.gov)
[(2)] Antonov *et al*. (2006)
[(3)] Drinkwater (1988), Harvey *et al*. (2006); Straneo and Saucier (2008b)
[(4)] Barber 1967; Prinsenberg 1986a; Baker *et al*. 1994
[(5)] portofchurchill.ca
[(6)] http://www.ice.ec.gc.ca/IA_NWCA_MCSI/ar_ctmed0401.gif
[(7)] Dohler (1968), Canadian Hydrographic Service (1982), NIMA (2002),
[(8)] Kuzyk *et* al. (2008)

Appendix 1. Data on last port of call, product import/export, and destination of ships using the Port of Churchill in 1998 through 2005 (I. Sawatzky, Hudson Bay Port Company, Churchill, MB pers. comm. 2008).

Port of Churchill 1998 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	TEXAS CITY	TEXAS, USA	GULF OF MEXICO	8514.5 OIL		NUUK, GREENLAND
2	LAKE HARBOUR	NUNAVUT	HUDSON BAY	88 PASSENGERS	69 PASSENGERS	STROMFJORD, GREENLAND
3	CANADA	CANADA	N/A	HYDROGRAPHIC SURVEY		CANADA
4	ALGECIERAS	SPAIN	MEDITERRANEAN		31562 WHEAT	NIGERIA
5	CHARLESTON	SOUTH CAROLINA, USA	SOUTHEAST US CONTINENTAL SHELF		26250 WHEAT	SUDAN
6	MONTREAL	QUEBEC	ST. LAWRENCE RIVER		24000 WHEAT	TUXPAN, MEXICO
7	NUUK	GREENLAND	WEST GREENLAND SHELF	16427 OIL		DONGES, FRANCE
8	BUTTERFLY BAY	NUNAVUT	BAFFIN BAY	102 PASSENGERS	109 PASSENGERS	NASSASSASRUAQ, GREENLAND
9	SETUBAL	PORTUGAL	IBERIAN COASTAL		31500 WHEAT	VERACRUZ, MEXICO
10	BRAKE	GERMANY	NORTH SEA		25458 WHEAT	GHANA, W. AFRICA
11	HAVANA	CUBA	CARIBBEAN SEA		29671 WHEAT	NIGERIA
12	PHILADELPHIA	PENNSYLVANIA, USA	NORTHEAST US CONTINENTAL SHELF		31500 WHEAT	VERACRUZ, MEXICO
13	AMSTERDAM	NETHERLANDS	NORTH SEA		33000 WHEAT	PORT HARCOURT, NIGERIA
14	HUELVA	SPAIN	IBERIAN COASTAL	11378 COPPER ORE DISCHARGED	21490 WHEAT	TUXPAN, MEXICO
15	FALMOUTH	UNITED KINGDOM (England)	CELTIC-BISCAY SHELF		33000 WHEAT	VERACRUZ, MEXICO
16	PORSGRUNN	NORWAY	NORTH SEA		20980 WHEAT	MARACAIBO, VENEZUELA
TOTAL 1998					**318,911 GRAIN**	

Port of Churchill 1999 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	LAKE HARBOUR	NUNAVUT	HUDSON BAY	114 PASSENGERS	112 PASSENGERS	IQALUIT, NUNAVUT
2	TEXAS CITY	TEXAS, USA	GULF OF MEXICO	12856 OIL		IQALUIT, NUNAVUT
3	BARCELONA	SPAIN	MEDITERRANEAN		21000 WHEAT	TUXPAN, MEXICO
4	GOTHENBORG	SWEDEN (see Note 1)	NORTH SEA		32900 WHEAT	MOMBASA, KENYA
5	N/A	N/A	N/A	78 PASSENGERS	79 PASSENGERS	ST. PIERRE ET MIQUELON
6	N/A	N/A	N/A		22000 WHEAT	LA GUAIRA, VENEZUELA
7	N/A	N/A	N/A	150 PASSENGERS	124 PASSENGERS	PORTLAND, MAINE, USA
8	N/A	N/A	N/A	83 PASSENGERS	77 PASSENGERS	ST. PIERRE ET MIQUELON
9	NUUK	GREENLAND	WEST GREENLAND SHELF	11000 OIL		IQALUIT, NUNAVUT
10	N/A	N/A	N/A		32700 WHEAT	MISURATA, LIBYA
11	NEW YORK	NEW YORK, USA	NORTHEAST US CONTINENTAL SHELF		29000 WHEAT	VERACRUZ, MEXICO
12	IMMINGHAM	UNITED KINGDOM (England)	NORTH SEA		28500 WHEAT	VERACRUZ, MEXICO
13	MONFALCONE	ITALY	MEDITERRANEAN		23927 WHEAT	LA GUAIRA, VENEZUELA
14	GIJON	SPAIN	IBERIAN COASTAL		29700 WHEAT	MERSIN, TURKEY
15	N/A	N/A	N/A		36100 WHEAT	MERSIN, TURKEY
16	VALENCIA	SPAIN	MEDITERRANEAN		23576 PEAS	LISBON, PORTUGAL
17	LONDON	UNITED KINGDOM (England)	NORTH SEA		26250 WHEAT	FORTALEZA, BRAZIL
18	ROUEN	FRANCE	CELTIC-BISCAY SHELF		40775 WHEAT	TURKEY
19	N/A	N/A	N/A		24032 PEAS	DUBLIN, UNITED KINGDOM
20	ANTWERP	BELGIUM	NORTH SEA		33500 WHEAT	LAZERO CARDENAS, MEXICO
TOTAL 1999					**414,935 GRAIN**	

Port of Churchill 2000 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	LISBON	PORTUGAL	IBERIAN COASTAL		27500 PEAS	VERACRUZ, MEXICO
2	MONTREAL	QUEBEC	ST. LAWRENCE RIVER		27388 PEAS	BARCELONA, SPAIN
3	N/A	N/A	N/A	21500 OIL		GREENLAND
4	DUNKIRK	FRANCE	CELTIC-BISCAY SHELF		27000 WHEAT	VERACRUZ, MEXICO
5	NOVA SCOTIA	NOVA SCOTIA	SCOTIAN SHELF		DREDGE & SCOWS	CHURCHILL, MANITOBA
6	HUELVA	SPAIN	IBERIAN COASTAL		33000 WHEAT	DURBAN, SOUTH AFRICA
7	CEMENTON	NEW YORK	NORTHEAST US CONTINENTAL SHELF		30300 WHEAT	SOUTH AFRICA
8	LISBON	PORTUGAL	IBERIAN COASTAL		31200 WHEAT	PORT HARCOURT, NIGERIA
9	ALGECIERAS	SPAIN	MEDITERRANEAN		27500 WHEAT	VERACRUZ, MEXICO
10	N/A	N/A	N/A		22000 WHEAT	TEMA,GHANA
11	DAKAR	SENEGAL	CANARY CURRENT		17000 WHEAT	EAST AFRICA
12	SOUTHAMPTON	UNITED KINGDOM (England)	CELTIC-BISCAY SHELF		3700 PEAS	UNITED KINGDOM (IRELAND)
13	SAVONA	ITALY	MEDITERRANEAN		33000 WHEAT	PORT SUDAN, SUDAN
14	AMSTERDAM	NETHERLANDS	NORTH SEA		30500 WHEAT	NIGERIA
15	BREVIK	NORWAY	NORTH SEA		25600 PEAS	BREVIK, NORWAY
16	KLAIPEDA	LITHUANIA	BALTIC SEA		15810 WHEAT	MOROCCO
17	BARCELONA	SPAIN	MEDITERRANEAN		27500 PEAS	HUELVA, SPAIN
18	AVONMOUTH	UNITED KINGDOM (England)	CELTIC-BISCAY SHELF		35200 WHEAT	TURKEY
19	LONDONDERRY	UNITED KINGDOM (Ireland)	CELTIC-BISCAY SHELF		25804 WHEAT	SUDAN
20	GRUNDARTANGI	ICELAND	ICELAND SHELF		22800 PEAS	ORISTANO, ITALY
21	GIBRALTAR	GIBRALTAR	MEDITERRANEAN		25400 WHEAT	TUXPAN, MEXICO
22	N/A	UNITED KINGDOM	N/A		34446 WHEAT	TUXPAN, MEXICO
23	N/A	DENMARK	NORTH SEA		HELICOPTERS	MARCHWOOD, UNITED KINGDOM
24	N/A	BELGIUM	NORTH SEA		33000 WHEAT	VERACRUZ, MEXICO
25	GIBRALTAR	GIBRALTAR	MEDITERRANEAN		22000 WHEAT	CASABLANCA, MOROCCO
26	N/A	UNITED KINGDOM	N/A		27732 PEAS	GHENT, BELGIUM
27	N/A	VENEZUELA	CARIBBEAN SEA (?)		27500 WHEAT	TUXPAN, MEXICO
28	N/A	UNITED KINGDOM	N/A		29500 PEAS	GHENT, BELGIUM
29	N/A	BELGIUM	NORTH SEA		26300 WHEAT	VENEZUELA
30	N/A	N/A	N/A		21900 PEAS	CARTAGENA, SPAIN
TOTAL 2000					**710,580 GRAIN**	

Port of Churchill 2001 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	GLASGOW	UNITED KINGDOM (Scotland)	CELTIC-BISCAY SHELF		26600 WHEAT	PORT SUDAN, SUDAN
2	FALMOUTH	UNITED KINGDOM (England)	CELTIC-BISCAY SHELF		26643 WHEAT	NIGERIA
3	GRUNDARTANGI	ICELAND	ICELAND SHELF		22000 WHEAT	VERACRUZ, MEXICO
4	UDDEVALLA (see Note 2)	SWEDEN	NORTH SEA		30575 WHEAT	PORT HARCOURT, NIGERIA
5	FLUSHING	NETHERLANDS	NORTH SEA		47835 WHEAT	EGYPT
6	LIVERPOOL	UNITED KINGDOM (England)	CELTIC-BISCAY SHELF		30650 WHEAT	CASABLANCA, MOROCCO
7	ROTTERDAM	NETHERLANDS	NORTH SEA		26250 PEAS	BELGIUM
8	N/A	DENMARK	NORTH SEA		22000 WHEAT	MOROCCO
9	AUGHINISH	UNITED KINGDOM (Ireland)	CELTIC-BISCAY SHELF		56100 WHEAT	EGYPT
10	ANTWERP	BELGIUM	NORTH SEA		33000 WHEAT	NIGERIA
11	JORF LASFAR	MOROCCO	CANARY CURRENT		55050 WHEAT	EGYPT
12	MONTREAL	QUEBEC	ST. LAWRENCE RIVER		22000 WHEAT	VERACRUZ, MEXICO
13	HALIFAX	NOVA SCOTIA	SCOTIAN SHELF		27380 WHEAT	CASABLANCA, MOROCCO
14	N/A	UNITED KINGDOM (Ireland)	CELTIC-BISCAY SHELF		6050 WHEAT	BELGIUM
15	N/A	MOROCCO	CANARY CURRENT?		6000 WHEAT	BELGIUM
TOTAL 2001					**478,203 GRAIN**	

Port of Churchill 2002 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	N/A	N/A	N/A		PASSENGERS	N/A
2	N/A	N/A	N/A		PASSENGERS	N/A
3	FREEPORT	BAHAMAS	CARIBBEAN SEA		21000 WHEAT	RECIFE, BRAZIL
4	GEORGETOWN	SOUTH CAROLINA, USA	SOUTHEAST US CONTINENTAL SHELF		28950 WHEAT	GUAYAQUIL, ECUADOR
5	NORFOLK	VIRGINIA,USA	NORTHEAST US CONTINENTAL SHELF		31200 WHEAT	PORT SUDAN, SUDAN
6	FREDRICKSTAD	NORWAY	NORTH SEA		33000 WHEAT	LAGOS, NIGERIA
7	MONTREAL	QUEBEC	ST. LAWRENCE RIVER		27620 WHEAT	PUERTO CABELLO, VENEZUELA
8	HAMILTON	ONTARIO	GREAT LAKES		27500 WHEAT	CASABLANCA, MOROCCO
9	ROTTERDAM	NETHERLANDS	NORTH SEA		44000 WHEAT	SPAIN
10	ALGECIERAS	SPAIN	MEDITERRANEAN		33000 WHEAT	SENEGAUTOGO, IVORY COAST
11	AVONMOUTH	UNITED KINGDOM (England)	CELTIC-BISCAY SHELF		33000 WHEAT	NIGERIA
TOTAL 2002					**279,270 GRAIN**	

Port of Churchill 2003 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	GIJON	SPAIN	IBERIAN COASTAL		42450 WHEAT	GHENT, BELGIUM
2	AALBORG	DENMARK (see Note 3)	NORTH SEA		30250 WHEAT	BRAZIL
3	N/A	N/A	N/A		30000 WHEAT	FORT ALEZA, BRAZIL
4	FALMOUTH	UNITED KINGDOM (England)	CELTIC-BISCAY SHELF		22500 WHEAT	GREECE
5	STRAUMSVIK	ICELAND	ICELAND SHELF		41000 WHEAT	VADA, ITALY
6	GIBRALTAR	GIBRALTAR	MEDITERRANEAN		31600 WHEAT	BALBOA, SPAIN
7	ALGECIERAS	SPAIN	MEDITERRANEAN		30250 WHEAT	NIGERIA
8	BAIE COMEAU	QUEBEC	NEWFOUNDLAND-LABRADOR SHELF		35800 WHEAT	DOUALA, CAMEROON
9	GIBRALTAR	GIBRALTAR	MEDITERRANEAN		27000 WHEAT	MAPUTO, MOZAMBIQUE
10	CONTRECOU ER	QUEBEC	ST. LAWRENCE RIVER		27500 WHEAT	ITALY
11	DAKAR	SENEGAL	CANARY CURRENT		35200 WHEAT	PORT SUDAN, SUDAN
12	AMSTERDAM	NETHERLANDS	NORTH SEA		30000 WHEAT	ITALY & GREECE
13	ALGECIERAS	SPAIN	MEDITERRANEAN		21000 PEAS	SPAIN
14	ANTWERP	BELGIUM	NORTH SEA		26400 WHEAT	STAVANGER, NORWAY
15	N/A	UNITED KINGDOM (Ireland)	CELTIC-BISCAY SHELF		57750 PEAS	SPAIN
16	BILBAO	SPAIN	IBERIAN COASTAL		26800 CANOLA	VERACRUZ, MEXICO
17	HULL	UNITED KINGDOM (England)	NORTH SEA		31803 PEAS	SPAIN
18	N/A	ICELAND	ICELAND SHELF		26150 WHEAT	TURKEY
19	HALIFAX	NOVA SCOTIA	SCOTIAN SHELF		18000 WHEAT	ITALY
20	WILMINGTON	DELAWARE, USA	NORTHEAST US CONTINENTAL SHELF		25125 LINOLA	ANTWERP, BELGIUM
TOTAL 2003					**616,578 GRAIN**	

Port of Churchill 2004 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	PORT ALFRED	QUEBEC	ST. LAWRENCE ESTUARY		43550 WHEAT	PORT SUDAN, SUDAN
2	CAPE DORSET	NUNAVUT	HUDSON BAY		84 PASSENGERS	KANGERLUSSUAQ
3	BANGKOK	THAILAND	GULF OF THAILAND		23830 WHEAT	LAGOS, NIGERIA
4	TILBURY	UNITED KINGDOM (England)	NORTH SEA		29280 DURUM	TRIPOLI, LIBYA
5	NEWPORT NEWS	NEW JERSEY, USA	NORTHEAST US CONTINENTAL SHELF		26457 WHEAT	ITALY
6	NEW YORK	NEW YORK, USA	NORTHEAST US CONTINENTAL SHELF		34260 WHEAT	TAKORADI, GHANA
7	N/A	UNITED KINGDOM (Ireland)	CELTIC-BISCAY SHELF		26525 DURUM	ITALY
8	ANTWERP	BELGIUM	NORTH SEA		39600 WHEAT	ITALY
9	BRUNSWICK	GEORGIA, USA	SOUTHEAST US CONTINENTAL SHELF		13750 DURUM	TUNISIA
10	CHARLESTON	SOUTH CAROLINA, USA	SOUTHEAST US CONTINENTAL SHELF		28000 WHEAT	WEST AFRICA
11	MISSISSIPPI RIVER	LOUISIANA, USA	GULF OF MEXICO		13750 DURUM	TUNISIA
12	SETUBAL	PORTUGAL	IBERIAN COASTAL		31500 DURUM	TRIPOLI, LIBYA
13	GRUNDARTANGI	ICELAND	ICELAND SHELF		22700 DURUM	ITALY
14	HALIFAX	NOVA SCOTIA	SCOTIAN SHELF		27308 WHEAT	NIGERIA
15	BREMEN	GERMANY	NORTH SEA		39500 PEAS	SPAIN
TOTAL 2004					**400,010 GRAIN**	

Port of Churchill 2005 Shipping List

VESSEL	LAST PORT OF CALL			TONNAGE UNLOADED	TONNAGE LOADED	DESTINATION
	PORT	COUNTRY	LARGE MARINE ECOSYSTEM (LME)			
1	CANADA	CANADA	N/A		FUEL OIL	CANADA
2	BARCELONA	SPAIN	MEDITERRANEAN		25687 WHEAT	LAGOS, NIGERIA
3	CANADA	CANADA	N/A		FUEL OIL	CANADA
4	NEWPORT NEWS	NEW JERSEY, USA	NORTHEAST US CONTINENTAL SHELF		26369 WHEAT	ITALY
5	GREENORE	UNITED KINGDOM (Ireland)	CELTIC-BISCAY SHELF		29481DURUM	ITALY
6	CANADA NAVY	CANADA NAVY	N/A	COURTESY CALL		CANADA
7	CANADA NAVY	CANADA NAVY	N/A	COURTESY CALL		CANADA
8	NEWPORT NEWS	NEW JERSEY, USA	NORTHEAST US CONTINENTAL SHELF		27500 DURUM	ROTTERDAM, NETHERLANDS
9	PORT EVERGLADES	FLORIDA, USA	SOUTHEAST US CONTINENTAL SHELF		25695 WHEAT	LAGOS, NIGERIA
10	CANADA	CANADA	N/A		FUEL OIL	CANADA
11	BALTIMORE	MARYLAND, USA	NORTHEAST US CONTINENTAL SHELF		26502 DURUM	TUNISIA
12	QUEBEC	QUEBEC	ST. LAWRENCE RIVER		35625 DURUM	ITALY
13	IJMUIDEN	NETHERLANDS	NORTH SEA		52254 PEAS	SPAIN
14	CANADA	CANADA	N/A		FUEL OIL	CANADA
15	CAMDEN	NEW JERSEY,USA (see Note 4)	NORTHEAST US CONTINENTAL SHELF		22500 WHEAT	TUXPAN, MEXICO
16	PORT ALFRED	QUEBEC	ST. LAWRENCE ESTUARY		30800 WHEAT	LAGOS, NIGERIA
17	BALTIMORE	MARYLAND, USA	NORTHEAST US CONTINENTAL SHELF		19170 CANOLA	VERACRUZ, MEXICO
18	CANADA	CANADA	N/A		SCIENTIFIC	CANADA
19	BEJAIA	ALGERIA (see Note 5)	MEDITERRANEAN		36000 PEAS	SPAIN
20	CASABLANCA	MOROCCO	CANARY CURRENT		30000 WHEAT	GHENT, BELGIUM
21	GIBRALTAR	GIBRALTAR	MEDITERRANEAN		36300 WHEAT	EAST AFRICA
22	PORT ALFRED	QUEBEC	ST. LAWRENCE ESTUARY		36911 WHEAT	SUDAN
TOTAL 2005					**460,794 GRAIN**	

Note 1: Reported as Denmark but Gothenborg is in Sweden.

Note 3: Reported in original as Norway but Aalborg is in Denmark.

Note 4: The State was not given in the original. No unloading facilities were visible in photos of Camden, Maine.

Note 5: Reported in original as Bejais, which likely refers to the Port of Bejaia, Algeria.