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An ecological and oceanographical assessment of alternate ballast water exchange zones in the Canadian eastern Arctic

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Mid-ocean exchange of ballast water is recommended for vessels entering Canadian waters from outside Canadian jurisdiction to minimize the risk of ballast-mediated transfer of nonindigenous species (NIS). When this cannot be accomplished due to inclement weather or other circumstances, designated alternate ballast water exchange zones (ABWEZ) within Canadian waters may be used. Vessels entering Canadian waters to load commodities, such as iron ore in the eastern Canadian Arctic, may increase greatly by 2020. This study evaluates the relative risks from exchange at different locations in the eastern Canadian Arctic, including existing ABWEZs in Lancaster Sound and Hudson Strait, using a coupled-ice-ocean model with meteorological forcing and particle tracking.

In the model, ballast water discharge was simulated as the release of particles along vessel tracks into the surface layer of circulation models for Baffin Bay – Labrador Sea and Lancaster Sound. Particle transport provided metrics for comparing relative likelihood of exposure. The receiving habitats were differentiated and weighted for comparison based on relative likelihood of establishment and relative habitat sensitivity. The final relative risk to receiving habitats from ballast water exchange along each ship track was then calculated from the product of the likelihood of exposure, likelihood of establishment, and habitat sensitivity. Since the relationship between survival of NIS and various environmental parameters has not been empirically demonstrated in this region, different weighting scenarios were used to test the sensitivity of the model to establishment and habitat sensitivity metrics. The model was robust to these different weightings and consistently identified the same regions as having higher relative risk.

The modelling results indicate that existing ABWEZs in and around Lancaster Sound and Hudson Strait are among the areas of highest relative risk for introductions of NIS via ballast water. Lower risk portions of major vessel tracks should be considered as alternatives, including the Labrador Sea portion of all vessel tracks, and the Baffin Bay deep offshore vessel track at depths greater than 1000 m. Foreign coastal biota released along these tracks are least likely to reach shallow coastal habitats that offer favourable conditions for their survival and establishment. To further mitigate risks from organisms in the ballast sediment, it is recommended that vessels entering the Canadian Eastern Arctic from outside Canada's Exclusive Economic Zone (EEZ) not in ballast flush their residuals from the ballast tanks prior to entering waters under Canadian jurisdiction. Further research is recommended to assess the risk of species introductions associated with ballast water exchange in the Canadian Arctic, the effectiveness of exchange for reducing risk associated with the release of ballast water into the region's coastal waters, and options for ballast exchange by vessels operating within the EEZ.

Évaluation écologique et océanographique de la zone de renouvellement des eaux de ballast de l'Arctique canadien de l'Est

RÉSUMÉ

Le renouvellement des eaux de ballast est recommandé pour les navires en provenance de l'extérieur du territoire canadien qui entrent dans les eaux canadiennes; cette mesure aide à réduire le risque de transfert d'espèces non indigènes par l'eau de ballast. Lorsque ce renouvellement ne peut être effectué en raison des mauvaises conditions météorologiques ou d'autres circonstances, d'autres zones désignées de renouvellement des eaux de ballast dans les eaux canadiennes peuvent être utilisées. Le trafic de navires entrant dans les eaux canadiennes pour le chargement de marchandises, comme du minerai de fer dans l'Arctique canadien de l'Est, pourrait augmenter grandement d'ici 2020. La présente étude évalue les risques liés au renouvellement des eaux de ballast à divers endroits dans l'Arctique canadien de l'Est, y compris les zones de renouvellement des eaux de ballast existantes dans le détroit de Lancaster et le détroit d'Hudson, à l'aide d'un modèle couplé glace-océan avec un suivi des particules et du forçage météorologique.

Dans ce modèle, le rejet des eaux de ballast est simulé par la libération de particules le long de la route des navires dans la couche de surface des modèles de circulation pour la baie de Baffin – la mer du Labrador et le détroit de Lancaster. Le transport des particules fournit des paramètres pour comparer la probabilité relative d'exposition. Les milieux récepteurs ont été différenciés et pondérés aux fins de comparaison en fonction de la probabilité d'établissement et de la sensibilité relative de l'habitat. Le risque relatif final sur le milieu récepteur du renouvellement des eaux de ballast le long de chaque route de navire a alors été calculé comme le produit de la possibilité d'exposition, de la possibilité d'établissement et de la sensibilité du milieu. Puisque la relation entre la survie des espèces non indigènes et les divers paramètres environnementaux n'a pas été démontrée de façon empirique dans cette région, différents scénarios de pondération ont été utilisés pour mettre à l'essai la sensibilité du modèle aux paramètres de l'établissement et de la sensibilité de l'habitat. Le modèle a résisté à ces différentes pondérations et a constamment cerné les mêmes régions comme présentant le plus haut risque relatif.

Les résultats du modèle indiquent que les zones de renouvellement des eaux de ballast actuelles du détroit de Lancaster, du détroit d'Hudson et des environs figurent parmi les zones où les risques relatifs d'introduction d'espèces non indigènes par les eaux de ballast sont les plus élevés. Les tronçons des principales routes de navire présentant le moins de risque doivent être envisagés comme de possibles zones substitutives, notamment le tronçon de chaque route situé la mer du Labrador et la route profonde au large de la baie de Baffin à des profondeurs supérieures à 1 000 m. Le biote côtier étranger libéré le long de ces tronçons est moins susceptible d'atteindre les habitats côtiers peu profonds pouvant lui offrir des conditions d'établissement et de survie. Afin d'atténuer encore plus les risques associés aux organismes transportés dans les sédiments de ballast, il est recommandé que les navires entrant dans l'est de l'Arctique depuis l'extérieur de la zone économique exclusive du Canada sans ballast rincent les résidus des citernes de ballast avant d'entrer dans les eaux qui relèvent de la compétence canadienne. Des recherches supplémentaires devraient être entreprises afin d'évaluer le risque d'introduction d'espèces associé au renouvellement des eaux de ballast dans l'Arctique canadien, l'efficacité du renouvellement afin de réduire le risque associé à la libération d'eau de ballast dans la région des eaux côtières, et les options pour l'échange d'eau de ballast par les navires circulant dans la zone économique exclusive.

BACKGROUND

The discharge 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. Historically, ballast water has been the predominant ship-mediated vector for aquatic nonindigenous species (NIS) introductions to Canada (Ricciardi 2001; de Lafontaine and Costan 2002). These species are not native to the ecosystem under consideration but may, under some circumstances, be capable of establishing viable populations or becoming invasive[1]. Current Ballast Water Control and Management Regulations (SOR/2011-137) registered on 2011-10-27, under the *Canada Shipping Act*, 2001 (S.C. 2001, c. 26) require transoceanic and coastal vessels that travel outside Canada's Exclusive Economic Zone (EEZ) to exchange their ballast water (Figure 1). The objectives of this exchange are:

1) to release foreign coastal biota where they are least likely to colonize Canadian coastal waters, and
2) to replace them with oceanic species that are less likely to survive when the vessels discharge their ballast into Canadian coastal waters (Levings et al. 2004; Simard and Hardy 2004).

Current ballast water regulations apply to ships entering Canadian waters from outside the EEZ. Ships that operate exclusively in waters under Canadian jurisdiction are exempt from regulations on ballast water exchange, so whether or where ballast water is exchanged for these vessels is not regulated. Their ballast water poses an unknown but potentially important pathway for the transfer of NIS within Canadian waters (Lavoie et al. 1999; Levings et al. 2004; see also Ruiz and Reid 2007, NRC 2008, Casas-Monroy et al. 2014). Residual water and sediment in loaded vessels that require little ballast can also serve as a reservoir for non-indigenous species (Johengen et al. 2005). Flushing these tanks with saltwater may lower the abundance of these species (Bailey et al. 2007) but is only required under the regulations (Sec. 5) for vessels entering the Great Lakes.

Ballast water exchange is considered an interim solution to the ballast water problem (NRC 1996, 2008; Levings et al. 2004; Bailey et al. 2007; Ruiz and Reid 2007). Once the International Convention for the Control and Management of Ships' Ballast Water and Sediments, that was adopted by the International Maritime Organization (IMO) in 2004, has been fully ratified, vessels originating from outside Canada's EEZ will be required to treat their ballast water to reduce risks of NIS (IMO 2013), however treatment may not necessarily be effective for all species, particular some types of phytoplankton (Casas-Monroy et al. 2014). In the future, some Arctic-bound vessels may opt to conduct mid-ocean ballast water exchange and then treat their ballast tanks to further reduce the risk of species introductions (BIMC 2012).

The effectiveness of ballast water exchange as a means of reducing the risk of species introductions depends upon the exchange being complete, and on maximizing differences between intake and discharge environments. Optimally, water and biota loaded from shallow, warm, brackish coastal waters during ballasting is released into deep, cold, marine offshore waters during exchange. Ballast water exchange is an effective method for reducing the initial coastal and freshwater plankton assemblages in ballast tanks (by an average of 80-99%) (Gray et al. 2007; Ruiz and Reid 2007; Ruiz et al. 2007; see also Locke et al. 1993; Levings et al.

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

2004; Johengen et al. 2005). However, when natural mortality observed in control tanks is considered, the efficacy of exchange alone can be much lower (29-40% for microplankton, 23-54% for zooplankton) (Simard et al. 2011). Little is known about the survival rates of the biota that are discharged during exchange.

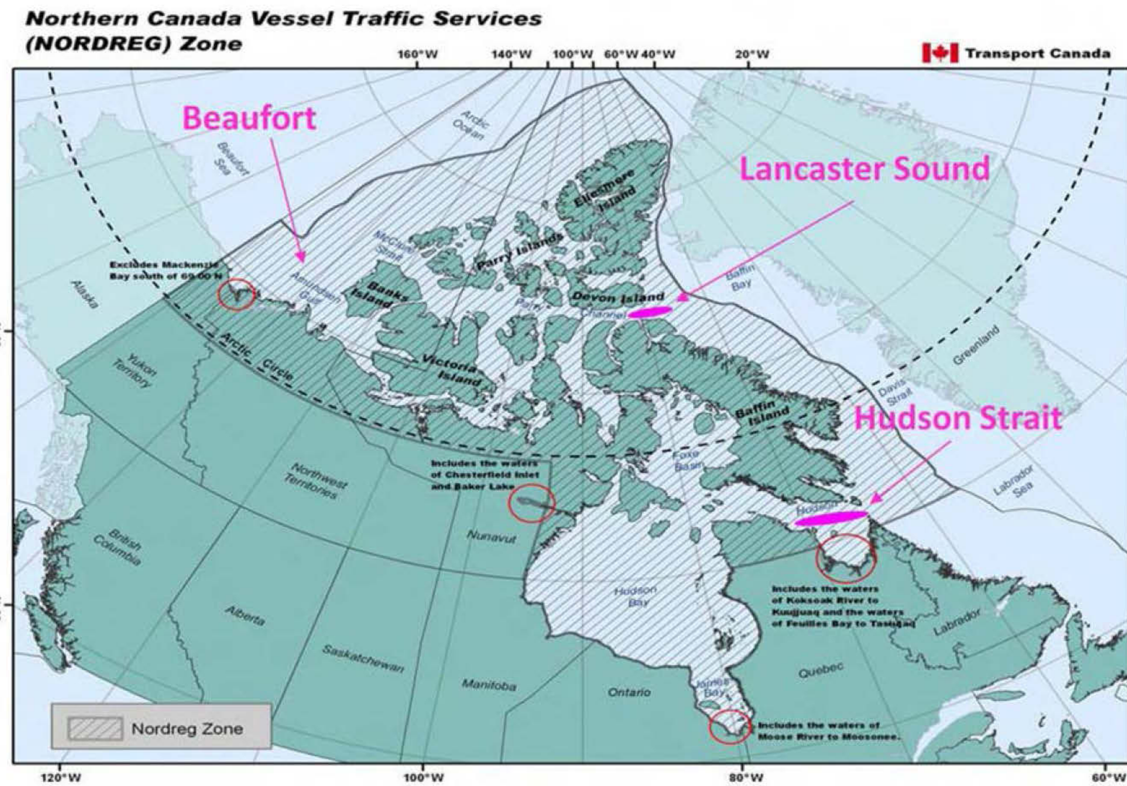

Figure 1. Locations of current alternate ballast water exchange zones (ABWEZ) within the NORDREG zone in the eastern Canadian Arctic. The NORDREG zone was established under The Northern Canada Vessel Traffic Services Zone Regulations and extends to the seaward limit of Canada's Exclusive Economic Zone (EEZ). Under these regulations certain vessels must report information before entering, while navigating within, and upon exiting Canada's northern waters.

The fate of biota released during ballast water exchange becomes increasingly important when ships are unable to exchange their ballast outside the EEZ and do so within Canadian waters. This can occur when inclement weather or other safety concerns prevent exchange outside the EEZ. In such cases ships are authorized to conduct their exchange in an alternate ballast water exchange zone (ABWEZ) within Canadian waters[2]. Two such zones have been designated for use by vessels from outside the EEZ westbound to ports in eastern Canada north of 60°N latitude, one in Lancaster Sound and the other in Hudson Strait (Figures 1 and 2). Neither zone was established on the basis of a scientific assessment. An assessment of the Hudson Strait ABWEZ by Fisheries and Oceans Canada (DFO) in 2009 recommended a broader geographic area to the east of Hudson Strait, including the Labrador Sea, be assessed and that it should incorporate oceanographic modelling of dispersion patterns (DFO 2010). The Lancaster Sound ABWEZ was not considered in the 2009 review.

[2] Ballast Water Control and Management Regulations

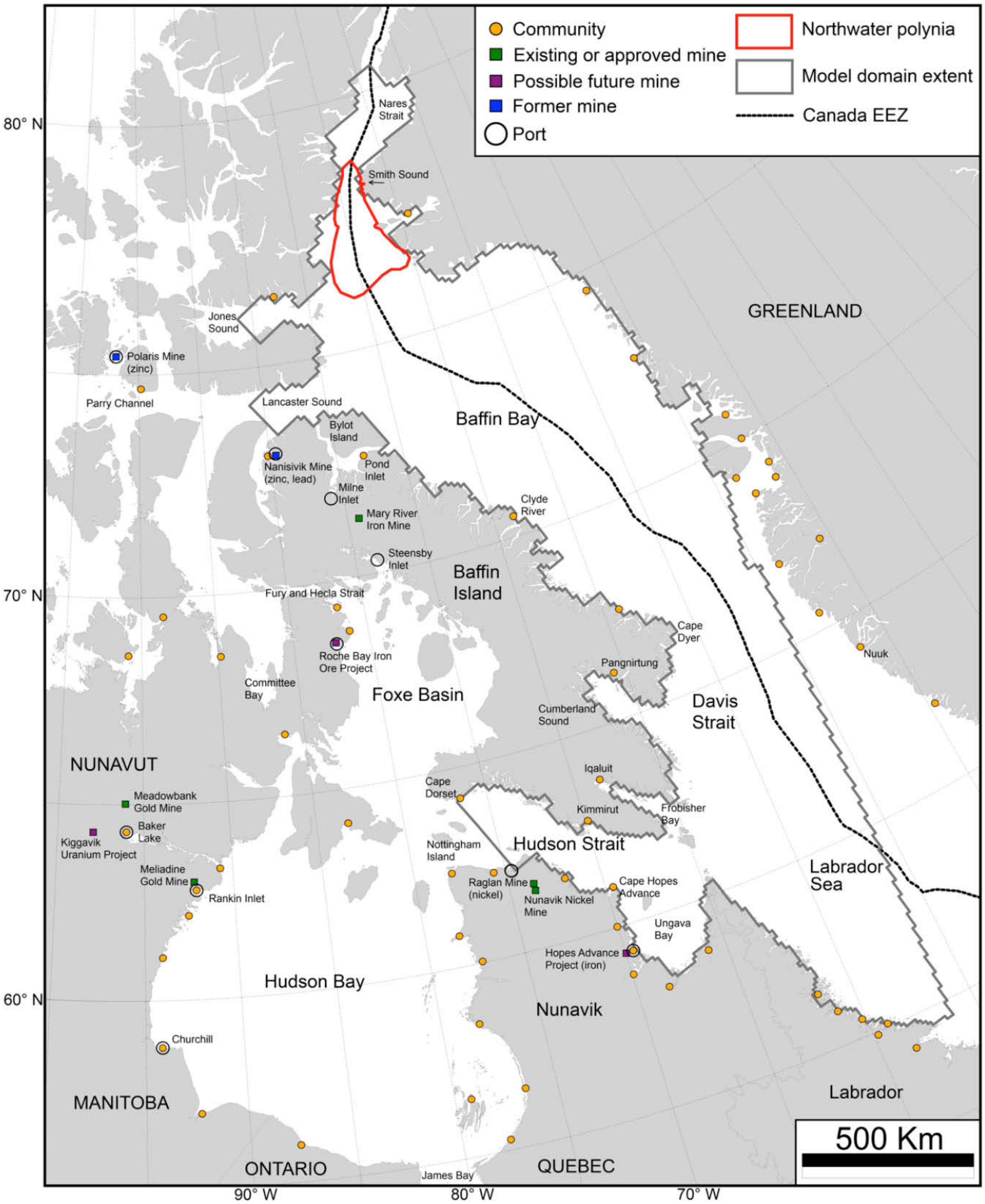

Figure 2. Place names in the Canadian Eastern Arctic.

Vessels that require ABWEZs will release ballast water from coastal ports into the upper 20 m of the Arctic water layer, where it will be diluted and dispersed. Biota in the released water should be small, with limited mobility relative to their transport by currents. Their fates following discharge mid-ocean or into ABWEZs are poorly known. Some organisms will suffer osmotic or thermal shock and die at or shortly after release. Others may descend in the water column, where their survival will be determined by their ability to withstand deep water conditions characterized by higher salinity, lower temperature, and lower light conditions than are common in coastal ports. The remainder will survive following release and be transported by surface currents. It is these latter organisms that are most likely to reach favourable coastal environments and have the potential to establish reproducing populations.

The impact of introduced species on the receiving ecosystem can be severe and widespread. 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, introducing parasites or diseases to which they have little resistance, and/or the uncoupling of important biological linkages (e.g., Carlton 1992; NRC 1996; Hallegraeff 1998; Claudia et al. 2002; Sax et al. 2007). 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 structure and function.

The potential for introductions will increase as ship traffic into the eastern Canadian Arctic, including the Hudson Bay complex[3], increases in response to the growing demand for resources, and to improvements in access related to climate change (Smith and Stephenson 2013; Stephenson et al. 2013). Little is known about what species might be introduced, their ability to establish, or potential impacts to indigenous species. Consequently, the ABWEZs must be situated in areas where species released in ballast water are least likely to reach coastal environments and where the conditions are least likely to favour their survival and establishment.

This work evaluates the suitability of existing ABWEZs in Lancaster Sound and Hudson Strait using a semi-quantitative model to assess relative risk from ballast water dispersion along major vessel tracks into the Canadian eastern Arctic. Recommendations are made regarding the suitability of the existing ABWEZs and preferred locations for ABWEZs. The objective is to identify areas where ballast water exchange is least likely to introduce NIS and thereby to avoid potential ecological damage.

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 discharge site. It is also affected by intrinsic and extrinsic biological factors but these are very complex. Because the eastern Canadian Arctic is vast, remote and seasonally ice covered, the level of oceanographic research effort, particularly in nearshore coastal waters, has been very low relative to the Atlantic and Pacific regions of Canada. This limits understanding of many key processes, particularly with respect to seasonal and inter-annual change, and it limits modelling potential. Depth, circulation, sea surface temperature (SST), sea surface salinity (SSS), and length of the open water season (OW) have sufficient data to enable modelling. Each of these parameters affects the ability of biota released at the surface to establish and is discussed below.

Bathymetry

Marine species have depth preferences based on their ecological requirements for completing key life processes. Each species has different requirements or tolerances for light, oxygen, pressure, substrate, temperature, salinity, etc. Plants, for example, are confined largely to the euphotic zone as they require light for photosynthesis, although some plants require more light

[3] The Hudson Bay complex includes Hudson Strait, Ungava Bay, Foxe Basin, Hudson Bay, and James Bay. It is one of a system of large marine ecosystems (LMEs) that have been identified worldwide.

or different wavelengths of light than others. Some invertebrates and fishes feed by sight, while others can feed in total darkness at greater depths. Birds and mammals require surface access to breathe air, whereas invertebrates and fishes require well-oxygenated water. Nearshore bathymetry is often an extension of coastal features that reflect differences in the underlying geology and there is typically a fining trend in the grain size of bottom sediments with depth (e.g., Grant 1971; Thomson 1982).

Ships unloading in foreign ports take their ballast from relatively shallow coastal waters (Stewart and Howland 2009), consequently most entrained species in their ballast water are well-adapted to shallow coastal waters. They are more likely to survive and establish at similar depths. In the context of this study, the depth preferences of benthic invertebrates are perhaps most important, as these species are often transported by ballast water (Reise 1999; Gollasch et al. 2009; Gooijer 2010) and their survival depends on access to suitable depths after ballast release.

Vessels enroute from the south and east to ports in the eastern Canadian Arctic progress from deep oceanic waters into shallow coastal waters (Figure 3). Their ballast water exchange location determines whether the biota they release remain over deep bottoms or disperse over a broad range of bottom depths and into shallow coastal waters where the risk of establishment is greater. The main eastern approach for both international and domestic vessel traffic to the eastern Canadian Arctic is from the Atlantic Ocean via the Labrador Sea. The sea extends north via Davis Strait (60°-70°N) and Baffin Bay (>70°N to the Lincoln Sea [82°30' N, 62°00' W]), separating Greenland from Canada. It penetrates deep into southeastern Baffin Island as Cumberland Sound and Frobisher Bay, and is connected to the Hudson Bay complex by Hudson Strait.

Aspects of bathymetry linked to the risk of ballast-mediated transfer of NIS include:

1) extent of deep, offshore water,
2) presence of shallow sills,
3) abruptness of the shelf break, and
4) width and depth of the coastal shelf (Figure 3).

Within the EEZ there is a broad corridor of water over 500 m deep that extends from the Labrador Sea north through central Davis Strait and Baffin Bay, and west into Lancaster Sound. This corridor is deepest and most extensive in the southeastern Labrador Sea (about 3,400 m deep) and central Baffin Bay (about 2,000 m). The depth decreases and the width narrows in central Davis Strait where it crosses the Canada-Greenland Ridge, a sill about 650 m deep that extends across Davis Strait from Baffin Island to Greenland, separating the deep basin of Baffin Bay from the Labrador Sea (Tang et al. 2004; Jørgensen et al. 2005). This ridge is a significant feature of the ocean bottom affecting Canadian sea ice regimes, as deep waters to the south provide a reservoir of heat energy that can readily reach the surface and melt ice incursions (Canadian Ice Service 2011). The corridor depth decreases to about 800 m at the entrance to Lancaster Sound. Depth within Lancaster Sound decreases to 150 m south of Bathurst Island (75°45' N, 100°00' W). Smaller deep-water basins (about 1,000 m) are present in Cumberland Sound and eastern Hudson Strait however shallower sills (about 300-400 m) separate them from the main deep corridor and limit deep-water exchange (Drinkwater 1986).

Figure 3. Summer circulation of water in the eastern Canadian Arctic (adapted from Fisheries and Oceans Canada poster 8: Eastern Canadian Arctic). BIC = Baffin Island Current, LC = Labrador Current, WGC = West Greenland Current.

Coastal shelves in the Arctic are important sites of ice formation (Polyak et al. 2010). They can also provide relatively broad areas for the establishment of benthic marine plant and animal communities and benthic habitats that are accessible to foraging marine mammals and diving birds. The width of the coastal shelf and depth of the shelf break along the continental margin are both variable, and the slope from the shelf break to the seafloor is typically steep. The continental shelf east of Labrador (Labrador Shelf) is about 150 km wide with shallow offshore banks, <200 m deep, separated by deep canyons (Sikumiut Environmental Management Ltd. 2008). The shelf break occurs at depths of 120 to 200 m off the banks, and depths of up to 500 m off the canyons (Piper 1987). The shelf break off Hudson Strait is at about 650 m, rising to about 500 m deep southeast of Baffin Island (southeast Baffin Shelf). Northeast of Baffin Island the continental shelf (northeast Baffin Shelf) is typically less than 60 km wide with a shelf break at about 300 m depth off the banks, and between 300 and 500 m off the deeper canyons that separate the banks. Farther north the coastline is steep so the area covered by shelf depths <200 m is small. The slope break off eastern Lancaster Sound occurs at about 1000 m.

The Hudson Bay complex, which in recent years has been the main destination for ships travelling to the eastern Canadian Arctic in ballast, is remarkably shallow for such a large area (Stewart and Barber 2010). Most of Foxe Basin, wide bands along the coasts of Hudson and Ungava bays, and all of James Bay are less than 100 m deep and often less than 20 m deep. Only Hudson Strait and Ungava Bay have extensive areas with depths over 300 m.

Circulation and Water Mass Characteristics

The physical and chemical characteristics of eastern Arctic waters will determine where biota released by ballast water discharge end up, how quickly they are transported, and whether they survive and are able to establish self-sustaining populations. These key aspects of invasion risk are related particularly to the circulation, water temperature, and salinity, all of which vary spatially and seasonally.

Surface circulation in the eastern Canadian Arctic is affected by inflow from the Arctic and Atlantic oceans (Figure 3). Arctic water that flows into the region originates mostly from the Pacific Ocean, via Bering Strait (Jones et al. 2003; McLaughlin et al. 2006). This relatively fresh, nutrient-rich water is cooled as it flows east through the Canadian Arctic Archipelago (Figure 4). It occupies the upper water column, overlying more saline, warmer waters of Atlantic origin. Most water flowing into Baffin Bay through Nares Strait, Jones Sound, and Lancaster Sound is Arctic water of Pacific origin. This water forms the Baffin Island Current that flows south via western Baffin Bay. Water flowing through Fury and Hecla Strait into Foxe Basin is also Arctic water of Pacific origin. As it flows to the Labrador Sea via Hudson Bay and southern Hudson Strait, it is diluted by freshwater runoff and mixes with water from the Baffin Island Current.

A small volume of Atlantic water enters northern Baffin Bay along the floor of Nares Strait (Münchow et al. 2011), but most enters from the south along the west coast of Greenland (Tang et al. 2004). The latter flow forms the West Greenland Current, which bifurcates in eastern Davis Strait. This current carries Atlantic water north along the Greenland coast as far as Smith Sound and mixes with Arctic water in Baffin Bay and northern Davis Strait. The largest branch of this current crosses central Davis Strait, where it joins the Baffin Island Current and outflow from Hudson Strait to form the Labrador Current, which flows south over the break and upper slope of the Labrador Shelf (Loder et al. 1998). Thermal oceanic fronts form where the shelf and oceanic water masses meet (Belkin et al. 2009).

Together the inflows of Arctic and Atlantic water create a cyclonic current pattern in Baffin Bay (Tang et al. 2004). Currents in deep water layers (at depths up to 1000 m) are consistently

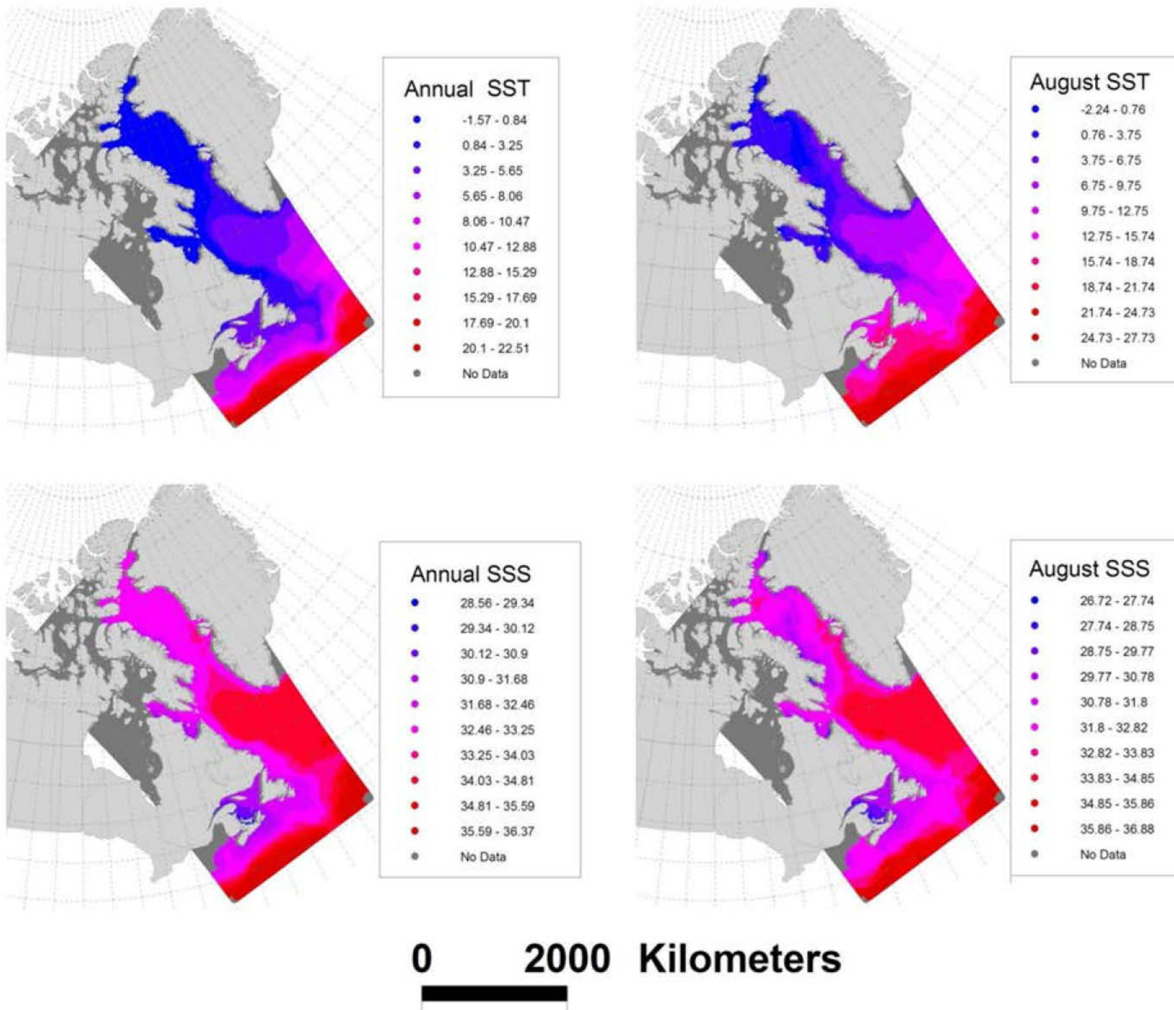

Figure 4. Mean annual and mean August sea surface temperature (SST) and sea surface salinity (SSS) (data from CECOM model courtesy of Y. Wu, DFO).

stronger than surface currents, although currents tend to be stronger at all depths in summer and fall than in winter and spring. In Davis Strait, the maximum observed currents including tidal and non-tidal components are found in the upper layer (10-50 m) near the Baffin Island (1.9-2.6 m/s) and Greenland (1.5-1.9 m/s) coasts, with slower currents in the surface (1.4 m/s) and deep (0.6 m/s; 300-500 m) layers of the central Strait (Wu et al. 2013).

Cold, saline (32.5 – 33.5 psu[4]) water from the Baffin Island Current flows northwest into the Hudson Bay complex along the north side of Hudson Strait (Drinkwater 1988; Straneo and Saucier 2008a, b). 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 1986). The rest crosses the Strait to join warmer, less saline

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[4] PSU = practical salinity unit, a dimensionless measurement of salinity that is based on electrical conductivity and roughly equivalent to chemical measurements of salinity that are reported in mg/L or parts per thousand (ppt).

water from Hudson Bay (<30 psu) and Foxe Basin (<32 psu) 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 3) (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 of Hudson Strait is a maximum of 0.3 m/s in the Cape Hopes Advance area (Drinkwater 1988). This current is forced by freshwater from spring runoff and the melting of sea ice (Straneo and Saucier 2008b). This forcing is seasonal (June to March), due to the time it takes currents to transport the freshwater from Hudson Bay and James Bay to eastern Hudson Strait, and peaks as the freshest waters pass in November and December. 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 (Figures 5 and 6) (Drinkwater 1988). Vertical mixing is intense near the eastern entrance of Hudson Strait (Collin and Dunbar 1964). The combined flow, with Arctic properties of low temperature and salinity, feeds into the Labrador Current at the north end of the Labrador Shelf and is carried southward to influence the coastal ocean climates of Atlantic Canada (Stewart and Lockhart 2005).

Tang et al. (2004) identified three distinct water masses or layers in Baffin Bay. The upper layer is comprised of cold, dilute Arctic water and is of greatest interest for ballast water exchange (Figure 7). Within Baffin Bay this layer extends down to the temperature minimum that occurs near a salinity of 33.7 psu; the upper layer is shallower (about 100 m) in the northeast and deeper (about 300 m) in the northwest. Water in the upper 100 m follows an annual cycle of surface dilution from runoff and ice melt in the spring; solar warming and wind mixing in summer; fall and winter cooling with ice formation that creates a surface barrier to wind mixing and sequesters fresh water, releasing salt into the water column; and winter convection that mixes the surface waters to a depth of about 100 m. This mixing carries nutrients into the surface waters where they are used for primary production, and the cycle repeats itself each spring.

The greatest seasonal variability in temperature and salinity in Baffin Bay is found in the upper 300 m of eastern Davis Strait, northern Baffin Bay and the mouth of Lancaster Sound (Tang et al. 2004). Arctic water below 100 m maintains a narrow range of salinity and temperature year-round. The Arctic water layer exits Baffin Bay on the western side of Davis Strait. The West Greenland Intermediate Layer that underlies the Arctic layer between 300 and 800 m is relatively warm (>0°C) and salty (>34 psu) (Tang et al. 2004). This water enters the region primarily via eastern Davis Strait and cools as it circulates around Baffin Bay. Beneath the West Greenland Intermediate Layer, the Baffin Bay Deep Water Layer has a nearly constant salinity of about 34.5 psu to the bottom, with temperature that declines with depth to about -0.5°C.

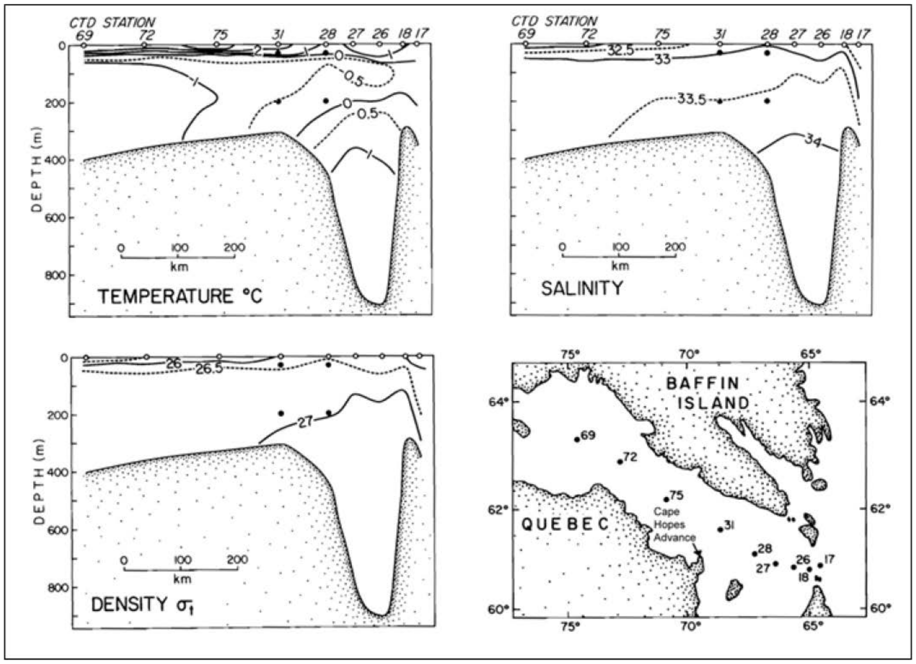

Figure 5. Summer temperature, salinity and density along a transect parallel to the axis of Hudson Strait (from Drinkwater 1988, p. 258).

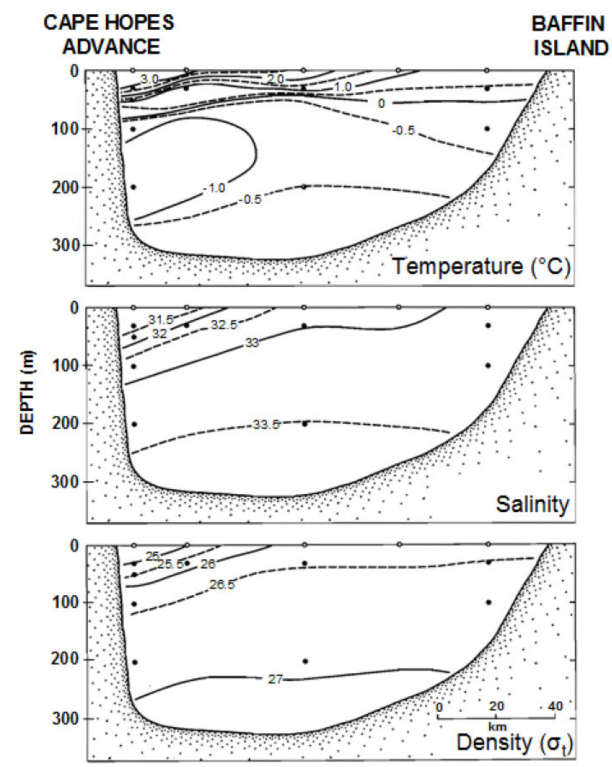

Figure 6. Summer temperature, salinity, and density across Hudson Strait from Cape Hopes Advance to Baffin Island (modified from Drinkwater 1988). See Fig. 5 for location of Cape Hopes Advance.

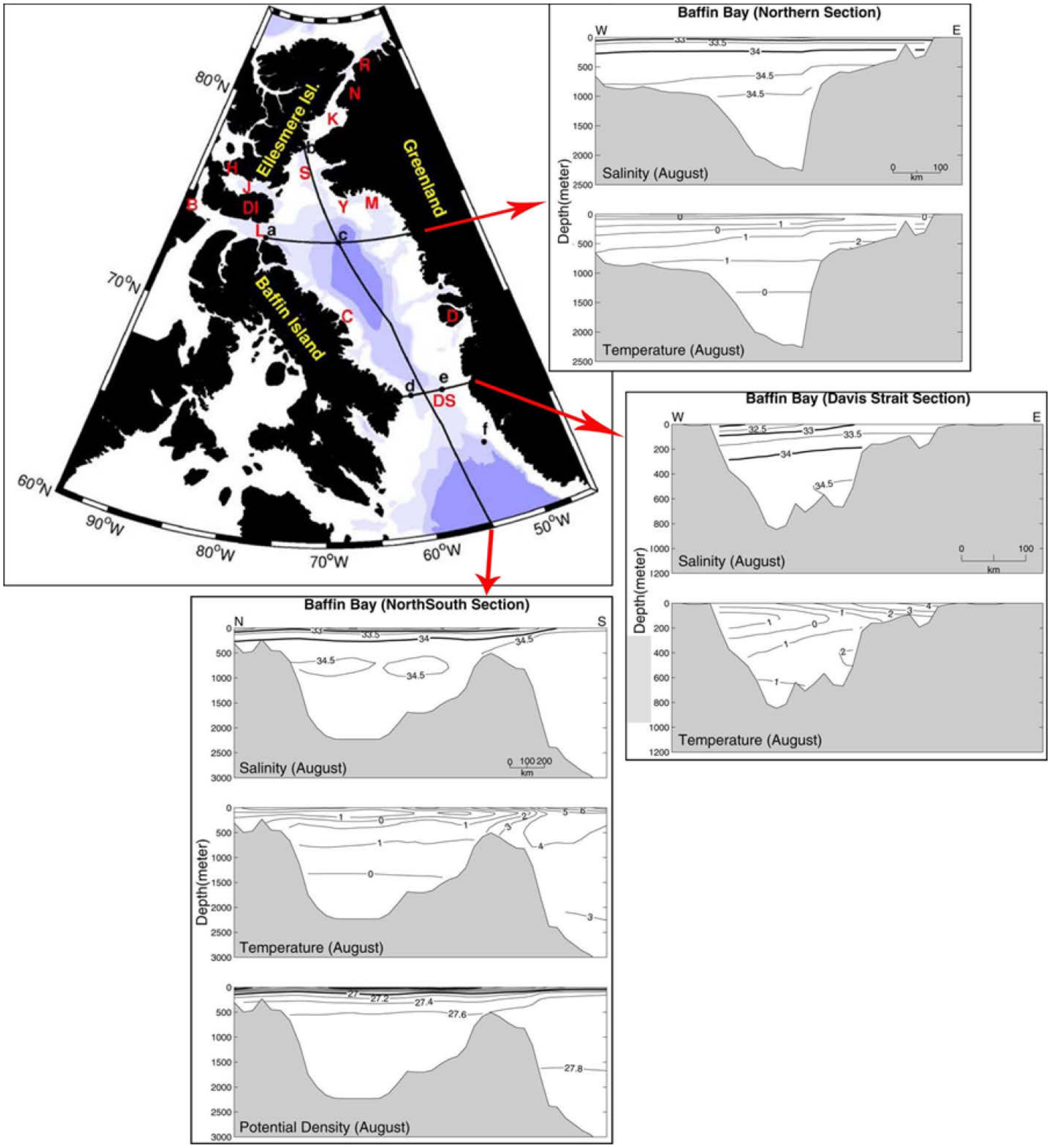

Figure 7. Salinity and temperature (°C) sections in August from west to east across northern Baffin Bay (73.86°N) and Davis Strait (66.6°N) and from north to south along Baffin Bay and Davis Strait, including potential density (from Tang et al. 2004).

Sea Ice

Sea ice strongly affects the region's physical and biological oceanography, the surrounding land, and human activities (Stewart and Barber 2010). 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. Aspects of sea ice cover of particular interest from the perspective of ballast water risk include:

1) the presence and duration of seasonal ice cover,
2) the amount and quality of ice present, and
3) the presence of persistent areas of open water (e.g., flaw leads, polynias).

Most waters along the main ship tracks in the eastern Canadian Arctic are seasonally ice–covered (Figures 8 and 9; Canadian Ice Service 2011). Depending upon weather conditions, the timing of freeze-up or breakup may be delayed or advanced by up to a month, but the basic pattern of ice formation is similar from year-to-year. Ice concentrations are typically at their minimum in mid-September; sometimes ice persists year-round in southwestern Foxe Basin, Committee Bay, and northern Baffin Bay (Figure 8). As the year progresses the ice cover expands from northwest to southeast, reaching its maximum extent around 1 April when all but eastern Davis Strait and the northeastern Labrador Sea are ice-covered (Canadian Ice Service 2011). Both the landfast and pack ice consist predominately of thick first-year ice.

Landfast ice that forms along the coasts is most extensive in sheltered bays and sounds, and along shallow coasts with extensive shoreline development *(*i.e., irregular) (Figure 9). This ice can continue to thicken and increase in volume until mid-June in the south and late June in the north (Table 1).

Table 1. Maximum thickness (cm) of landfast ice over the period 1959-1999 from Canadian Ice Service, Ice Thickness Program Collection, 1947-2002.

Community	Years (#)	Mean (SD)	Range	Dates
Cape Dorset	21	149 (19)	117-183	March 26-June 14
Iqaluit	39	168 (20)	110-202	March 28-June 12
Clyde River	33	170 (21)	133-210	April 24-June 30
Pond Inlet	18	167 (23)	120-199	April 30-June 22

Offshore the landfast ice and steeper, exposed coastlines, the pack ice continues to move throughout the winter. Modelling indicates that the pack ice continues to thicken after reaching its maximum extent. Modelling results for the end of May 2011, indicate that the pack ice was thickest (2.5-3.0 m) along the Baffin coast north of Clyde River; thick (2-2.5 m) throughout western and central Baffin Bay, Lancaster Sound, Foxe Basin and northeastern Hudson Bay; thinner (0.5-1.5 m) in eastern Baffin Bay, western Davis Strait, western Labrador Sea, and Hudson Strait; and, largely absent from eastern Davis Strait and much of the Labrador Sea. As in Hudson Bay (Prinsenberg 1988), ice ridging may add significantly to the ice volume (Ingram and Prinsenberg 1998).

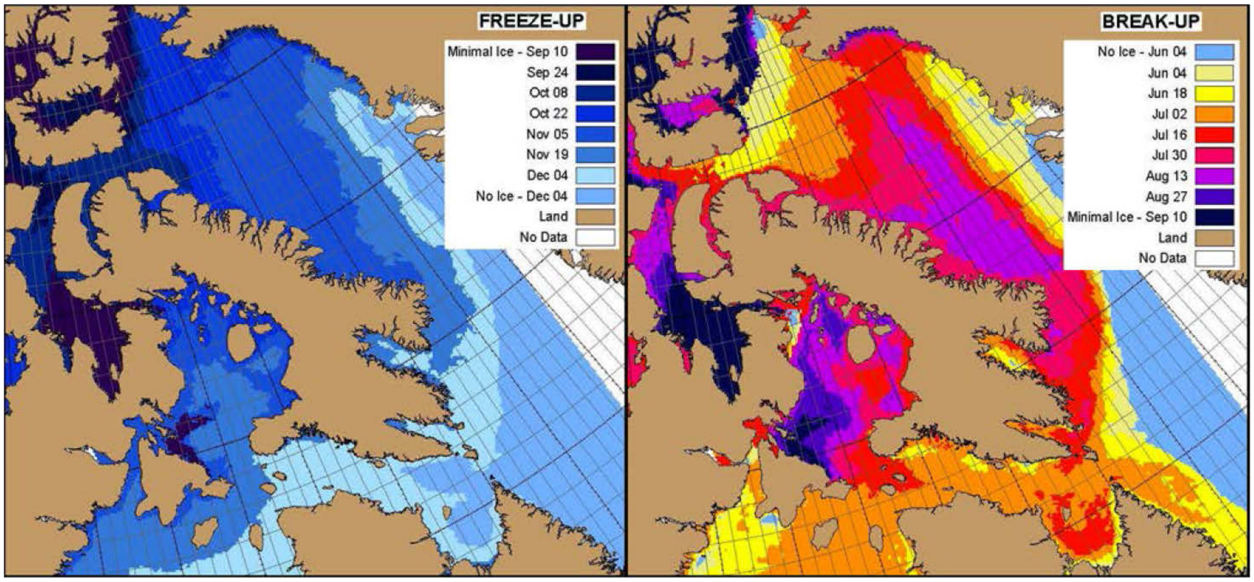

Figure 8. Ice formation (left) and breakup (right) in the eastern Canadian Arctic based on the median of ice concentration over the 30-year period 1981 to 2010 (from Canadian Ice Service 2011).

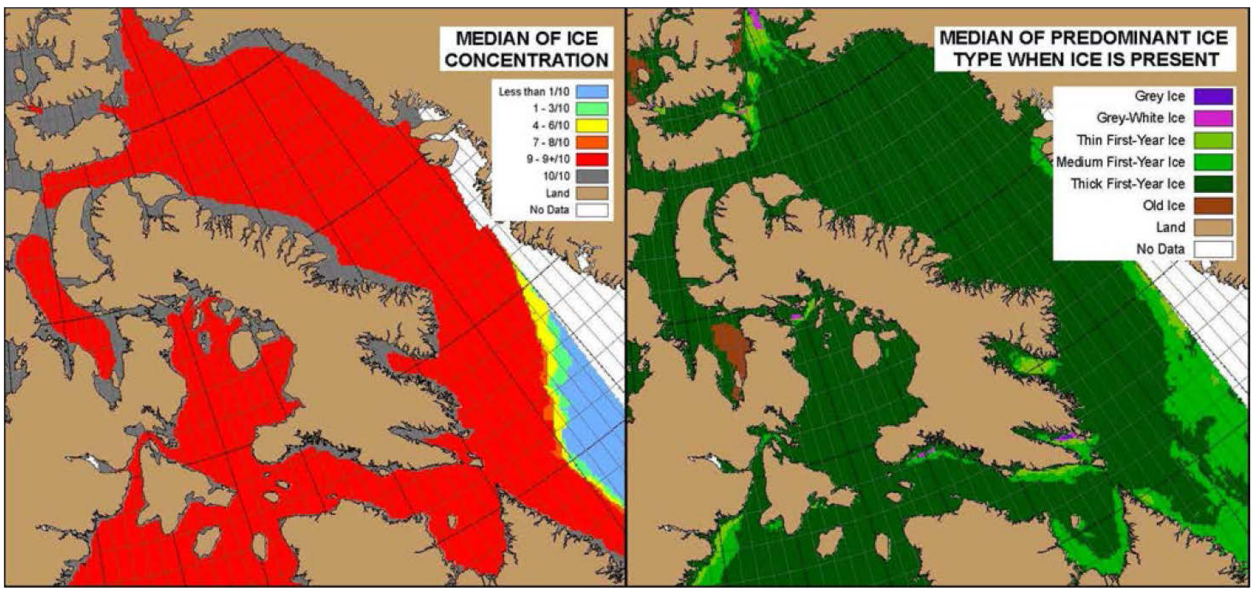

Figure 9. Median of sea ice concentration (left) and of predominant ice type when ice is present (right) in the eastern Canadian Arctic on 1 April over the 30-year period 1981 to 2010 (from Canadian Ice Service 2011). Landfast ice is shown in grey (i.e., left panel: 10/10ths). Polynias and persistent flaw leads appear within the Thick First-Year Ice (right panel) as Grey Ice to Thin First-Year ice.

Polynias and flaw leads, characterized by thin ice and persistent open water, are vitally important to overwintering species and early spring migrants (Stirling and Cleator 1981; Stirling 1997). These open water areas are particularly well-developed in the North Water polynia of northern Baffin Bay; at the mouths of Frobisher Bay and Cumberland, Lancaster and Jones sounds; near Coburg Island (75°57' N, 79°26' W); in northwestern Hudson Strait; and in northern Foxe Basin (Figure 9, see Figure 2 for place names). The presence of polynias strongly affects biological processes by increasing underwater light levels, breaking down water-column stratification, increasing the rate of nutrient renewal in the surface waters, and advancing the timing of production cycles (Ingram et al. 2002). Ice surrounding these openings provides an important platform for resting birds and mammals, providing access to both air and water, and the ice edges are important sites of mixing that enhances productivity.

The North Water polynia develops when an “ice bridge” forms across Nares Strait, limiting the export of sea ice from the Lincoln Sea south into northern Baffin Bay (Barber et al. 2001). This polynia is maintained primarily by strong winds and currents that transport young ice southward as soon as it forms (Ingram et al. 2002). Sensible heat[5] makes a localized contribution to the open water during the fall, winter and spring along the Greenland side of the polynia. When the ice bridge breaks up in late June the concentration of ice in the North Water increases (Ingram et al. 2002). In 2007, when there was no ice bridge, the export of ice from the Arctic Ocean into northern Baffin Bay was about twice the 1997-2009 average (Kwok et al. 2010).

The North Water is characterized by enhanced heat loss from the sea to the atmosphere and by ice growth (Tang et al. 2004), as are the leads that form when winds and currents move ice away from the coasts (Hannah et al. 2009). Tidal currents appear to make important contributions to the dynamics of many recurring polynias in the eastern Canadian Arctic (Hannah et al. 2009), although their contributions have not been measured within the study area. Tidal mixing may enhance summer phytoplankton production in these areas.

Sea ice begins to decay in April, with breakup spreading gradually to the north and west starting in June from open water in southeastern Davis Strait and the Labrador Sea (Canadian Ice Service 2011). Ice breakup also progresses southward from the North Water (see also Barber et al. 2001). Snowmelt pools on consolidated ice surfaces while thin ice in the polynias melts. Breakup along the ship tracks is slowest in west-central Baffin Bay where ice often remains into mid-August, and in southwestern Foxe Basin and northwestern Baffin Bay where in many years not all ice has melted. Inter-annual variation in the ice extent is correlated to winter air temperature (Tang et al. 2004).

The southward transport of ice from Baffin Bay represents a large freshwater flux and a large heat sink to the water columns of Davis Strait and the Labrador Sea (Ingram and Prinsenberg 1998). Icebergs, particularly those produced by glaciers on the west coast of Greenland north of 68°30’N, also contribute to these effects (Marko et al. 1982; Newell 1993; Nazareth and Steensboe 1998; Karlsen et al. 2001). Grounding of icebergs is common along the coastal shelf of eastern Baffin Island (Marko et al. 1982).

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 Atlantic walruses (*Odobenus rosmarus rosmarus*). 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.

Tidal ranges and currents modify ice cover and its effects on biota. In coastal areas the tidal ranges are an important determinant of the vertical range of ice scour and the exposure of benthic habitats to drying and freezing. The tidal ranges in the eastern Arctic are typically 2 or more m with a maximum in excess of 15 m in Ungava Bay (see below). These ranges are much larger than in the Arctic Ocean or the western Canadian Arctic where ranges are typically of the order of 10 cm or so. Scouring and exposure should limit establishment of benthic biota adapted

[5] Sensible heat is the energy required to change the temperature of a substance without changing its phase (i.e., solid, liquid, gas). In contrast, latent heat is the energy required to change the phase of a substance (e.g., melt sea ice) without changing its temperature.

to warmer intertidal and sub-tidal waters, particularly species and life stages with low mobility. These effects are particularly strong along the southern coast of Baffin Island and coasts of Hudson Strait (Figure 10).

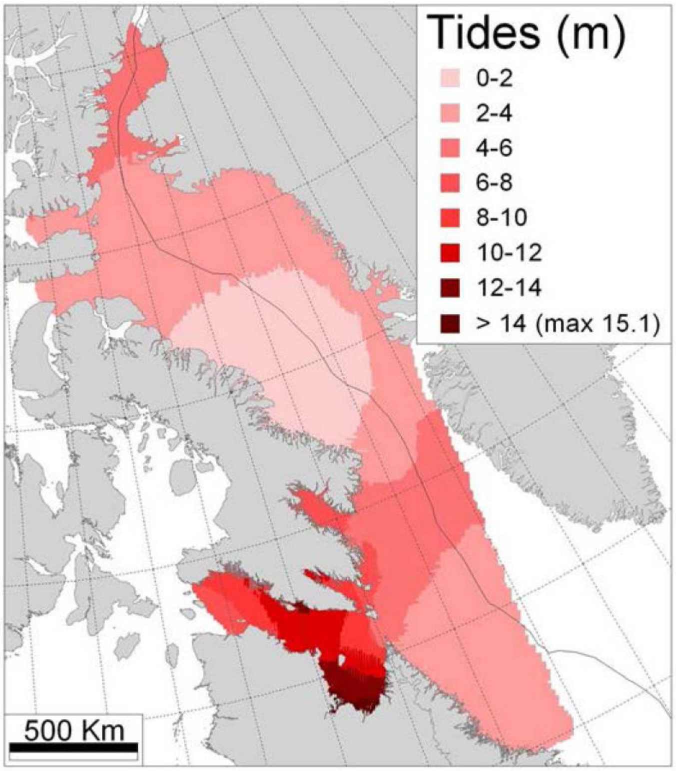

Figure 10. Tidal ranges in the eastern Canadian Arctic based on the WebTide Tidal Prediction Model. Data from the Arctic9 (Collins et al. 2011), Nwatl (Dupont et al. 2002), and Hudson (Saucier et al. 2004) models were merged to provide regional coverage. White areas were not considered or data deficient. The models tend to underestimate tides in extreme areas such as Ungava Bay.

In Leaf Bay (58°56' N, 69°05' W), at the head of Ungava Bay, the maximum recorded spring rise was 16.7 m, the highest in the world (Dohler 1968; NIMA 2002; Kuzyk et al. 2008). In Hudson Strait the spring tide range (i.e., twice the amplitude) 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.

Offshore of the scour zone, strong tidal currents that contribute to polynia formation may make it easier for some benthic and pelagic taxa to establish by maintaining open water areas year-round. The tides set up strong currents at the eastern entrance to Hudson Strait (up to 2 m/s; Drinkwater 1986). Polynias may form where currents exceed 1.5 m/s (Prinsenberg 1986). By eliminating the seasonal barrier to light penetration created by ice and snow cover and by mixing nutrients into the surface waters these currents could make it easier for some benthic and pelagic taxa to establish at polynias.

Since 1960, significant ($p \leq 0.05$) declines in summer sea ice coverage have been observed along the shipping routes through Hudson Bay (11% to 15% decade^{-1}) and along the southern route of the Northwest Passage (i.e., Coronation Gulf (68°08' N, 112°00' W); 6% to 10% decade^{-1}), the latter is linked to increases in early summer surface air temperature (Tivy et al. 2011). However, no significant trends were found between 1960 and 2008 along the northwestern Parry Channel route of the Northwest Passage. Due to changing ice conditions shipping use of the Northwest Passage will likely increase in the future (see also Smith and Stephenson 2013; Stephenson et al. 2013).

Modelling suggests that projected changes in climate might cause landfast ice in the eastern Canadian Arctic to decrease by 30 to 50 cm in maximum thickness and 1 to 2 months in duration by the years 2041-2060 and 2081-2100, respectively (Dumas et al. 2006). The thickness and duration of pack ice cover is also projected to decline (Steiner *et al*. 2013; Stephenson *et al*. 2013). These changes could have important ramifications for indigenous biota, shipping activities, and invasive species.

SHIPPING PATTERNS

Current shipping patterns within the eastern Canadian Arctic are likely to serve as a suitable indicator of future shipping patterns (Figure 11). There are limited options for navigating through this region due to the presence of islands and restricted corridors for entering the Hudson complex or the Northwest Passage. In contrast, current ballast water discharge volumes are expected to be a poor predictor of future discharges enroute to or within the eastern Canadian Arctic (Figure 12). This is because shipping from outside the EEZ into the region is likely to increase substantially during the next decade and even more by mid-century. These changes are being driven primarily by demand for mineral resources and by climate change. More ballast water will be exchanged enroute. Most of these exchanges will occur outside the EEZ but when this is not possible exchange within an ABWEZ may be permitted. The objective of these exchanges is to minimize the release of biota from foreign coastal waters into Canadian coastal waters during ship loading. Individual discharges of ballast water at ports will be larger and more frequent and discharges in some coastal port areas will recur at short, regular intervals year-round over decades. Regardless of these changes, ABWEZs should offer effective emergency alternatives to open-ocean exchange while providing the best protection for eastern Arctic waters from species introductions.

Vessels that remain within the EEZ are not required to conduct mid-ocean exchange, so if in ballast they have the potential to transport water and entrained organisms directly from port to port.

Recent Past (2002-2012)

The annual volume of ballast water discharged at ports in the eastern Canadian Arctic has been low, (2005-2008 mean annual discharge 275,714 m^3) reflecting the region’s limited exports relative to Atlantic (42,486,855 m^3) and Pacific (2008 annual discharge 18,024,247 m^3) ports in Canada (Chan et al. 2012, Adams et al. 2013, Linley et al. 2014). Most ships that entered the eastern Canadian Arctic in ballast between 1998 and 2005, had last visited temperate ports but a few visited subarctic or tropical ports (Stewart and Howland 2009). At present and over the past decade, most vessels enroute to the region in ballast have entered from the east via Hudson Strait to load ore concentrate (Ni, Cu, Co) from the Raglan Mine at Deception Bay (62°09'39" N, 74°41'41" W) or grain at the Port of Churchill (Stewart and Howland 2009; Chan et al. 2012). In the past, ore concentrate (Zn, Pb) was also exported south via Lancaster Sound from the Polaris Mine on Little Cornwallis Island (1981-2002) and Nanisivik Mine on Baffin Island (1976-2002) (Harris 2002). In 2008, the Mary River Iron Mine project exported three bulk ore samples weighing a total of 113,225 t (tonnes) via Milne Inlet to ports in Europe (BIMC 2008). Merchant vessels loaded with cargo or fuel (e.g., sealift), cruise ships, fishing vessels, and government vessels (scientific, Coast Guard, navy) also visit the eastern Canadian Arctic. These vessels require less ballast water to ensure stability than the unloaded bulk carriers and often remain within Canada’s EEZ.

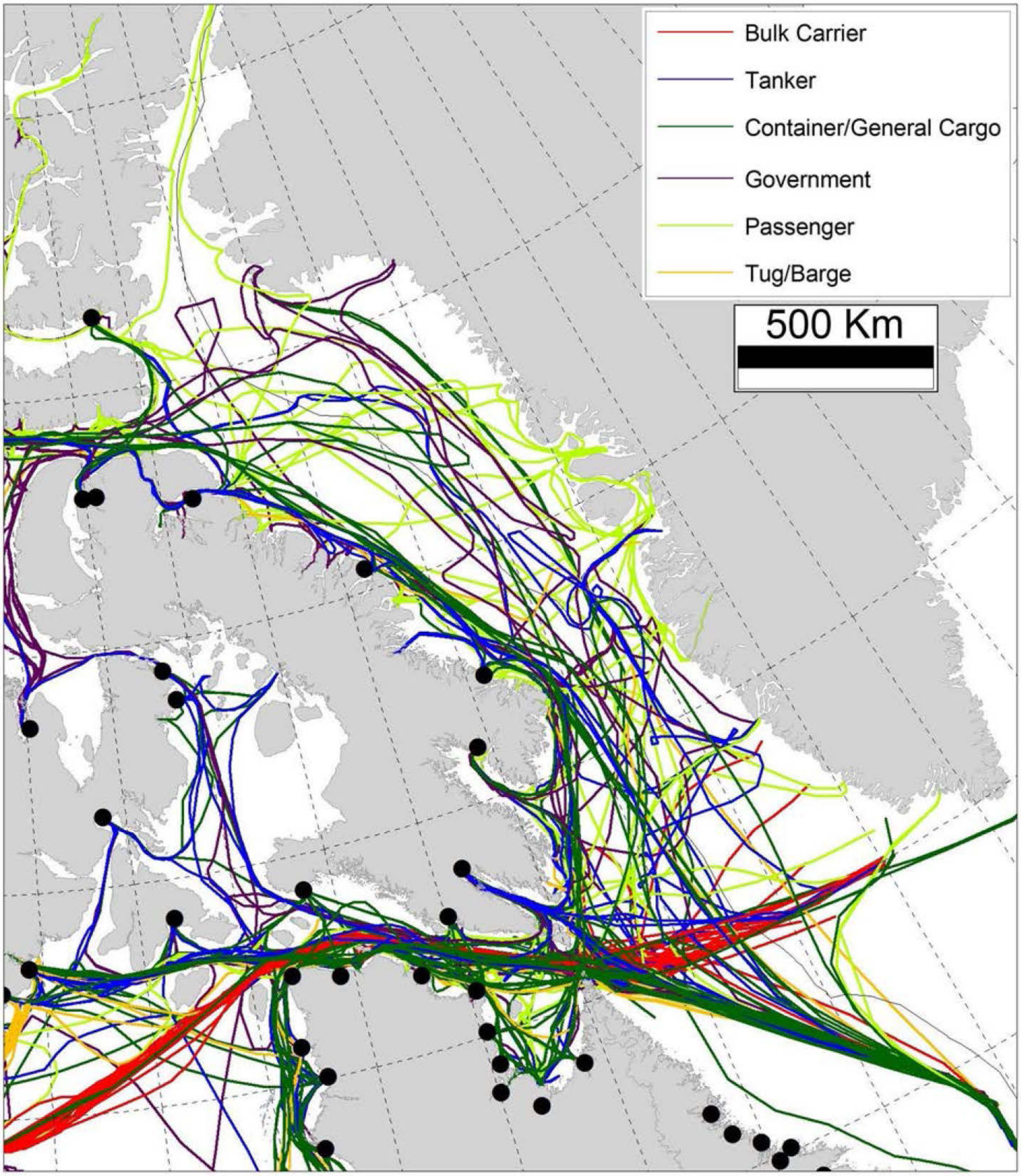

Figure 11. Ship tracks into the eastern Canadian Arctic during the 2010 shipping season, not including fishing vessels (data source: Transport Canada 2011 as cited in Gaston et al. 2013 online supplementary geospatial data).

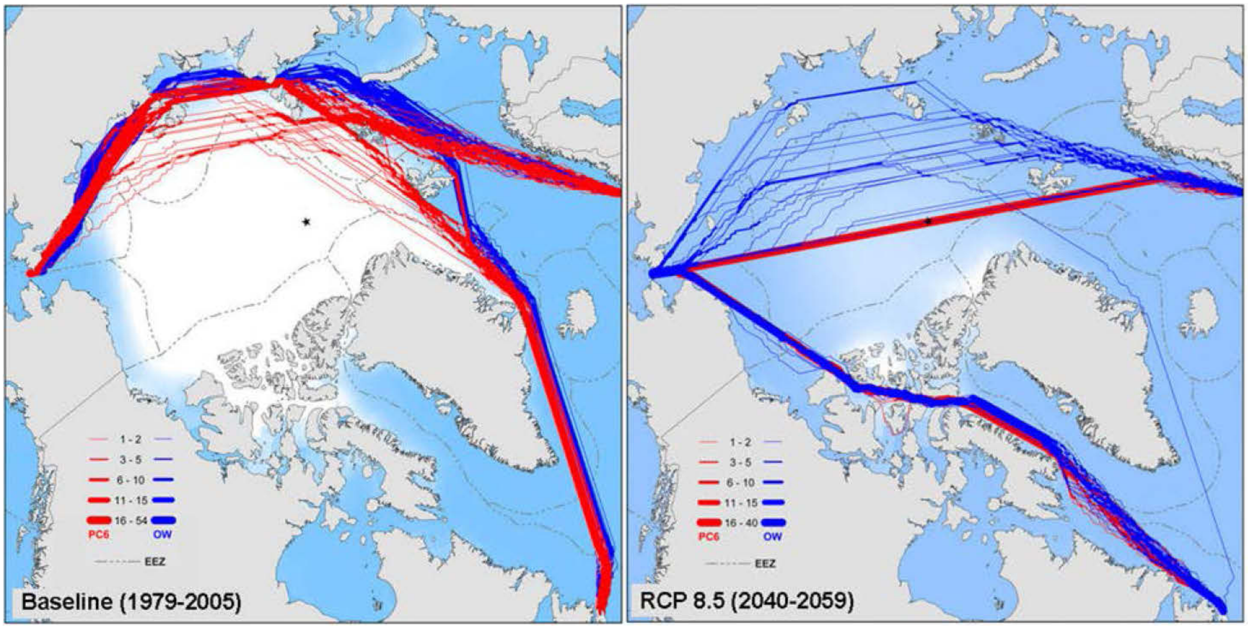

Figure 12. Optimal September navigation routes derived by modelling (Arctic Transportation Accessibility Model) for ships seeking to cross the Arctic Ocean Between the North Atlantic (Rotterdam and St. John's) and the Bering Strait. Left panel is for baseline conditions (1979-2005); right panel is for projections of sea ice concentration and thickness assuming high radiative forcing (RCP 8.5; ensemble average). Red Lines = fastest available trans-Arctic routes for Polar Class 6 icebreaking ships (PC6); blue lines = ditto for common open water (OW) ships. Where overlap occurs, line weights indicate the number of successful transits using the same navigation route. White Indicates period average sea ice concentration (Source: Smith and Stephenson 2013).

The Port of Churchill has been and remains the largest receiver of ballast water in the region (2005-2008 mean annual discharge 157,675 m^3) (Stewart and Howland 2009; Chan et al. 2012). Annual grain exports over the past decade (2003-2012) have averaged just over 0.450 million tonnes (Mt) (see Billinger 2012), with peak export of 0.816 Mt in 1977 (see Barker 2010). Vessels loading at the port arrive primarily from outside the EEZ, most are in ballast but some arrive loaded with cargo. Most exchange their ballast outside the EEZ, although exchange has occurred immediately east and west of Hudson Strait (Stewart and Howland 2009). This ballast water is then discharged in port as they load cargo.

In 2009, the Raglan Mine milled 1.3 Mt of ore to produce 172,668 t of ore concentrate (Ni, Cu, Co), which was transported to Quebec City by the *M.V. Arctic* (T. Keane, FedNav, pers. comm. 2012). This ice-breaking vessel remains in coastal waters but voluntarily exchanges ballast water on the trip north. It has a capacity of about 28,000 deadweight tonnes (DWT[6]), so the 2009 production would have taken about seven voyages to deliver.

Deception Bay and Churchill are connected to other locations in the region by merchant vessels that discharge ballast water (Stewart and Howland 2009; Chan et al. 2012). These connections could facilitate the transfer of nonindigenous species from these ports to other areas within the region. However, Iqaluit is more likely to serve as a hub for the spread of NIS within the region

[6] Deadweight tonnage (DWT) is the sum of the weight a ship is carrying or can safely carry, including cargo, fuel, fresh water, ballast water, provisions, passengers, and crew.

as it receives more ballast water from coastal domestic vessels that have not conducted mid-ocean exchange (Chan et al. 2012).

Next Decade (2013-2023)

Transfers of ballast water into the eastern Canadian Arctic will triple within the next decade (ca 2020) if the Mary River Iron Mine project on northern Baffin Island proceeds as approved by the Government of Canada (BIMC 2012, 2013; NIRB 2012, 2014). The project's "early revenue phase" plans to export 3.5 Mt of ore annually (as of 2016) during the summer via Milne Inlet to Rotterdam (BIMC 2013; NIRB 2014) but has approval to export up to 4.2 Mt/year. The planned Milne Inlet shipments would discharge about 662,000 m^3 of ballast water annually over the open water season, making Milne Inlet the top Arctic port at risk for aquatic NIS by both ballast water and hull fouling invasions (DFO 2014). The main project has been postponed until ca 2018 (BIMC 2013) but has government approval to export 18 Mt of iron ore annually over a period of at least 21 years (BIMC 2012; NIRB 2012). This would require 102 trips annually by ice-breaking vessels each capable of carrying about 180,000 t of ore. The ore would be loaded at Steensby Inlet in northern Foxe Basin and delivered to Rotterdam in the Netherlands. Project vessels enroute from Rotterdam are expected to conduct mid-ocean exchange of ballast water and then treat the ballast water they have loaded enroute before it is discharged into Foxe Basin or Steensby Inlet (BIMC 2012, v.10, app.10D-10, s.4.2 and app. 6; see also BIMC FEIS response to QIA-IR-D-02, p. 49 of 55). Treatment methods have yet to be determined and their efficacy under Arctic winter conditions is untested. Shipping would continue year-round with discharges of ballast at intervals of about every 43 h. The project Proponent has estimated the total annual discharge at 20.4×10^6 m^3/year (BIMC 2012, v.8, s.2.6.2.2, p.17, par. 4). This is about 70x greater than the average annual discharge of ballast water that Chan et al. (2012) reported at Canadian Arctic ports in 2005 through 2008 and exceeds the total annual discharge for the Pacific coast of Canada reported for 2008 (Linley et al. 2014). If the mine operates as planned the Steensby Inlet area would receive 3x more ballast water of foreign origin annually than the port of Sept-Îles, Québec (50°13' N, 66°23' W), which is currently the leading recipient of foreign ballast water on the east coast of Canada (see Adams et al. 2013).

Project expansions may further increase shipping exports from the region within the next decade. The Raglan Mine is constructing new underground mines and upgrading its facilities to increase production in 2016 by about 38% from 2009 levels (Xstrata Nickel 2011). This could increase the annual voyages required by the *M.V. Arctic* to about nine. The Mary River Iron Mine could also increase annual iron ore exports by 3.35 Mt without triggering further environmental review (i.e., 121 compared to 102 round trips annually; NIRB 2012:TC179), and it has numerous other iron deposits that may be mined either in sequence or in parallel.

New mining projects may also increase shipping exports from the region within the next decade. Canadian Royalties Inc., which is developing a nickel mining operation in Nunavik, shipped its first two loads of copper concentrate from Deception Bay in October-November 2013 (Canadian Royalties Inc. et al. 2013). The maximum output of the 4500 t/day crusher is about 1.65 Mt/annum, so if the efficiency is similar to Raglan and the ships have the same capacity this mine could also require about nine voyages annually (George 2012). A new icebreaking ore carrier, *M.V Nunavik*, has been built to service the mine (Nunatsiaq News 2014). This vessel is equipped with a ballast water treatment system.

A feasibility study has recently been released for mining the iron deposit at Roche Bay on Melville Peninsula (Advanced Explorations Inc. 2012; Saul et al. 2012). If it proceeds to development an additional about 8 Mt of iron ore could be shipped annually through southern Foxe Basin and Hudson Strait. Oceanic Iron Ore Inc. has proposed the Hopes Advance Iron Mine project southwest of Ungava Bay (Nunatsiaq News 2012a). This project is preparing for review by the Canadian Environmental Assessment Agency (CEAA). If approved, it could be in operation by 2016, shipping 10 to 20 Mt of ore concentrate annually for the next 48 years. A deepwater port facility would be built on Ungava Bay and operate during the open water season. The ore would be stockpiled at a fiord near Nuuk, Greenland for trans-oceanic shipment to China. Exploratory work is ongoing at another massive iron deposit in the Belcher Islands, which would also require marine shipping (Nunatsiaq News 2012b).

Within the next 5 years the number of ships visiting from temperate ports is likely to increase dramatically as the Mary River Iron Mine begins operation (NIRB 2012). More ships in ballast visit from the North Sea than from other large marine ecosystems (Stewart and Howland 2009), and this too will increase dramatically, since ships visiting the mine will be delivering their ore to the Port of Rotterdam (BIMC 2012). If the Hopes Advance Iron Mine project proceeds to operation, many more vessels could be visiting from Chinese ports within the next decade (Nunatsiaq News 2012a). The departure ports of vessels servicing other potential mining developments are uncertain.

There are a number of smaller initiatives that may alter ship traffic to eastern Arctic communities. In 2013, the first small craft harbour in Nunavut was completed at Pangnirtung to support the local fishing industry and enable larger vessels to dock and offload catches (CBC 2013). In 2014, the Rankin Inlet Harbour Corporation requested proposals for work to support development of a port facility planned for Rankin Inlet. Changes in government grain marketing policy may affect future grain exports from the Port of Churchill but the direction of that change is uncertain (Billinger 2012).

Mid-century (2040-2059)

Climatic warming is increasing the duration of the open water period, which improves seasonal access and lengthens the shipping season in Canadian Arctic waters (e.g., Parkinson and Cavalieri 2008; Hochheim and Barber 2010; Hochheim et al. 2011; Stroeve et al. 2012; Parkinson 2014). Climate model projections of sea ice properties driven by the representative concentration pathways (RCP[7]) 4.5 and RCP 8.5 climate-forcing scenarios suggest that this trend will continue (Smith and Stephenson 2013). These RCPs represent medium-low (+4.5 Watts/m^2) and high (+8.5 W/m^2) radiative forcing increases respectively. Currently, the navigation season for common open water vessels is near zero in much of Parry Channel (Stephenson et al. 2013). The modelling projections suggest that by mid-century (2040-2059) these vessels may be able to traverse the Northwest Passage for about 14 days of the summer under RCP 4.5 and 39 days under RCP 8.5 (Figure 12) This short period would limit use of the passage for trans-Arctic voyages by common open water vessels, but the change serves to illustrate the magnitude of the possible increase in vessel access.

If these projections are accurate the volume of ballast water exchanged mid-ocean or within the eastern Canadian Arctic will increase. Access to non-renewable mineral and hydrocarbon resources elsewhere in the eastern Canadian Arctic and the economics of their extraction will also improve, stimulating further development. Discharges by vessels loading non-renewable resources could increase substantially. Where current and planned shipments are to markets in the east, future shipments from the same developments could be redirected to markets in the west.

[7] Representative concentration pathways (RCPs) are greenhouse gas concentration trajectories used for climate modelling and research.

These projections have important ramifications for ABWEZs in the eastern Canadian Arctic. They suggest that the sea surface conditions, shipping patterns and volumes, origins of ballast water, and volumes exchanged mid-ocean or within the eastern Canadian Arctic could all change substantially. These uncertainties argue for a particularly precautionary approach to ABWEZ establishment, given that:

1) use of these zones may increase,
2) risk of cross-transfer of Atlantic and Pacific biota may increase, and
3) introduced biota may be more likely to survive as climate changes.

These ABWEZs may also be used in future by domestic coastal traffic to avoid unwanted species introductions (Stewart and Howland 2009).

INTRODUCTION

The vulnerability of indigenous biota in the Canadian eastern Arctic to species introduced through ballast water exchange or another vector will depend on the species introduced, and the ecological impacts, and linkages to the indigenous species (Stewart and Howland 2009). Optimally, exchange should take place where organisms released with ballast water are swept offshore into deep-water environments, rather than into shallow coastal areas that might provide more hospitable habitat for establishment of NIS entrained with ballast water from foreign ports. Relative to the Atlantic and Pacific coasts, very little is known of spatial and temporal patterns in the oceanography or ecology of the region. If shipping activities increase as expected in response to non-renewable resource developments and climate change, the use of ABWEZs is likely to increase, making the region more vulnerable to future invasions. This work assesses relative risk from ballast water dispersion along major vessel tracks into the Canadian eastern Arctic to identify optimal exchange areas for reducing the risk of ecological damage.

Risk is typically determined based on the likelihood (probability) of an event occurring and the magnitude of potential consequences (impacts) should that event occur (Mandrak et al. 2012). In the case of this study, quantitative assessment of risks associated with ballast water exchange requires knowledge of:

1) the likelihood of exposure of receiving habitats to NIS,
2) the likelihood of these NIS surviving and establishing reproducing populations, and
3) the potential impact of introduced NIS on the receiving ecosystem.

Since this quantitative information is mostly lacking for the eastern Canadian Arctic, the relative risks of exchange at different locations were considered using mathematical modelling. Such modelling requires broad, consistent regional coverage of important aspects of the environment that can be related to the transport and survival of organisms released with ballast water, and to the sensitivity of the receiving habitats.

To assess potential for exposure of receiving habitats to foreign biota, Brickman's (2006) semi-quantitative risk assessment model for dispersion of ballast water in shelf seas was adapted for use in the eastern Canadian Arctic (Figure 2). This involved using coupled ice-ocean models with atmospheric forcing to simulate the trajectories of particles released along ship tracks into the eastern Canadian Arctic. These hindcasts use rate of passive transport in surface waters (upper 5 m) under open water conditions to estimate arrival time (how long it takes particles to travel from a release site to a particular area) and frequency of occurrence (a combined measure of abundance and residence time for particles in a given area). These two metrics are used to calculate the relative likelihood that a particular receiving habitat may be exposed to NIS released in ballast water (relative likelihood of exposure).

To assess relative risk for ballast-mediated introduction of NIS, the receiving habitats were weighted for modelling purposes based on physical and chemical oceanographic parameters that influence the survival and establishment of self-sustaining populations of NIS (relative likelihood of establishment), and on parameters that reflect biological importance and provide the best available proxy for predicted magnitude of impact (relative habitat sensitivity). Final risk (relative risk) was calculated as the product of the likelihood of exposure, likelihood of establishment, and habitat sensitivity.

Uncertainty was evaluated using model sensitivity analysis following the risk assessment guidelines outlined in Mandrak et al. (2012). Below we provide detailed information, rationale and formulae for each of the individual components of the risk assessment model as well as the approach that was used to test model sensitivity.

METHODS

ICE-OCEAN CIRCULATION MODELS

The primary circulation model used for this assessment was the Canadian East Coast Ocean Model (CECOM). CECOM is a coupled ice-ocean model, with the ocean component based on the Princeton Ocean Model (POM). The domain extends from northern Baffin Bay to just north of the Gulf Stream and from the St. Lawrence Estuary to 42°W (Figure 13). The horizontal resolution is 1/10 degree (about 10 km) and the model has 21 vertical levels. For this application CECOM was forced with 3-hourly meteorological forcing from the Canadian Meteorological Centre (CMC) Global Environmental Multiscale (GEM) model (Mailhot et al. 1998; Mailhot et al. 2006; Gauthier et al. 2007; Laroche et al. 2007). A full description of the configuration and numerical methods can be found in Yao et al. (2000) and Tang et al. (2008). CECOM has been providing real time forecasts of ice and ocean conditions since 2007 (Tang and Dunlap 2011; Wu and Tang 2011).

The surface currents are provided to the Canadian Coast Guard for search and rescue applications. Model validation has been carried out for the mean currents in Baffin Bay (Tang et al. 2004; Dunlap and Tang 2010), the storm forced currents on the Grand Banks (Tang et al. 2006; Wu et al. 2011), and the Labrador Current (Han and Tang 2001). A comprehensive description of the mean currents is provided by Wu and Tang (2011) and Wu et al. (2012).

The CECOM domain has open boundaries in both Hudson Strait and Lancaster Sound that raise concern about the quality of the model solutions in those regions. No alternative model exists for Hudson Strait, but additional simulations were done for the route segments in Lancaster Sound using an Arctic model developed by DFO at the Bedford Institute of Oceanography (Dartmouth, Nova Scotia, Canada). This model is based on NEMO (Nucleus for European Modelling of the Ocean) v2.3 (Madec 2008; Vancoppenolle et al. 2012). Its domain includes the Arctic Ocean with a boundary through Bering Strait and across the North Atlantic at about 45°N (Figure 14). The model is forced with monthly fields from the Common Ocean-Ice Reference Experiments (CORE; Large and Yeager 2008), developed at the National Center for Atmospheric Research. The horizontal resolution is 1/6 degree (about 18 km), however, using an adaptive grid refinement tool (AGRIF), a high-resolution sub-domain is embedded in the pan-Arctic domain such that the resolution throughout the Canadian Arctic Archipelago (including Lancaster Sound) is 1/18 degree (about 6 km).

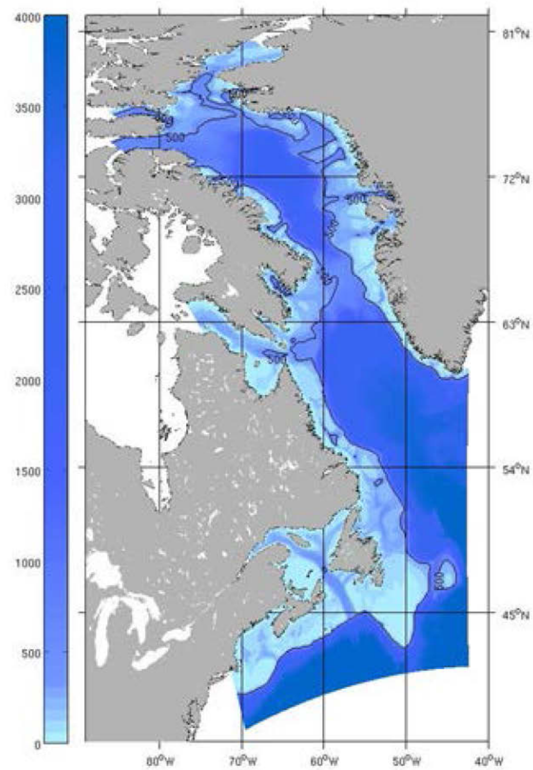

Figure 13. CECOM domain and bathymetry.

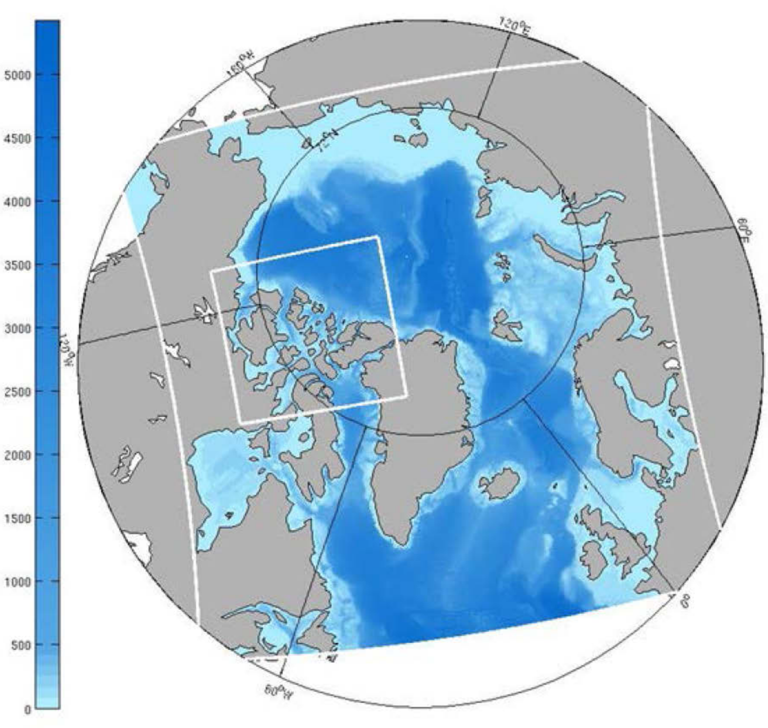

Figure 14. NEMO Domain and bathymetry with embedded AGRIF domain.

This Arctic model is still under development (Lu et al. 2010) and validation is ongoing. The primary validation is with the 10 years of observed transport in western Lancaster Sound, where the monthly transport fluctuations are correlated with the observations ($R^2 = 0.54$) but the magnitude of the modelled fluctuations is about 75% of that observed. The modelled mean transport is overestimated (0.9 Sv[8] compared to 0.7 Sv observed), so the mean flow will likely transport the virtual drifters out of Lancaster Sound a bit too quickly and may underestimate the penetration of released biota into Lancaster Sound. However, results from these simulations are presented to assess how sensitive the results may be to the use of different circulation models.

To facilitate comparison between the NEMO and CECOM model results all analyses in this study were done on the lower resolution CECOM grid. Each grid cell was about 10 km by 10 km and the grid covered the entire study area (see Figure 2).

The models used were those 3D model implementations for the eastern Arctic that provided broad spatial coverage and were available for use in 2010 when this study was initiated. No new circulation models were developed for this assessment.

SHIPPING ROUTES

Four main shipping routes were used for this study (Figure 15):

1) Labrador Sea to Lancaster Sound via central Baffin Bay (deep route);
2) Labrador Sea to Lancaster Sound via western Baffin Bay over depths >300 m (coastal route);
3) eastern Hudson Strait; and
4) Cumberland Sound.

The deep and coastal routes through Baffin Bay were selected to bound potential ABWEZ exchange zones rather than follow specific ship tracks. The deep route should approximate the ballast water exchange track of least risk from a biological perspective, as it follows a central track through Davis Strait and Baffin Bay over deep water. The other three routes correspond approximately to the major shipping tracks identified by Transport Canada which are expected to be representative the routes that would be used in the future regardless of how much shipping increases (Figure 11). The coastal route is positioned just outside the 300 m depth contour, which has been used as the minimum acceptable depth for exchange of ballast water in existing Canadian ABWEZs (Ballast Water Control and Management Regulations SOR/2011-137). The spur routes into Hudson Strait and Cumberland Sound were selected to assess exchange within these frequently transited, more confined entry points. Although the entrance to Frobisher Bay is also heavily used to access the Port of Iqaluit, this route was not included in this assessment because Frobisher Bay was not part of the CECOM model domain. The complicated geometry with many islands and narrow channels leads to very small spatial structures in the oceanographic properties and currents that make modelling difficult for this bay. We are not aware of any detailed three-dimensional circulation models of the eastern Arctic that include Frobisher Bay.

[8] Sv = Sverdrup, a unit of volume transport equal to 1,000,000 m^3/s.

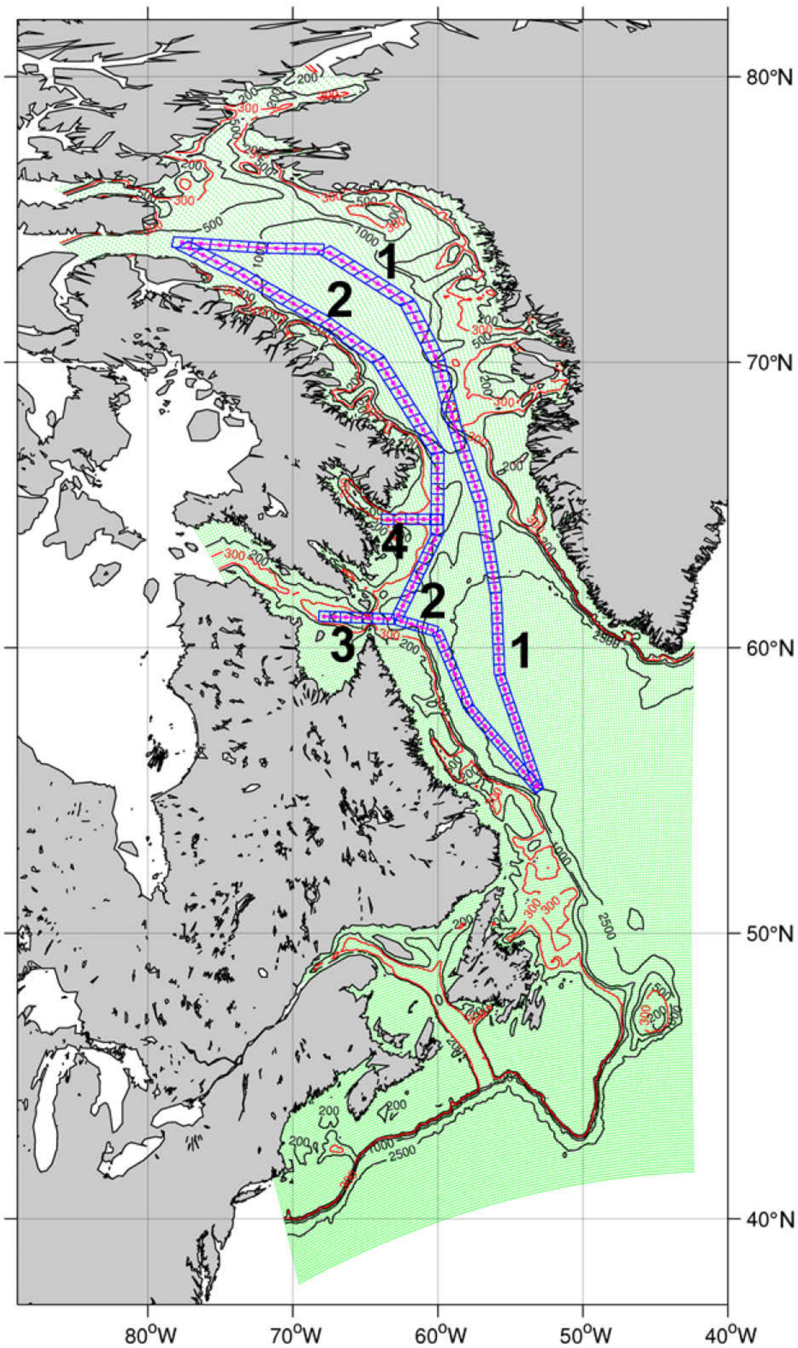

Figure 15. Ship routes divided into 40 km x 40 km boxes for modelling particle dispersal. 1= Deep route, 2 = Coastal route, 3 = eastern Hudson Strait, and 4 = Cumberland Sound.

PARTICLE TRACKING

Particle tracking techniques were used to simulate the movement of ballast water from the ship tracks throughout the model domain (Figure 16). A version of the 3D Generalized Bottom Boundary Layer Transport Model (BBLT3D; Drozdowksi 2009) was adapted for this purpose. BBLT3D is an offline particle tracking scheme that computes trajectories following a spatially varying and time varying velocity field. For these simulations, the two-dimensional velocity field of the surface currents (5 m depth) was used. Surface currents were used because the surface waters they move are most directly affected by ballast water exchange, sea ice, and most human activities. These currents are better known than those at greater depths, as are other seasonal oceanographical properties at the surface, which facilitates modelling. Hourly outputs from CECOM, and 6-hourly outputs from NEMO, were used. Linear interpolation of the velocity fields was used to allow for particle tracking with a time step of 6 minutes. This smaller time step reduces distortion of the particle tracks caused by the curvature of the velocity fields and interactions with the coastal boundaries.

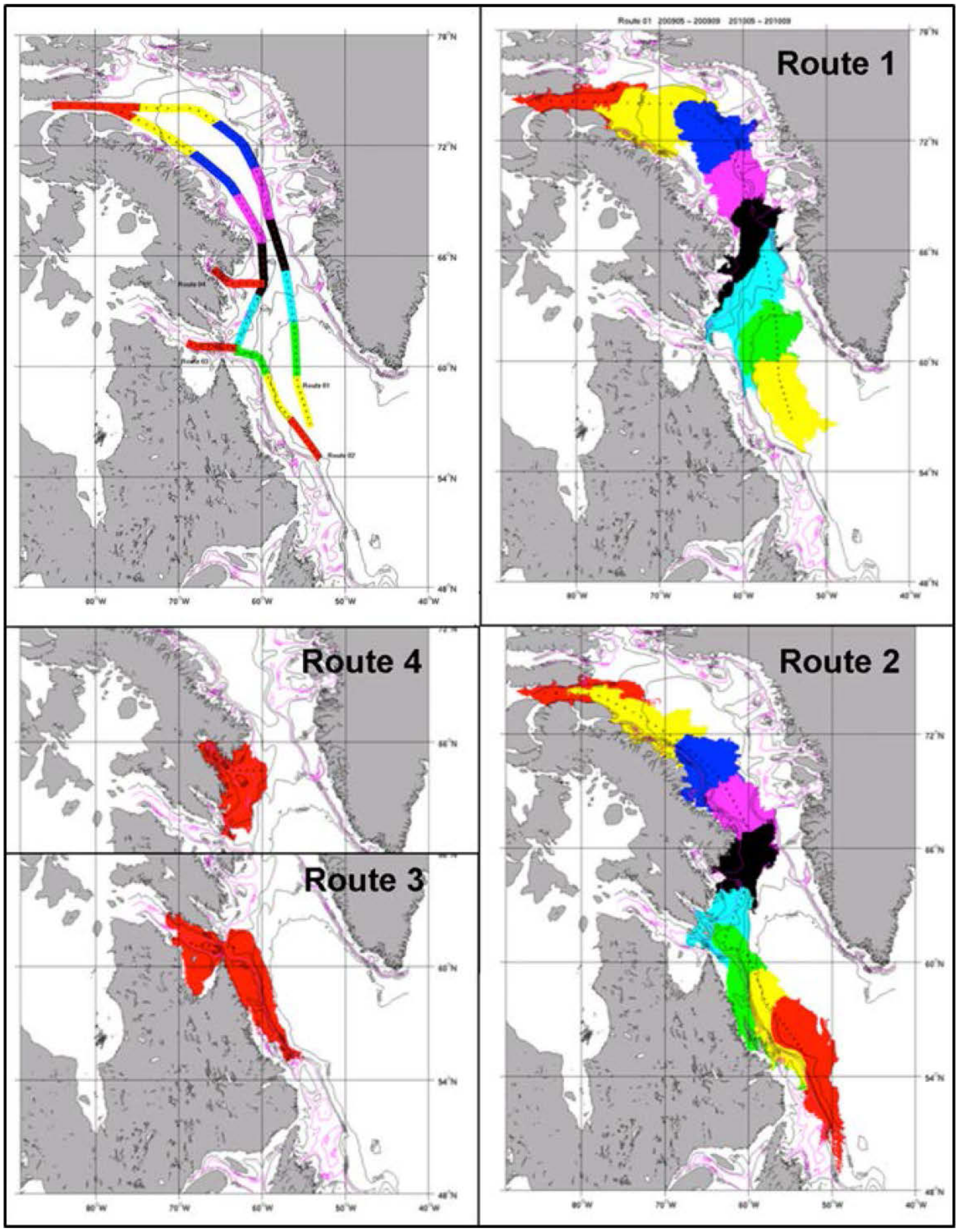

Figure 16. Extent of 30-day particle dispersal from sections of the shipping routes (upper left). The dispersed particles are the same colour as the sections from which they were released. Some northern particles are overlain by southern particles.

The primary circulation model used was CECOM with meteorological forcing data from 2009 and 2010; these two years were chosen since they were the most recent data available at the time the risk assessment was initiated in 2010. Additional simulations were also done with a second model, an Arctic model based on NEMO with forcing data from 2003 and 2004; these years were chosen because simulations showed the highest correlation with real observations during this period.

Each shipping route was divided into 40 km x 40 km release boxes, wherein 1000 randomly distributed particles were released for the CECOM simulations and 2500 for the NEMO simulations. The simulations were done for May, June, July, August and September (the ice-free season) of 2009 and 2010 in CECOM, and 2003 and 2004 in NEMO (2009 and 2010 forcing was not available for the NEMO model). Particles were released on the first day of the month and tracked for 30 days. In some cases, the simulations were shorter than 30 days because of missing atmospheric forcing data for the CECOM model. The 30-day duration facilitates comparisons in the absence of data on the species released and their ability to survive. It recognizes that the species will have a wide range of chemical (e.g., salinity) and physical (e.g., temperature) tolerances and a variety of life histories, some with stages that are particularly sensitive or robust.

Relative Likelihood of Exposure

Two metrics based on particle modelling were used to calculate the relative likelihood that a particular receiving habitat may be exposed to biota released in ballast water**: arrival time** or the amount of time it takes particles to travel from a release box to a particular zone of interest and **frequency of occurrence** which combines abundance and residence time for particles in a given zone (Figure 17). Both of these metrics were computed for each release box along the shipping routes, for each zone (described in next section) and for each of the 10 monthly simulations over the ice-free season (5 months/year over 2 years). The final metric for each release box for each zone was the mean of the 10 monthly simulations. The use of these relative risk metrics reminds us that the particles are not simulating actual organisms with behaviour and life history and therefore we are not assessing the actual (absolute) probability of a ballast water organism becoming established (Brickman 2006). We are simply assessing the relative risk of ballast water releases from different locations.

Arrival time (T) reflects the idea that organisms have a limited survival time so the faster an organism reaches a given zone the greater its chance of survival and thus the greater the likelihood for exposure of receiving habitats to NIS. To allow for model error in the trajectory analysis, arrival time was defined as the number of days it takes for 10% of the particles to travel from a release box to a given zone, regardless of whether or not the particles remained in that zone. For example, where the CECOM simulations used 1000 particles per box, the arrival time for a particular zone is the number of days it takes for the 100^{th} particle to reach the zone, regardless of whether or not the first 99 were still there. It is important to note that a particle can contribute timing information to more than 1 zone as it can enter and leave multiple zones during the 30-day simulation.

Because the simulation length is limited to 30 days, T ranges between 0 and 30. Arrival time is inversely proportional to the likelihood of exposure. An arrival time of zero indicates that the particles were released within or immediately upstream of a particular zone of interest, in which case the relative likelihood of exposure was high. Often the particles did not reach a given zone during the 30 day simulation, in which case it was tagged as >30 and the relative likelihood of exposure was low. Cases where the simulations were shorter than 30 days (due to lack of forcing data for the CECOM model), and the arrival time was undetermined (i.e., greater than simulation length but not necessarily > 30), were not included in the final calculation.

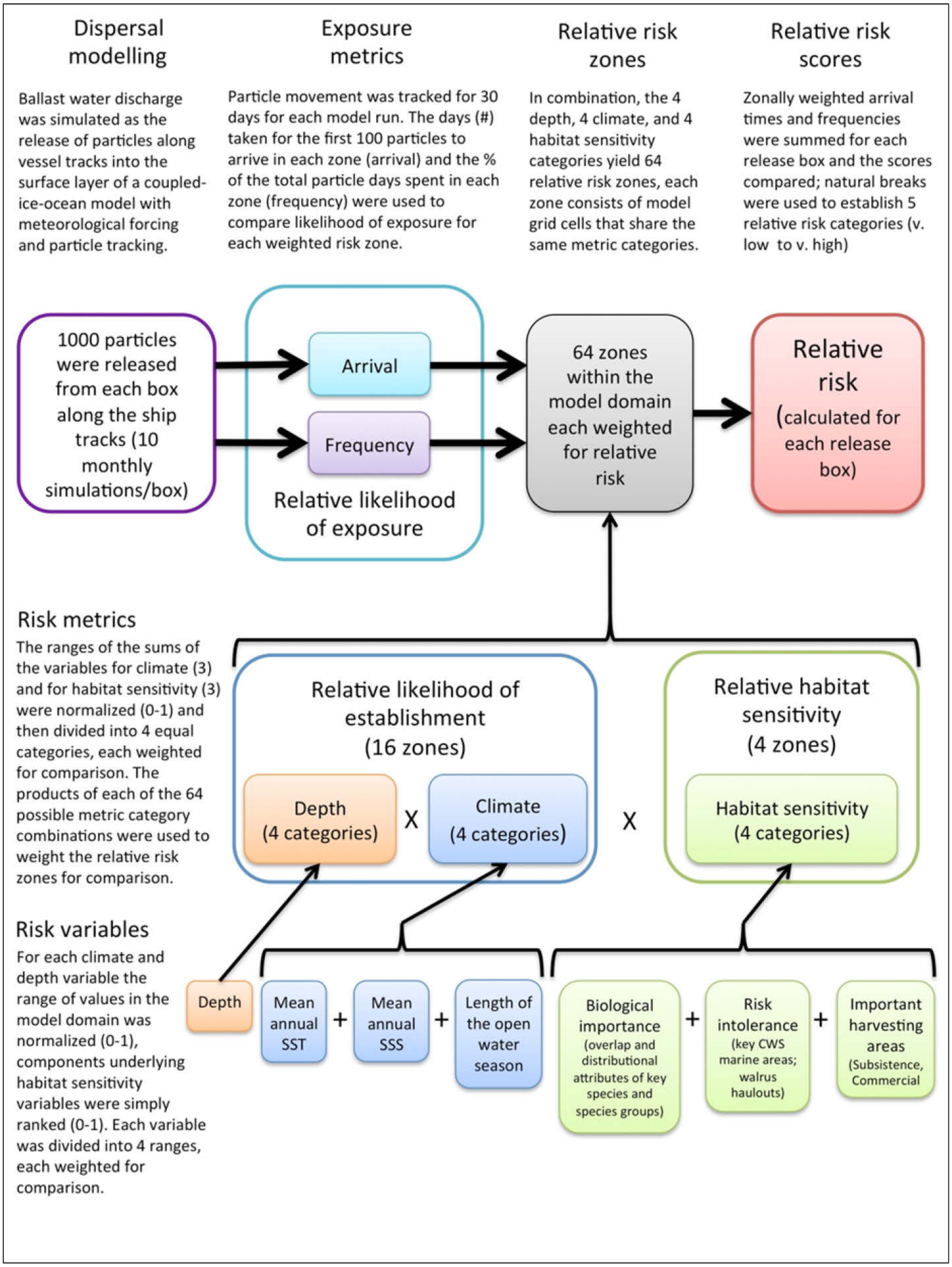

Figure 17. Relative risk assessment modelling schematic.

Frequency of occurrence (F) is used to reflect that the more abundant a species is and the longer it remains in one place, the more likely it is to survive and reproduce. Frequency of occurrence is the particle based equivalent to the integrated concentration metric of Brickman (2006). The definition is based on the number of days that particles spend in a given zone. One particle spending 10 days in a zone and 10 particles spending 1 day in a zone both result in 10 particle days. To create an index ranging from 0 to 1 the number of particles days in a given zone was expressed as the fraction of total potential particle-days (i.e., the product of the number of particles released from the box and the number of simulated days--usually 30 days). Once again, a particle can contribute frequency of occurrence information to more than 1 zone as it can enter and leave numerous zones during the 30-day simulation.

ZONE DEFINITIONS AND WEIGHTINGS

The conceptual frameworks for risk typically express risk as the product of likelihood and impact:

$$\text{Risk} = \text{Likelihood} \times \text{Impact}$$

In the context of this assessment the relative likelihood of introduction was based on likelihood of exposure and establishment of NIS, and the impact of introduction was related to the relative habitat sensitivity. The method chosen allowed us to map the risk back onto the particular discharge locations (i.e., particle release boxes along a ship track)(Figure 17). Habitats within the model domain were characterized based on physical and chemical oceanographic variables expected to influence the **relative likelihood of establishment** of introduced NIS and on biological variables expected to reflect **relative habitat sensitivity** to introduced NIS. These variables were quantified, relative weights were assigned to their ranges, and they were combined to identify zones with similar characteristics that were each given relative weights. The defined zones were not necessarily physically continuous – in general they were disjointed. They should be considered zones in the sense of municipal land use zoning. The risk was then assessed by combining these weights with the relative likelihood of exposure metrics from the particle tracking (arrival time and frequency of occurrence) to compute a relative risk score. The sensitivity of the risk calculation to alternative weighting schemes was considered.

Data for the depth variable was obtained directly from the CECOM model, however data preparation and manipulation steps for climate variables as well as habitat sensitivity variables (below) were conducted using ArcView 3.3 GIS software (ESRI, Redlands, CA), the Spatial Analyst extension, and various third-party scripts and extensions. All data layers used in the risk assessment were mapped to the locations (latitude-longitude) of the centre of the CECOM grid cells, which use a rotated spherical coordinate system where the equator of the rotated earth runs north-south through the middle of the Labrador Sea (Wu et al. 2012). Locations of grid cell centre points were exported from CECOM and imported into ArcView as a vector point shapefile. Analyses were conducted using unprojected (i.e., geographic) data, mapped to the centre points of the CECOM grid, although all GIS maps are presented using a Lambert Conformal Conic projection. The final data layers for climate and habitat sensitivity variables (see below) were exported as a text file with associated location data to import back into the CECOM domain for particle modelling.

Variable and metric ranges were each divided into equal bins for modelling. To avoid null values all weightings (presented below) were calculated for the upper end of each range.

Relative Likelihood of Establishment (habitat suitability)

Environmental factors that influence marine zoogeography have been used in other studies to calculate environmental distances between donor and recipient waters as a metric for comparing the relative risk of species introductions via ballast water. For port-to-port comparisons these distance calculations often incorporate mean annual salinity and various temperature variables, including the mean annual, mean of the coldest month, and mean of the warmest month (e.g., Barry et al. 2008; Hayes and Barry 2008; Chan et al. 2012). The latter are intended to capture seasonal variability. Depth is not a commonly used variable, as the range of port depths is typically small (<100 m). The use of ice cover is likewise uncommon because most ports are ice-free year-round. However, both depth and ice cover are important variables to consider when assessing the relative likelihood of establishment of species introduced via offshore ballast water exchange in Arctic waters.

Zones for assessing the likelihood of establishment were identified and weighted for inclusion as metrics in this risk analysis based on differences in depth and in three climatic variables: salinity, water temperature, and ice cover. The purpose of these zones was to differentiate habitats that are more or less likely to favour the establishment of entrained NIS originating from shallow, nearshore coastal waters. Shallow-water coastal species typically have different habitat requirements than those found offshore and/or at greater depths. These requirements can be related to tidal effects, surface access, light, salinity, temperature, substrate, slope, pressure, and other factors. These differences in habitat requirements are expected to be most relevant for benthic species, since they often show preference for a particular range of depths (e.g., Bilyard and Carey 1980; Thomson 1982; Jørgensen et al. 2005) or associated water mass and temperature regimes (Stewart et al. 1985). Salinity and temperature are important environmental variables for determining benthic macroafaunal assemblages (Cusson et al. 2007) and demersal and larval fish assemblages (Norcross et al. 2009) on Arctic shelves. Benthic species, particularly those with pelagic larval stages, are often entrained from and introduced to coastal ports, as are coastal plankton.

Depth (*Variable 1*; shallowest water = highest likelihood of establishment)

Depth is important to consider as the exchange within an ABWEZ occurs some distance from shore where depths differ and affect a released organism's ability to survive and potentially colonize; this variable may be particularly relevant for determining if benthic biota are likely to survive once they descend in the water column to the bottom substrate. This differs from port-to-port transfers where ballast water is loaded and released dockside in relatively shallow water (<50 m).

The depth variable was treated separately from the three climate variables, which were combined for analysis. This approach recognizes that depths remain relatively fixed, except for tidal variations and forcing (e.g., runoff, wind, atmospheric pressure), while the climate variables vary seasonally. Depth information was obtained from the CECOM model.

Four depth ranges (Figure 18) were used for analysis:

- **Coastal (<100 m depth)** encompasses the euphotic zone, which extends to a depth of about 60 m (NASA Giovanni euphotic depth). Within the euphotic zone there is sufficient light penetration to support benthic plant growth and the associated biological communities. Nonindigenous coastal biota transported into the shallow coastal waters should have the greatest likelihood of survival and establishment so this depth range was assigned the highest-relative weight. Further subdividing the coastal depth range was not possible, as the depths of coastal waters in the region are not well known. The <100 m lower depth limit provides a margin for error and for possible vertical movement of biota that settle out at greater depths but are capable of significant movement. Annual mixing processes of the surface waters typically extend to a depth of about 100 m (Tang et al. 2004). To ensure likelihood of establishment was not underestimated in areas where the coastal depth range extends <20 km from shore, the coastal depth range was extended two 10 km x 10 km model grid cells from the shore for analysis in these areas.

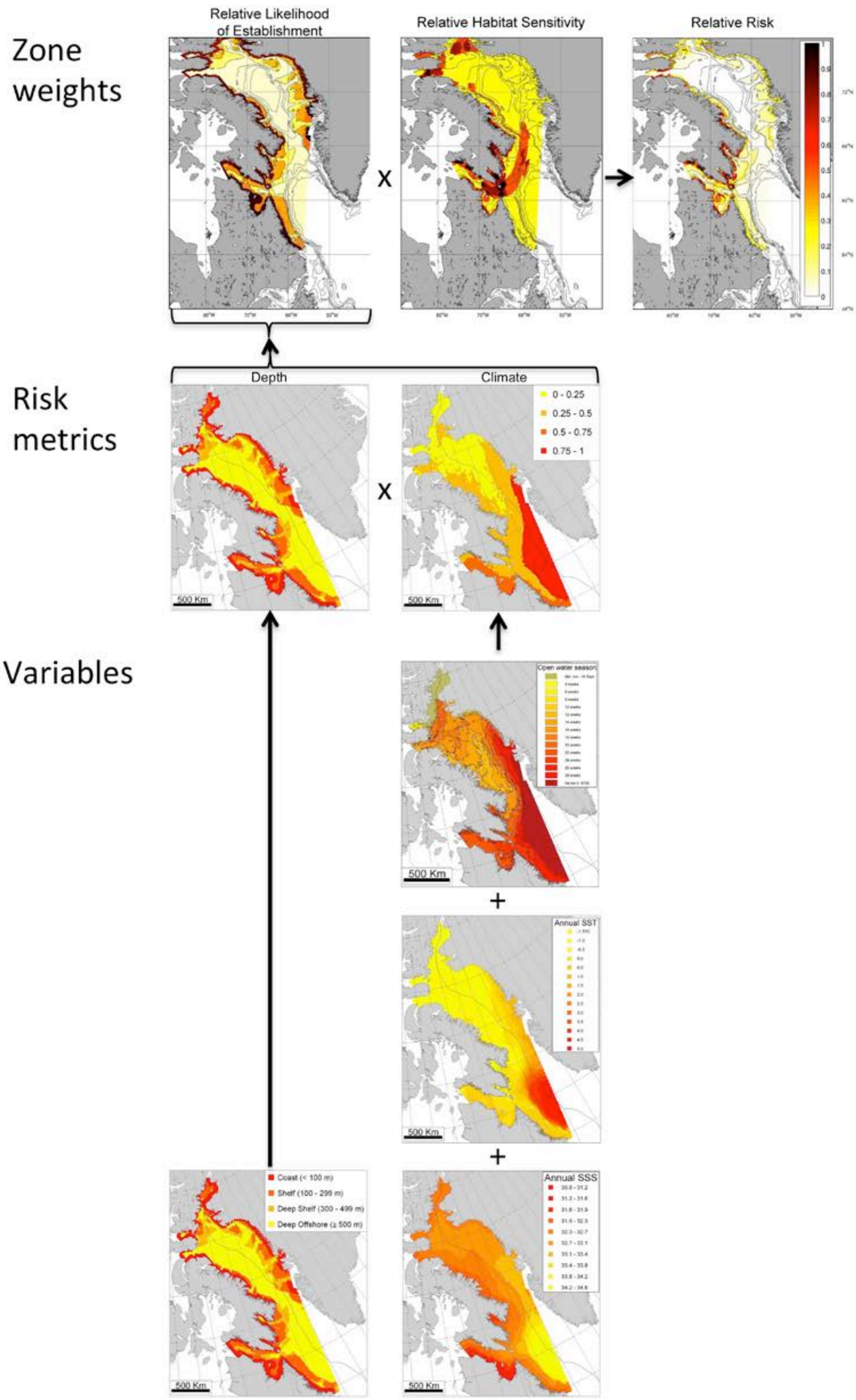

Figure 18. Relationships of the variables (i.e., depth, mean annual sea surface salinity (SSS), mean annual sea surface temperature (SST), length of the open water season) and risk metrics (i.e., depth, climate) used to calculate the zone weights for comparing relative likelihood of establishment. See text for details.

- **Shelf (100 m to <300 m)** extends from below the euphotic zone to near the lower limit of the relatively cold, dilute Arctic surface water layer (Tang et al. 2004). This depth range is immediately inshore of the shallowest exchange depth allowed by existing ABWEZ regulations. It typically extends offshore to or near the shelf break except in the fiords and along the coasts south of Cape Dyer (Figure 2), where the coastal shelf has a more gradual decline. The likelihood of coastal species surviving and becoming established in this depth range should be less than in the euphotic zone but greater than in deeper waters.
- **Deep shelf (300 m to <500 m)** is offshore the shallowest exchange depth that has been allowed in the existing Transport Canada regulations. It is typically narrow along the east coast of Baffin Island, where depths often drop sharply from 200 m to 1000 m and deeper, except along the coasts south of Cape Dyer. Benthic habitats in this depth range are largely below the Arctic surface water layer in the warmer, saltier water of the Atlantic intermediate layer (Tang et al. 2004). This is expected to be a difficult depth range for coastal biota to survive and establish.
- **Deep offshore (≥500 m)** includes the steep coastal slope and relatively flat profundal habitats covered with warmer, saltier Atlantic deep water. This depth range has conditions that should make survival of most coastal benthic species unlikely, so it was assigned the lowest weighting.

The relative likelihood of introduced coastal NIS surviving and establishing at different depths is unknown but should be higher in shallow waters than deep waters, since most biota in the ballast will be from shallow waters that are presumably their preferred habitat. Since we have no empirical information regarding the relationship between survival/establishment of coastal NIS and depth for the Eastern Arctic, we tested sensitivity of the relative risk analysis model (next section) using two different weighting scenarios for depth (linear, geometric) (Table 2), reflecting plausible relationships between depth and likelihood of survival (Figure A1-1—see Appendix 1).

Table 2. Depth category weightings (linear, geometric) for comparing relative likelihood of establishment.

Depth suitability:	Coast	Shelf	Deep shelf	Deep offshore
Linear decline in suitability	1.000	0.750	0.500	0.250
Geometric interval decline in suitability	1.000	0.467	0.200	0.067

Climate variables were used to facilitate comparisons of the surface waters, which undergo seasonal changes in their chemical and physical properties that vary spatially and influence species' survival. Key rationales for concentrating on the surface waters are:

1) the ballast water taken on in source ports is from within 20 m of the surface, so most of the organisms entrained within tanks should be planktonic species or species with planktonic larval stages that live in shallow near shore waters;
2) this layer is directly influenced by ice formation, incident light and wind mixing; and
3) satellite monitoring facilitates comparisons at regular intervals over a very large area. Deeper waters are less influenced by climate and tend to have more stable conditions year-round.

Three climate variables were combined for use in the analysis (Figure 18):

- **Mean annual sea surface salinity (SSS; psu)** (*variable 2*: lowest salinity = highest likelihood of establishment) was used as a variable because species have different salinity tolerances. Indeed, one of the rationales for conducting mid-ocean exchange is to expose biota from dilute coastal waters to osmotic shock. Those that are unable to adjust die. Salinity in the Arctic surface layer changes seasonally, declining in the spring when melting sea ice releases large volumes of fresh water at the surface, and increasing as the year progresses in response to mixing and to ice formation that sequesters freshwater. Salinity also increases with depth. While mean annual SSS was the best available large-scale measure, it does not fully capture the seasonal variability in Arctic and Subarctic waters and may underestimate the risk in coastal areas where salinities may get low enough to be biologically relevant in the context of ballast-mediated NIS introductions.
- **Mean annual sea surface temperature (SST; °C)** (*variable 3*: warmest = highest likelihood of establishment) was used as a variable because species have different temperature tolerances. Many species are unable to survive the sub-zero temperatures found in Arctic surface waters. Temperature can also have more subtle effects on aspects of physiology that determine species' ability to survive and successfully reproduce.
- **Length of the open water season (weeks)** (*variable 4*: longest open water = highest likelihood of establishment) was used as a variable because of the importance of ice as a limiting factor and as a measure of seasonal variability. Ice cover and temperature, while both temperature-related have rather different impacts on the marine environment and its species. Arctic sea ice forms a surface barrier that is not present in warmer climes. Its presence alters seasonal mixing, stratification, and nutrient availability and creates habitat for ice-adapted species—all of these affect food chain structure and dynamics (Stewart and Barber 2010). Temperature is also limiting but is less apt to elicit such an abrupt threshold response.

The monthly temperature and salinity climatologies used for analysis are based on the historical temperature-salinity dataset archived at the Bedford Institute of Oceanography (Wu et al. 2012). This set includes bottle and CTD data collected over the past 50 years and Argo data collected in the past decade (2000-2009). Wu et al. (2012) describe how the climatologies were constructed. Length of the open water season was calculated from the Canadian Ice Service 30-year ice atlas (1981-2010) data for median week of break-up and freeze-up, which were defined as < 50% and >50% ice cover, respectively (Canadian Ice Service 2011).

The spatial extent of the climate layer was influenced by the availability and spatial extent of the data for each variable. For example, open water season length data were available for western Hudson Strait and Foxe Basin but the CECOM model lacked field SST and SSS data for those waters. Conversely, SST and SSS data were available for southern areas that are not included in the Arctic and Northern Waters zone as defined by the Canadian Ice Service. The final climate layer only included areas with data for all three variables (i.e., missing cells were excluded from the analysis).

The three climate variables were each normalized on a 0-1 scale to facilitate combining data layers. For SSS, 0 represents the highest salinity value and 1 the lowest (i.e., lower salinity equals higher likelihood of survival/establishment of NIS) and for SST and open water period, 0 represents the lowest and 1 the highest value (i.e., warmer water and longer open water season equates to higher likelihood of survival/establishment). Reasoned arguments can be made for various weighting schemes when combining the three variables; to test sensitivity to different weighting schemes, four different approaches were compared. The first weighted each climate variable equally (33%). The other three weighted one variable higher (50%) and the other two lower (25%) (e.g., SSS 50%, SST 25%, open water 25%).

For the risk analysis (next section) the combined climate variables were weighted for modelling over a range of 1 to 0.667, with the Subarctic region highest (1) and the Arctic region lowest (0.667). The terms “Arctic” and “Subarctic” were used for convenience. They do not reflect latitudinal definitions or necessarily correspond to existing zoogeographical or oceanographical definitions. A relatively narrow range of weighting values was used for climate to reflect the relatively narrow range of natural conditions in the Eastern Arctic, relative to the global range of conditions for this metric. Sensitivity to the number of climate categories was tested by mapping the data using 3, 4, and 5 categories. Since we have no empirical information regarding the relationship between climate and survival/establishment of ballast mediated NIS for the Eastern Arctic, we tested sensitivity of the relative risk analysis model (next section) using two different weighting scenarios (linear, geometric) (Table 3), reflecting plausible relationships between climate and likelihood of survival.

Table 3. Climate category weightings (linear, geometric) for comparing relative likelihood of establishment.

Climate suitability:	**sub-Arctic**	**high sub-Arctic**	**low Arctic**	**Arctic**
Linear decline in suitability	1.000	0.917	0.834	0.750
Geometric interval decline in suitability	1.000	0.822	0.734	0.689

The use of minimum SSS and of mean SSS and SST during the coldest and warmest months as a measure of seasonal variability was considered but not used. Minimum SSS could be very important in survival/establishment but occurs during spring breakup when salinity values are highly variable and data tend to be unreliable due to lack of empirical measurements. Values during the coldest month are obscured by ice and fall within a narrow range. Values during the warmest month vary widely and are quite different than the mean annual values but their normalized values are highly correlated for both SST (Pearson correlation coefficient, $r = 0.933$) and SSS (0.964) ($n = 40,868$), so only the mean annual values were used.

Relative Habitat Sensitivity (magnitude of consequences or potential impact)

Determining the actual sensitivity of marine ecosystems in the eastern Canadian Arctic to species introduced with ballast water is beyond the scope of this assessment. There are too many unknowns related to species that might be introduced and to their potential impacts on the receiving ecosystems. Consequently, areas identified as particularly biologically important and/or risk intolerant were used as a proxy for relative habitat sensitivity reflecting potential magnitude of consequence or impact should ballast-mediated NIS survive and establish. These data sets tend to be anthropocentric and positively biased toward harvested species, inshore areas, and open water conditions but they are the best available. Each is based on a broad regional review or study that integrates a range of different parameters (e.g., species). Where overlap in coverage occurs it serves to emphasize areas of particular biological importance.

Three variables were used to differentiate relative habitat sensitivity zones (Figure 19):

- **Marine areas of high biological importance** were used to compare biological richness, or at least areas where more wildlife might be exposed to NIS. These areas were identified by the interdisciplinary Arctic Marine Workshop that DFO convened in 2010 (Stephenson and Hartwig 2010: 26 ff. and Fig. 24). Identified areas were based on the overlap of important distributional attributes of key species or species groups. Common seasonal presence, birthing areas, and areas of high productivity are examples of these distributional attributes. The areas of importance form an outer envelope around smaller areas of greater importance.

  Nine species or species groups were considered, including:

  1) toothed whales (beluga *Delphinapterus leucas*, narwhal *Monodon monoceros*, killer whale *Orcinus orca*),
  2) bowhead whale (*Balaena mysticetus*),
  3) phocid seals (ringed seal *Pusa hispida*, bearded seal *Erignathus barbatus*, harbour seal *Phoca vitulina*, harp seal *Pagophilus groenlandicus*, and hooded seal *Cystophora cristata*),
  4) Atlantic walrus,
  5) fishes (e.g., Arctic Char *Salvelinus alpinus*),
  6) polar bear (*Ursus maritimus*),
  7) seabirds (key habitat sites),
  8) invertebrates (shrimp *Pandalus* spp., corals and sponges), and
  9) hotspots of primary productivity.

  While these species and species groups are biased towards charismatic megafauna, most require substantial primary and secondary productivity to support their presence.

  The weighting of habitat sensitivity ranges from highest (1) to lowest (0.25) for this variable was:

≥ 6 overlapping species or groups	= 1.0
5 overlapping species or groups	= 0.75
4 overlapping species or groups	= 0.5
≤ 3 overlapping species or groups	= 0.25

  The areas of importance that were identified correspond well to multi-species harvesting areas mapped using Inuit Land Use and Occupancy data (Freeman 1976) but extend farther offshore and along the Nunavik coasts - although coverage in Ungava Bay may be incomplete. They also correspond well with the marine hotspots identified by Parks Canada's 1994 Arctic Marine Workshop (Mercier et al. 1995) and with the presence of polynias (Mallory and Fontaine 2004).

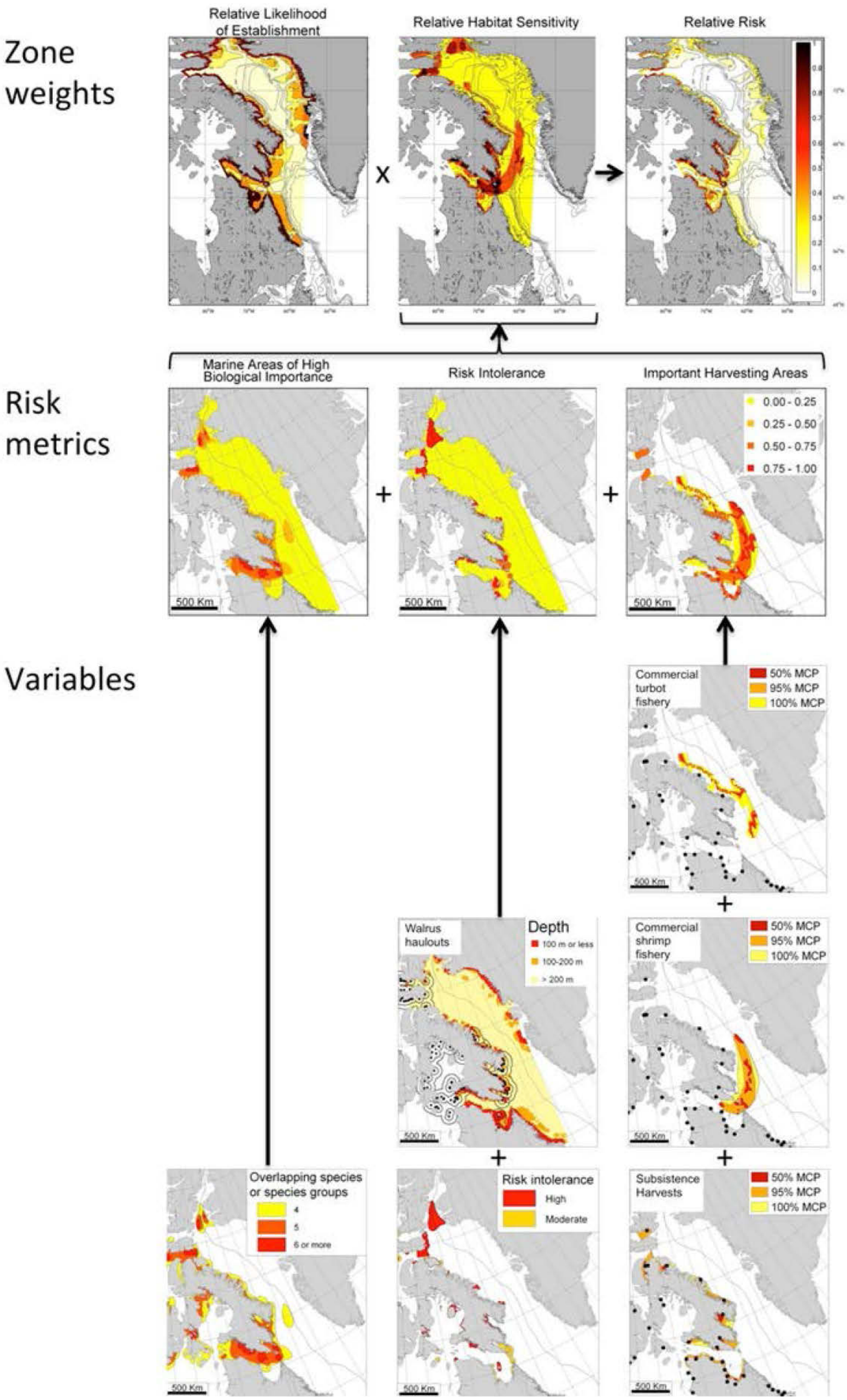

Figure 19. Relationships of the variables and risk metrics used to calculate the zone weights for comparing relative habitat sensitivity. See text for details.

- **Risk intolerance**, which assesses how important it is to avoid damage to a particular habitat, was used to refine our comparisons of relative habitat sensitivity. This variable is based primarily on an assessment of the risk intolerance of Key Canadian Wildlife Service (CWS) Marine Areas that the CWS conducted as part of a Nunavut Land Use Plan (NLUP) exercise (S.-L. Han, Environment Canada, pers. comm.), but has been augmented with data from walruses (Figure 19). The NLUP exercise assessed the intolerance for activities such as shipping, hydrocarbon development, and harvesting that could pose a risk to habitat/fauna based on the numbers of individuals present and potential for population-level repercussions. It did not assess the biophysical resilience of the species or the sites, both of which are unpredictable. Sites were considered 'highly risk intolerant' if they contained either:

    1) ≥ 10% of a national population,
    2) 5-10% of a population known to be in decline,
    3) a percentage greater than or equal to the estimated 'tolerable sustainable loss' the population could absorb (for harvested species), or
    4) Endangered or Threatened species at risk (Mallory and Fontaine 2004; S.-L. Han, Environment Canada, pers. comm.).

  Sites that are 'moderately risk intolerant' are those meeting minimum criteria for 'Important Bird Areas' (i.e., 1% or more of a national population), but not meeting the criteria above. Sites outside the Nunavut Settlement Area (NSA) were identified by CWS as "trans-boundary" and not assigned a risk tolerance. For this study, these sites (n = 6) were assigned a risk intolerance based on information from Mallory and Fontaine (2004) and discussions with CWS staff (S.-L. Han, Environment Canada, pers. comm.).

  The NLUP exercise was biased towards large marine bird colonies that rely upon rich concentrations of small pelagic and/or benthic fishes and/or invertebrates within foraging range. This reliance makes the colonies sensitive to changes in lower trophic levels (Gaston et al. 2012; Smith and Gaston 2012). It also means that the colonies could become hubs for the concentration and distribution of NIS. Individuals of some colonial bird species forage over a large area. This may increase the likelihood that they will encounter NIS, transport NIS to the colony, and distribute NIS from the colony. Key walrus haulouts on southeastern Baffin and in western Hudson Strait were not considered risk intolerant by CWS. This suggests that CWS underestimated the risk to walruses, which have localized areas of concentration and forage heavily on benthic molluscs in relatively shallow water (COSEWIC 2006). Walruses are also under-represented in the biological importance and harvesting variables, as they typically occupy areas that are remote from communities and harvests have been declining (Stewart et al. 2014).

  Walrus haulout sites were obtained from the DFO GPS database (B. Dunn and R.E.A. Stewart, DFO Winnipeg, unpubl. data) and updated with relevant literature (e.g., Freeman 1976; Born et al. 1995; Reeves 1995; Stewart et al. 2013, 2014a, 2014b). Buffer zones were established around each site based on the kernel ranges and foraging depths (Figure 19). The 75% kernel range of male walrus tagged on southeastern Baffin Island extended about 75 km from the tagging location (haul-out) and about 60 km for females (Dietz et al. 2014; Stewart et al. 2014a). The 95% kernel range for both sexes combined was a maximum distance of about 100 km. For recent population estimates, the criterion used to eliminate possible double counting was either 40 km/day (Stewart 2008; Stewart et al. 2014c) or 45 km/day (Stewart et al. 2013, 2014a). To be conservative, we used 50 km and 100 km buffers. Several haulouts that appear abandoned were included in the buffer zones as the underlying reasons for their past use likely remain – presumably suitable haulout habitat and rich, accessible shellfish beds. Walrus require shallow depths for benthic foraging and show preference for areas <80 m deep (COSEWIC 2006), so buffers were also sub-characterized into 100 m and 200 m depth classes using bathymetric data from the CECOM model. Waters within the 50 km buffer with depth ≤ 100 m were considered highly risk intolerant; waters within the 50 km buffer with depth ≤ 200 m or within the 100 km buffer and depth ≤ 100 m somewhat risk intolerant; and waters within the 100 km buffer with depth <200 m were considered equal to background (i.e., other).

When the Key CWS Marine Areas and walrus data were combined, only the highest ranking for an area (i.e., grid cell) was kept to avoid double-counting. No area is completely risk tolerant and the risks are very uncertain, so areas without CWS rankings or walrus haulouts (i.e., other) were given a low but still significant ranking. The ranking of habitat sensitivity from highest (1) to lowest (0.25) for this variable was:

Highly risk intolerant	= 1.0
Moderately risk intolerant	= 0.75
Somewhat risk intolerant	= 0.5
Other	= 0.25

- **Important harvesting areas** were also used to refine comparisons of relative habitat sensitivity. This variable is based primarily on inshore, open water subsistence harvesting from Nunavut waters, and on offshore open water commercial harvesting from the eastern Canadian Arctic (Figure 19). While these activities highlight areas of direct socio-economic interest where local harvesting activities might promote the spread of introduced species, they were not used here as a socioeconomic indicator. Instead their inclusion complemented both biological importance and risk intolerance by identifying areas that these abundance–based variables may undervalue. Northern communities typically develop in resource-rich areas and then reduce the local abundance of harvested species by altering their distribution and/or abundance. Variables based on the abundance of harvested species therefore may underestimate biological importance and risk intolerance, since the underlying ecological conditions that made these areas resource-rich remain unchanged. In essence, harvesting is used to correct for the previous and ongoing impacts of human activities rather than to place a value on them.

  The subsistence harvest data were collected during the open water seasons (June-October) of 1996 to 2000 from Inuit in Nunavut (Priest and Usher 2004), and are archived by the Nunavut Wildlife Management Board. Harvests include charismatic megafauna (walrus, narwhal, beluga), marine birds, and fish. These point data were used to calculate 50%, 95% and 100% minimum convex polygons (MCP) for each Nunavut community in the study area (Figure 19). They provide an indicator of harvesting effort, areas of direct importance to local harvesters, and potential for coastal transport of biota by humans. By doing so they also identify areas where the biological importance and risk intolerance variables are most likely to underestimate the habitat sensitivity.

  Similar data are lacking for Nunavik communities on Hudson Strait and Ungava Bay, so buffers for communities in southern Hudson Strait were estimated based on the MCPs calculated for Kimmirut and Cape Dorset. These Nunavut communities have similar resources and environmental conditions—at least relative to the more northerly communities that are situated in deep bays or inlets or in areas with fiords. For each Nunavik community the 50% MPC equivalent extended 20 km offshore and 20 km along shore in each direction (i.e., north-south, or east-west) and the 95% MCP extended 30 km offshore and 100 km along shore in each direction. Any remaining areas within 30 km of the Hudson Strait shoreline were considered equivalent to the 100% MCP for Nunavut community harvests.

Commercial shrimp (*Pandalus* spp.) and turbot (*Hippoglossoides greonlandicus*) harvests were added to capture important offshore harvesting. The shrimps are pelagic and closely associated with ocean fronts that carry deep waters to the surface creating temperature and salinity anomalies and nutrient enrichment (Belkin et al. 2009:230). They undertake extensive vertical movements and are concentrated in areas with bottom depths of 200 to 600 m (DFO 2008). Bounding polygons (50%, 95%, and 100%) were estimated around commercial set locations in Canadian waters with harvests between 1979-2012 (T. Siferd, DFO, pers. comm.) (Figure 19). Over 95% of the harvests were less than 8 t (n=101,459).

Turbot large enough to be recruited into the offshore commercial fishery live on or near the bottom. These fish are closely associated with the 1000 m depth contour, which corresponds to the shelf slope (Jørgensen et al. 2005), and they attract narwhals to feed (Heide-Jørgensen and Dietz 1995; Heide-Jørgensen et al. 2002). Both the shrimp and turbot fisheries are associated with other commercially harvested species, suggesting that they occupy habitats that are relatively rich and productive (Treble 2011). Depth (from CECOM) was used to approximate the MCPs for turbot catches within the harvest areas identified by Treble (2011). The 50% MCP equivalent corresponds to depths of 900-1100 m; the 75% polygon to depths of 750-900 m and 1100-1250 m; and the 100% polygon to depths of 500-750 m and 1250-1500 m (Figure 19). While turbot fisheries have concentrated on western Baffin Bay-Davis Strait, turbot also use deep water in Cumberland Sound and likely elsewhere in Baffin Bay, Davis Strait, Hudson Strait, and the Labrador Sea. The Cumberland Sound fishery was not included in this layer as it lies within the 50% MCP for the Pangnirtung subsistence harvests and thus already receives the highest ranking.

When the subsistence and commercial harvesting data were combined, only the highest ranking for an area (i.e., grid cell) was kept. This was done to avoid double-counting in areas where both types of harvesting may have a similar obscuring effect on the underlying biological importance and risk intolerance. The 100% MCPs were given a low ranking as these locations are at the outer edges of current harvesting areas and few harvests (the most-dispersed 5%) occur there; areas without harvesting were not ranked. The ranking of habitat sensitivity from highest (1) to lowest (0.25) for this variable was:

50% MCP (or equivalent)	= 1.0
95% MCP (or equivalent)	= 0.75
100% MCP (or equivalent)	= 0.25

For the risk analysis (next section), the three relative habitat sensitivity variables were averaged for each model grid cell; normalized on a 0-1 scale, where 1 represents the highest sensitivity (highest magnitude of consequence); and then divided into four equal bins that were ranked based on the upper limit of each bin (Table 4).

Table 4. Weightings for comparing relative habitat sensitivity.

	High	Moderate	Fair	Low
Relative habitat sensitivity	1.000	0.750	0.500	0.250

Combined Weightings for Likelihood of Establishment and Relative Habitat Sensitivity

To estimate the relative risk (next section) a weight was assigned to each zone based on its expected habitat suitability for survival and establishment of, and its sensitivity to, introduced species. This weight was calculated as the product of the depth, climate, and habitat sensitivity values for each grid cell. The risk calculations were run using 64 zones (i.e., 4 depth x 4 climate x 4 habitat sensitivity). Four different weighting schemes were used to investigate the sensitivity of the analysis (Appendix 1):

> Case 1: linear depth-linear climate (i.e., linear decrease in weight from shallow coastal waters to deep offshore waters—linear decrease in weight from sub-Arctic to the Arctic waters)
>
> Case 2: linear depth-geometric climate (i.e., linear decrease in weight from shallow coastal waters to deep offshore waters—geometric decrease in weight from sub-Arctic to the Arctic waters)
>
> Case 3: geometric depth-linear climate (i.e., geometric decrease in weight from shallow coastal waters to deep offshore waters—linear decrease in weight from sub-Arctic to the Arctic waters)
>
> Case 4: geometric depth-geometric climate (i.e., geometric decrease in weight from shallow coastal waters to deep offshore waters—geometric decrease in weight from sub-Arctic to the Arctic waters)

Weighting all zones equally was not considered a plausible scenario and was therefore not considered in these analyses. The geometric weightings were based on geometric intervals, which yield a similar pattern of decline over different ranges, where geometric progressions do not (Appendix 1). Different combinations of depth, climate, and habitat sensitivity category weightings can produce the same weightings in more than one relative risk zone (Appendix 1).

All zones are treated separately because those that are mathematically equal do not share the same combination of underlying variables.

RELATIVE RISK CALCULATIONS

The final risk for each 40 x 40 km particle release box along a given ship track is based on the combined values of the zonally weighted arrival time from that box to each zone (e.g., Figure 20) and the zonally weighted frequency of occurrence for that box. Below we describe the calculations for each of these risk scores individually and then combined.

Zonally Weighted Arrival Time Risk Score

The calculation proceeds as follows. First, the arrival time from release box i to zone j is computed for each of the 10 release scenarios. Then the average arrival time is computed across the release scenarios. The average arrival time from release box i to zone j is defined as $t(i,j)$. Since risk is inversely proportional to arrival time the arrival time risk for release box i on zone j ($T(i,j)$) is defined as:

$$T(i,j)=1-t(i,j)/max(t(i,j) ,$$

In cases where 10% of the particles from release box *i* did not arrive in zone *j* within 30 days, the arrival time as defined on page 27 was undefined. In this study it was set to 31 days and as a result the value of max(t(*i,j*))=31 days.

The zonally weighted arrival time risk score for each release box was calculated as:

$$R_T(i)= \Sigma\ (T(i,j) * w_j) / \Sigma\ w_j ,$$

where w_j are the weights for each zone from Appendix 1 (Table A1-4) and j = 1 - 64 (i.e., 64 zones). The definition of R_T was chosen so that it would be a dimensionless number scaled from 0 to 1 where 0 represents lowest risk (longest weighted arrival time) and 1 represents highest risk (shortest weighted arrival time).

Zonally Weighted Frequency of Occurrence Risk Score

The frequency of occurrence was calculated by counting particles in each zone at each time step (units of particle days) for each of the 10 release scenarios. Then the average number of particle days in zone *j* from release box *i* was computed (f(*i,j*)). The frequency of occurrence index (F(*i,j*)) was calculated as:

$$F(i,j)=1-f(i,j)/max(f(i,j) ,$$

where f(*i,j*) is the number of particle days contributed to zone *j* from release box *i* and max(f(*i,j*)) is the maximum potential value of f (product of the number of particles released and the length of the simulation).

The final, but still relative, risk for each release box based on frequency of occurrence was determined using the weightings for each zone in the following way:

$$R_F(i) = \Sigma\ (F(i,j) * w_j) / \Sigma\ w_j$$

where w_j are the weights from Appendix 1 (Table A1-4) and j = 1 - 64 (i.e., 64 zones)

Combining Arrival Time and Frequency of Occurrence Scores

For this study the arrival time and frequency of occurrence scores were weighted equally, so the combined risk score is:

$$R(i) = 0.5R_T(i)+ 0.5R_F(i),$$

with 0 being low relative risk, and 1 being high relative risk.

APPROACHES FOR PRESENTATION OF RISK RESULTS

The sensitivity of the results to various presentation approaches was tested by partitioning the data into five relative risk categories using equal numerical breaks (i.e., linear scale) and using natural breaks, and without partitioning using monochromatic colour shading from black (highest) to white (lowest). The natural breaks were calculated using k means to cluster the data into five categories for risk comparison, but with randomness eliminated from the algorithm. The "Jenks" method of identifying natural breaks was also tested but not used, as it was insensitive to local differences created by features such as pinch-points and shallows. When using natural breaks, the relative risk definitions vary depending upon the weighting scheme (see below).

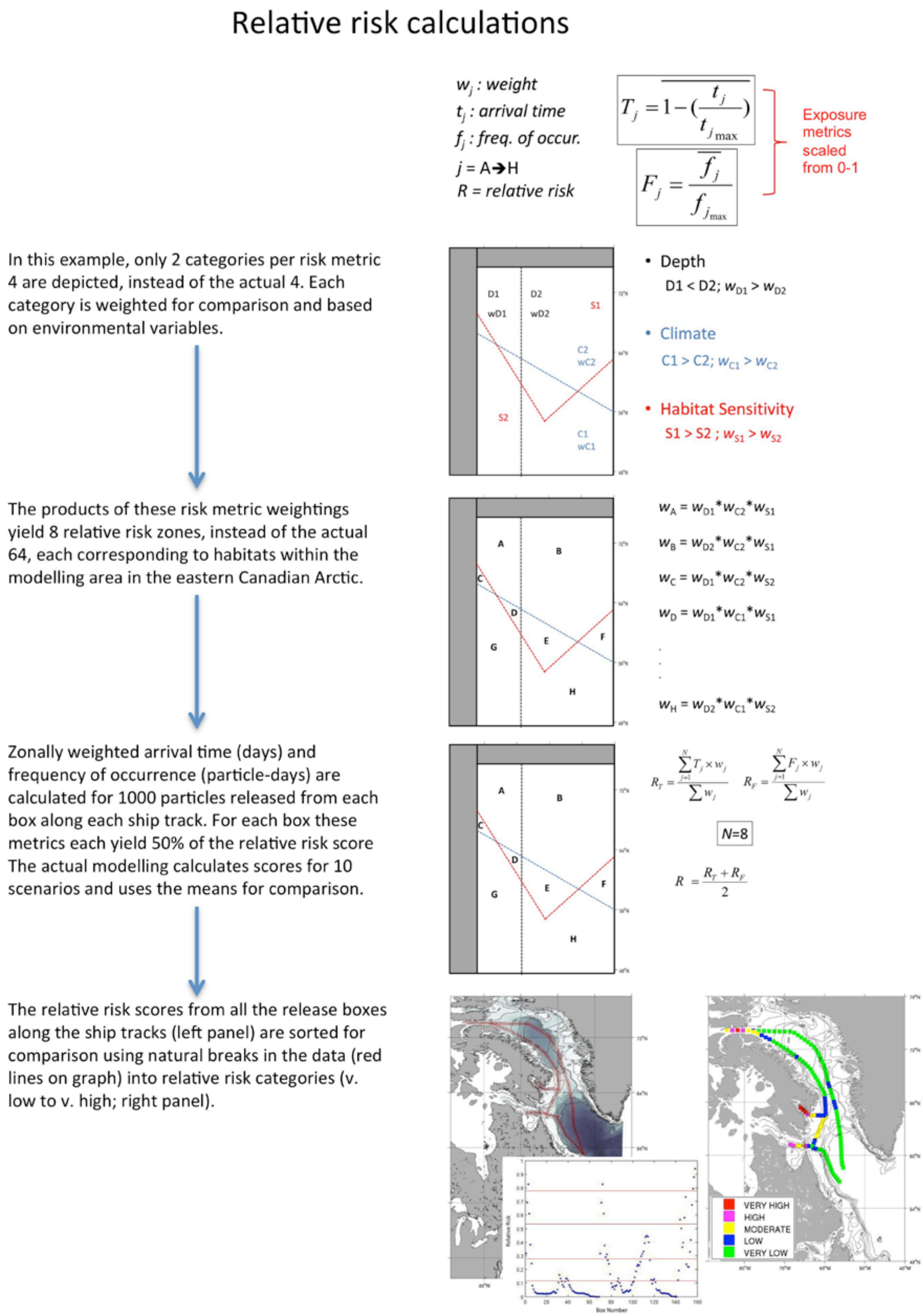

Figure 20. Schematic illustrating key steps in the relative risk calculations and comparison.

RESULTS

PARTICLE DISPERSAL

Summer surface currents embedded in the CECOM model (Figure 21) disperse particles released along the ship tracks at different rates and in different directions (Figure 22). Particle frequencies are greatest in the immediate area of the ship tracks and decrease with distance. Currents tend to disperse the particles from north to south, although east to west currents across the northern Labrador Sea (West Greenland Current) and west to east outflow from southern Lancaster Sound and southern Hudson Strait broaden the dispersal patterns in these areas. The strongest currents driving particle dispersal are predicted along shelf edges, particularly in Davis Strait, southwest of Greenland, and east of Labrador.

SENSITIVITY TESTING

Sensitivity tests helped to inform modelling approaches (e.g., for climate, and ice ocean-circulation models below), assess how robust the modelling results were to different weighting schemes and evaluate different methods for presentation of risk results. The outcomes from these tests are detailed below.

Climate Variables and Categories

No compelling arguments were identified for how best to weight the climate variables (SSS, SST and open water period) relative to one another when developing the climate metric, so four climate index formulations were compared (Figure A2-1—see Appendix 2). All four were significantly correlated (r = 0.746-0.985). These correlations were lowest for 50% SSS and 50% open water period, and highest for equal weighting and 50% SST (n = 11,924). Equal weightings produce results intermediate between the other cases so the climate variables (SST, SSS, open water) were weighted equally for all further modelling.

Based on comparisons of climate maps generated using three, four, or five categories, four climate categories was considered optimal for modelling as this map yielded a pattern that was consistent with the regional oceanography (e.g., it distinguished areas with known freshwater inflows) without greatly increasing the analyses required (Figure A2-2).

Comparisons of Ice-ocean Circulation Model Results

Sensitivity to the underlying circulation models was tested by comparing results from the CECOM and NEMO models (Figure 23) for the Lancaster Sound area. The relative likelihood of establishment, relative habitat sensitivity, and relative risk patterns for Lancaster Sound are similar for both the NEMO and CECOM modelling results, and hold for all weighting schemes. They suggest increasing risk with proximity to the eastern entrance, particularly near the northeastern coast of Bylot Island, and moderate to high risk within Lancaster Sound. [Note: the natural breaks are different for the two models as the ranges of weightings and numbers of points are different.]

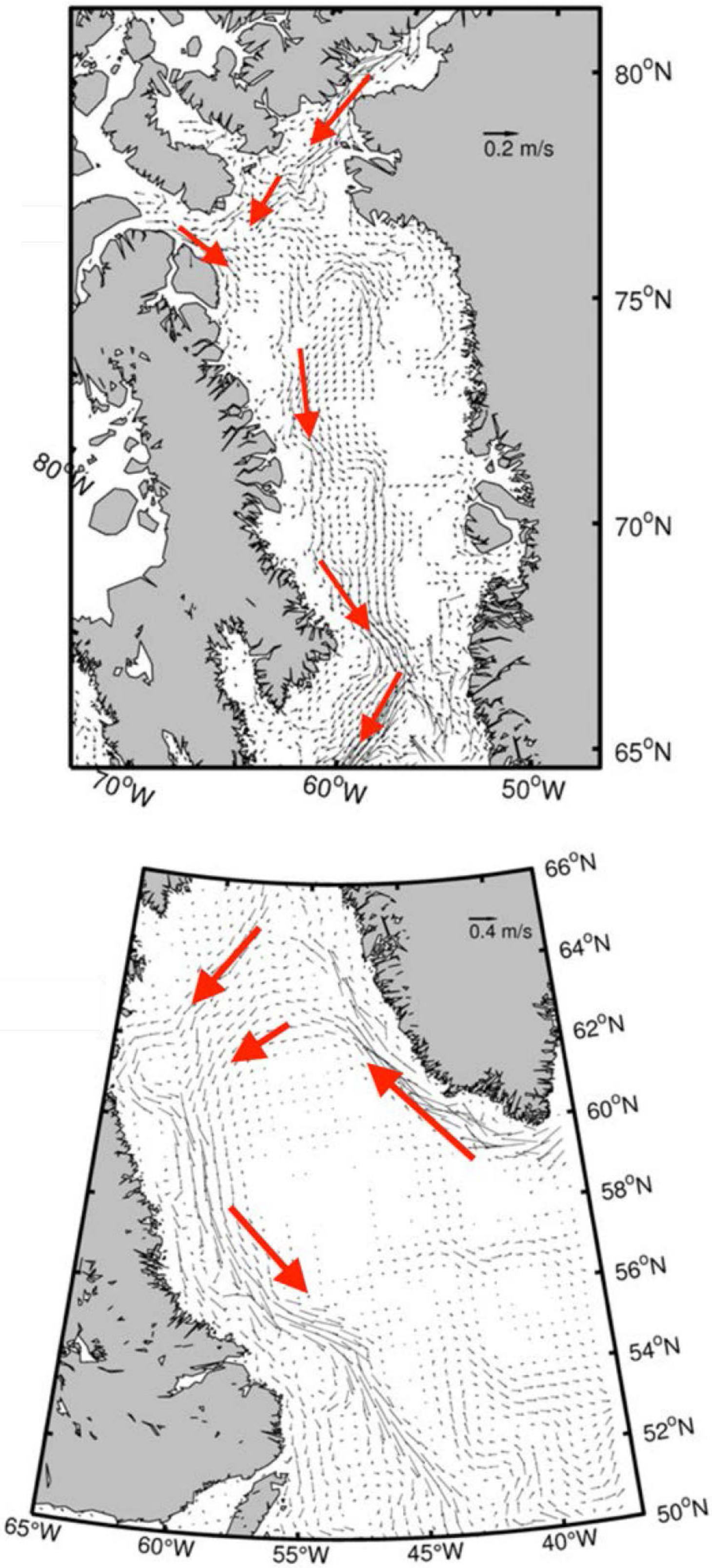

Figure 21. Summer currents at 5 m depth in Baffin Bay-Davis Strait (top) and Davis Strait-Labrador Sea (from CECOM Model).

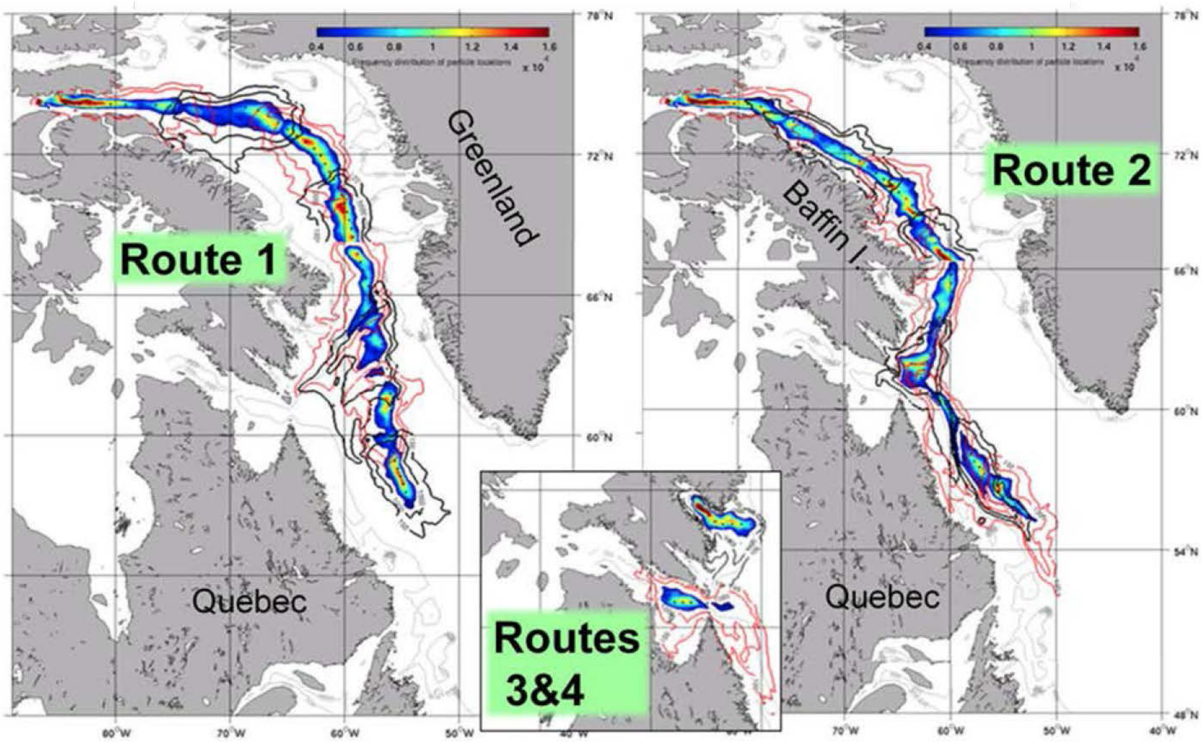

Figure 22. Distribution of particle days per model grid cell (10 km x10 km) 30 days after the particles were released along each shipping route. A black dot denotes the center of each release box (40 km x 40 km). The low values of frequency of occurrence (inner = 1000 particle days; outer = 100 particle days) are shown with red lines for 2 segments and black for 2 segments so both the segments and frequencies can be distinguished.

Comparison of Weighting Schemes

Among the different weighting schemes tested, the combination of depth-geometric and climate-linear were the preferred weightings for modelling and considered most likely to reflect the true relationship between these metrics and likelihood of establishment. The preferred geometric scheme for depth weightings recognized that:

1) light extinction with depth is non-linear,
2) salinity and density increases with depth are non-linear (temperature also changes with depth but not in a consistent pattern),
3) species have different habitat preferences, and
4) likelihood of establishment in offshore pelagic and deepwater benthic habitats is greater than zero.

The geometric interval weightings were preferred as linear weightings did not adequately reflect the exponential decline in light penetration while the other modifying factors (2-4) have more gradual and less predictable patterns of change with depth. Linear weightings were preferred for climate because the incremental changes in risk are uncertain.

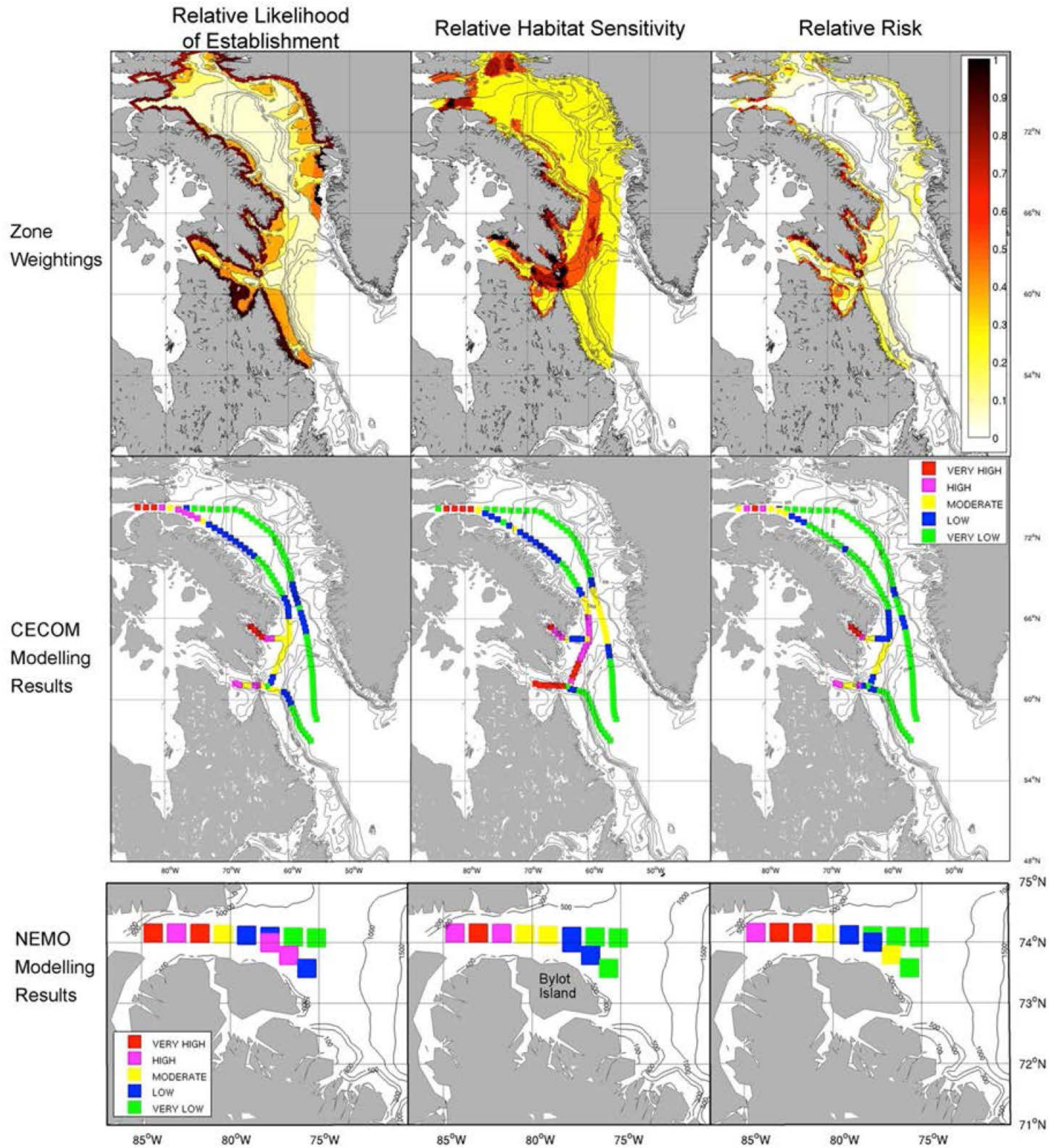

Figure 23. Comparison of the zone weightings and CECOM and NEMO modelling results for relative likelihood of establishment, relative habitat sensitivity, and relative risk from ballast water exchanges along ship tracks into the eastern Canadian Arctic, based on the preferred weighting scheme for relative likelihood of introduction (i.e., depth-geometric, climate-linear).

Despite the above scenario being preferred, all possible combinations of the linear and geometric weighting schemes for climate and depth produced similar results for relative likelihood of establishment (Figure A2-3) and final relative risk (Figures A2-4). This pattern held for both the CECOM and NEMO models. This does not mean that the results are identical, rather that the results are robust to variations in these metrics (Appendix 1). Below we highlight results based on the preferred weighting scenario, but results with other weighting scenarios are presented to allow for comparison.

Approaches for Presentation of Risk Results

Visual comparisons are a simple, powerful method for comparing the risk results, provided the method of depiction does not skew the results. A variety of methods were considered and the most promising were tested: linear breaks, natural breaks, and sequential monochromatic shading. We found that key patterns in the results were apparent with all three approaches tested (Figure A2-5). However, natural breaks calculated with k-means clustering were chosen to depict the results from releases along the ship tracks because they provided the clearest understanding of the relationships between the weightings at different locations. Drawbacks of the other approaches include: partitioning the results into equal bins can arbitrarily group widely different values in one bin and closely similar values in another bin; equal breaks can group many more results into one bin than another; and sequential monochromatic shading can obscure wide differences in the values of sequential cells.

RELATIVE LIKELIHOOD OF ESTABLISHMENT

The relative likelihood of establishment was based on the depth and climate metrics ranked both linearly and geometrically (Table A1-1a+b, Figures A1-2 and A1-3). For depth, the shallow coastal depth range was weighted highest (1.0) for comparison under both the linear and geometric weighting schemes. This range, unlike the other depth ranges, was set to a precautionary minimum of two grid cells to ensure that shallow habitats were not missed in areas where depths drop sharply from the coast. The remaining depth ranges were weighted higher under the linear case as compared to the geometric case. For climate categories, the sub-Arctic located in the eastern portions of Davis Strait and the Labrador Sea had the highest ranking of 1.0 under both linear and geometric weighting schemes. The remaining three categories (High Sub-Arctic to Arctic) had slightly higher rankings and were better differentiated with the linear weighting scenario. When depth and climate weightings were combined for analysis the preferred case (depth-geometric, climate-linear) had a broader range of weightings and a more abrupt decline in weightings with depth than the depth-linear cases (Table A1-2, Figure A1-4; see also Figure 23). The climate-geometric, depth geometric case was similar to the preferred case, but with slightly lower weightings and differentiation among depths, particularly near shore.

Under the preferred case, the relative likelihood of establishment from releases along the ship tracks is typically very high or high within the confines of Lancaster Sound, Cumberland Sound, and Hudson Strait (Figure 23). It is moderate to high near the entrances of these areas and over the relatively shallow shelf southeast of Baffin Island, dropping to low at the shelf edge and over the Canada-Greenland Ridge, and to very low offshore the shelf break. The relative rankings increase by about one category (e.g., very low to low) over areas of the Baffin Shelf and within Hudson Strait under the linear cases (depth-linear, climate-linear) but the patterns remain similar (Figure A2-3). The climate-geometric cases have slightly lower relative likelihood of establishment in the high sub-Arctic to Arctic categories compared to the climate-linear cases.

RELATIVE HABITAT SENSITIVITY

The relative habitat sensitivity weightings were developed from variables that provide broad comparisons of biological importance, intolerance to risk, and importance to harvesters (Figure 19). Overlap of highly ranked areas for all three variables suggest that there are particularly sensitive areas of marine habitat in Lancaster Sound, Cumberland Sound, Frobisher Bay, and Hudson Strait (Figure 23). The North Water Polynya, Jones Sound, and coastal waters of eastern Bylot Island (Figure 2) and southeastern Baffin Island also have moderately sensitive habitats, often in the vicinity of communities. Moderately sensitive areas offshore in eastern Hudson Strait and along the shelf break east of Baffin Island are currently important areas for commercial harvesting. Particles released along the ship tracks in Hudson Strait, Lancaster Sound and Cumberland Sound, over the shelf southeast of Baffin Island, and over the Canada-Greenland Ridge are most likely to affect sensitive habitats (Figure 23).

RELATIVE RISK

Combining the relative likelihood of establishment and relative habitat sensitivity weightings to model relative risk effectively concentrates the high-risk weightings in the shallowest waters (i.e., coastal depth range) of southeastern Baffin Island (south of ca. 70°N), eastern Lancaster Sound, Hudson Strait, and Ungava Bay (Table A1-4, Figure A1-6; see also Figure 23). Compared to likelihood of establishment and habitat sensitivity by themselves there is an overall reduction in weighting with distance offshore and with increasing Arctic character. As with relative likelihood of establishment, the preferred case (depth-geometric, climate-linear) has a broader range of weightings and a more abrupt decline in weightings with depth than the depth-linear cases (Figure A2-4). The climate-geometric cases also have slightly lower weightings for the high sub-Arctic to Arctic categories compared to the climate-linear cases.

Under the preferred case, the relative risk from releases along the ship tracks is very high to moderate high within the confines of Lancaster Sound, Cumberland Sound, and Hudson Strait (Figure 23). It is moderate to low near the entrances of these areas and over the relatively shallow shelf southeast of Baffin Island, dropping to low to very low at the shelf edge and over the Canada-Greenland Ridge, and to very low offshore the shelf break. The relative risk rankings are somewhat higher for the depth –linear cases but the overall patterns are quite similar for the four risk model cases (Figure A2-4).

DISCUSSION

All of the CECOM model results show the same basic patterns of elevated likelihood of introduction, habitat sensitivity, and relative risk within confined areas (e.g., Hudson Strait, Cumberland Sound, Lancaster Sound) and where shelves extend well offshore (e.g., SE Baffin shelf and Canada-Greenland Ridge). Analyses using the preferred weightings (depth-geometric and climate-linear) provide a robust example for discussion purposes (Figure 24). They also suggest that live biota discharged during ballast water exchange in or near these areas are more likely to find suitable habitats for establishment and to affect areas considered intolerant of risk. Consequently, ABWEZs should be established in areas where biota released during exchange are least likely to disperse into these habitats.

The anthropocentric, nearshore nature of the variables used to develop the relative habitat sensitivity metric reflects current limitations on knowledge of the study region. Most human marine activities are coastal, which limits offshore observations, and the region is remote, which limits research by making it difficult and expensive. Charismatic megafauna are over-represented because they are important to humans and more readily observed than plankton. A consequence of these biases is that areas considered intolerant of risk on the basis of limited knowledge may not accurately reflect habitat sensitivity (relative or absolute). There are no easy solutions to this problem, nor is one likely in the near future. The area is too large, the problem too complex, and ice cover severely constrains *in situ* research and remote sensing as means of improving understanding.

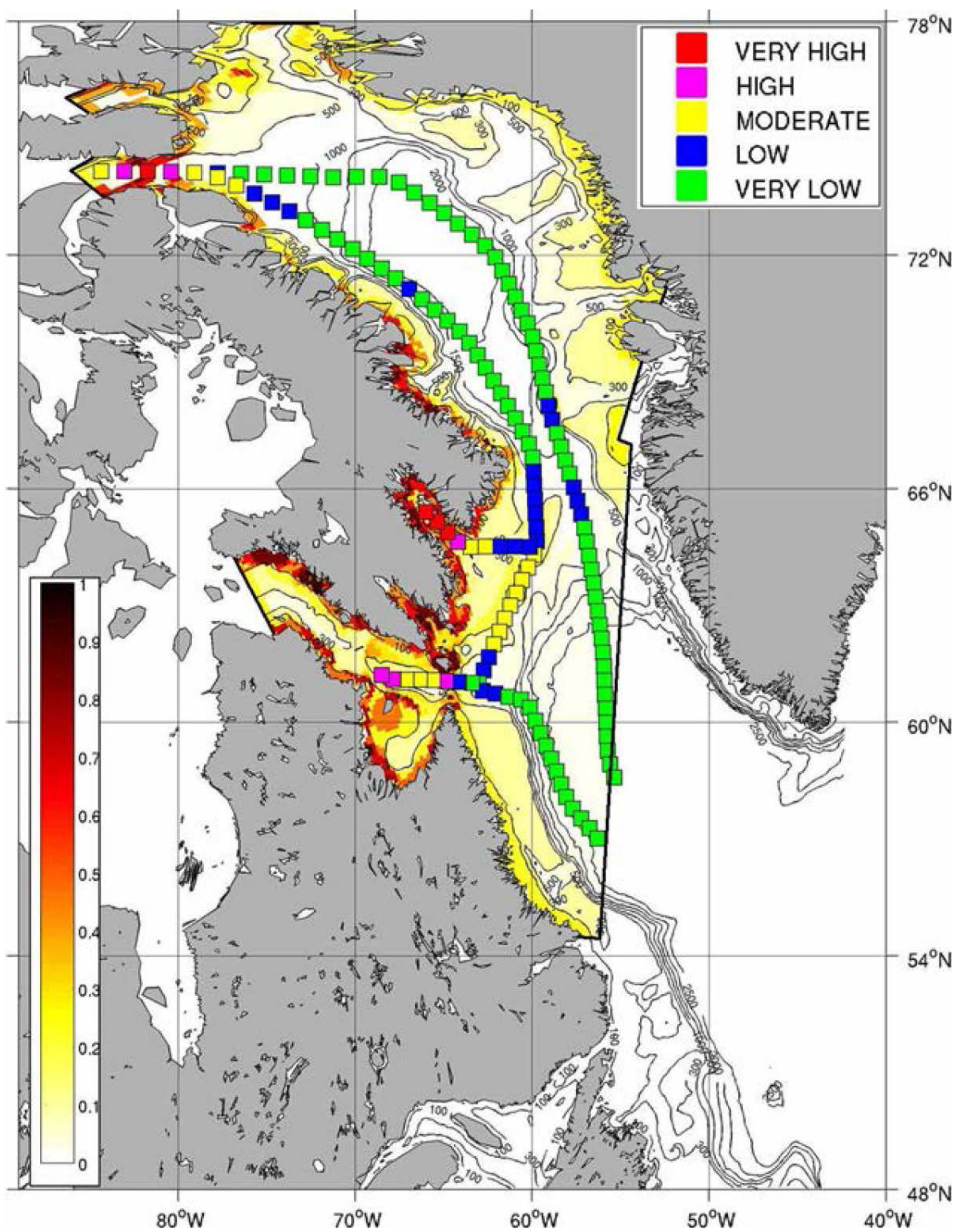

Figure 24. Relative risk from ballast water exchanges along ship tracks into the eastern Canadian Arctic (key upper right) overlain on the preferred weighting scheme for relative risk (i.e., depth-geometric, climate-linear; key lower left). Black lines indicate the extent of model grid cell weightings.

Charismatic megafauna, as integrators of biological productivity, probably provide the best available indicators of biologically important habitats. Chlorophyll a concentration (mg/m^3), which can be measured at the surface throughout the study area using satellite remote sensing (e.g., NASA Giovanni SWFMO), was considered as a habitat sensitivity variable but not used. Satellite estimates of mean concentrations at the surface are confounded by sea ice and cloud cover, and closely related to the duration of the open water. Because they measure concentration at the surface rather than productivity within the water column their value as an indicator of habitat sensitivity is uncertain. Given the potential for ecological damage from NIS introductions, the uncertainties surrounding habitat sensitivity and other factors support taking a precautionary approach to the selection of ABWEZs until the absolute (non-relative) risk from ballast water exchange is better understood.

Modelling under summer conditions should represent a precautionary worst-case scenario. In winter, the relative likelihood of establishment of biota from warmer coastal environments will be diminished by the presence of sea ice, colder water temperatures and higher salinity. Shipping may also be reduced in winter although ore carriers that do operate in winter will carry more ballast water to optimize their draft for icebreaking. The relative habitat sensitivity may be lowered by the seasonal reduction in migratory species such as anadromous fishes, marine mammals, and seabirds. In winter, the relative likelihood of exposure will also be lower in sensitive habitats. Winter surface currents have the same general direction of circulation but tend to be weaker as sea ice cover limits wind forcing, so particle dispersal should be slower in winter. Ice presence and quality also affect vessel travel routings and speeds.

Modelling particle dispersal using the surface layer is also precautionary. This approach does not factor in sinking losses so it should overestimate particle exposure of both deep offshore and shallow coastal habitats. Relative to deeper layers, the surface waters are less saline and offer a greater range of temperatures, which may increase risk. The surface waters are most directly affected by ballast water exchange, sea ice, and most human activities. Sea ice has year-round effects due to the barrier it creates, scouring action, and salinity changes. These effects are greater in winter than in summer but must be factored into both seasons. Most biota will be small enough that transport will be essentially passive. Underestimating particle dispersal rates, passive or active, could increase the relative exposure of coastal and shelf habitats although this could be offset somewhat by reduced residence time in a particular grid cell--and vice versa. In both instances the overall risk pattern is likely to remain similar albeit with localized shifts in relative risk. The 30-day modelling period provides a relative likelihood of exposure throughout the model domain (Figure 22). Modelling particle dispersal using shorter and longer periods will not reduce uncertainty related to the relative risk, since the species and their tolerances are unknown and the benefits of longer survival for locating suitable habitat may be offset by greater dispersal.

This study focused on the impacts to coastal species and not on deeper water species, and does not consider harmful phytoplankton, microalgae, zooplankton, and cysts of phytoplankton and algae that could be introduced by ballast water. Harmful phytoplankton and algae in particular may increase with temperature increases associated with climate change and could be harmful to species such as seabirds and walrus that consume shellfish. To mitigate underestimation of the offshore risks as a potential source of error the deep offshore depth range was given low but non–zero weightings for most variables. This approach should tend to overestimate the relative risk associated with deeper water, particularly along the deep route where particles are released directly into deep offshore grid cells giving them much greater relative likelihood of exposure. Habitat sensitivity data from Greenland and Labrador were not included in the model. This will tend to underestimate relative risk in these areas but the overall patterns should remain due to the influence of depth and climate variables that have been used to compare relative likelihood of establishment.

The linear weighting of climate may overestimate northern risks related to establishment and impact somewhat but is risk averse since risk may change in response to climate change. The climate categories that were developed from SSS, SST, and duration of the open water period correspond well to biogeographical delineations of Arctic and Subarctic waters based on bivalve molluscs (Lubinsky 1980) and on physical, chemical and biological oceanography (Dunbar 1953:214; see also Dunbar and Moore 1980). Their similarities add confidence to the use of these categories for modelling likelihood of establishment. The Arctic–boreal ichthyofaunal boundary proposed by Mecklenburg et al. (2011) for fish is less useful for comparison with this work as it relied heavily on seafloor topography and deepwater species.

The Arctic water mass is typically more stable in the water column and therefore less productive than the Subarctic (Dunbar and Moore 1980). This lower productivity, the scouring action of ice, low air and water temperatures, and seasonal freshening of the surface waters limit the intertidal fauna (Dunbar and Moore 1980; Lubinsky 1980; Lee 1973, 1980). In the Subarctic these intertidal fauna increase gradually moving southward, beginning with the appearance of the common barnacle *Balanus balanoides*, snails within the genus *Littorina*, and a few Gammarid amphipods. The diversity of flora and fauna is much lower in the Arctic zone, which supports species that are strictly Arctic in distribution and some Subarctic species whereas the Subarctic zone contains species of wide distribution (Arctic-Subarctic, Subarctic-Boreal, Panarctic-Boreal), and a few strictly Subarctic species.

Lubinsky (1980) did not agree with Dunbar's classification of Cumberland Sound as "Arctic". She was supported in this by Aitken and Gilbert (1986) on the basis of the occurrence and abundance of Subarctic species such as *Littorina saxatilis*, *Macoma balthica*, *Balanus balanoides*, *Fucus vesiculosus* and *Lathromorphum circumscriptum* in Pangnirtung Fiord (66°07'00" N, 65°37' 35" W). Many North Atlantic species are near the northern edge of their distribution in the waters of southeastern Baffin Island and southwestern Greenland, which are transitional zones between Arctic and Subarctic waters (see also Dunton 1992). Based on this uncertainty the model may underestimate the relative risk from ballast water exchanges in Cumberland Sound, which may provide a more favourable environment for establishment than modelled climate categories suggest.

Tidal range, bottom substrate, and coastal morphology are modifiers of invasion risk that were not included directly in the modelling. Tides may increase the risk of pelagic establishment by creating strong currents that maintain polynias. Tidal effects will be largely coastal but high tides and related ice scour should reduce risk in some high risk areas—particularly for species with limited mobility that are sensitive to exposure to air, freezing, or crushing. The upper 3 m of the nearshore zone is often depauperate, with benthic flora present in low numbers and low variety, giving the impression from shore that the Arctic marine environment is barren and unproductive. While ice scour must contribute to this phenomenon, exposure to cold air and water temperatures and to low salinity during and following ice melt will also contribute (Lee 1973, 1980). Below this zone there are often well-developed benthic communities consisting of a wide variety of kelp, anemones, sponges, etc. The greatest tidal effects should occur along the coasts and in shallow areas of Ungava Bay and Hudson Strait and along the southeastern coast of Baffin Island (Figure 10). Bottom substrate types and coastal morphology tend to be closely associated with depth so they have not been considered separately. Exceptions may occur in close proximity to glaciers that release large inputs of fine sediment (glacial flour) (e.g., Gilbert 1982) and in areas where coastal development protects habitats from or exposes them to wave action.

Based on our modelling, particles released in central Baffin Bay tend to move toward Baffin Island and then disperse south with the Baffin Island Current; those released in Davis Strait and Labrador tend to move along the shelf edge or offshore due to strong currents in the coastal and shelf depth ranges. The farther east of the deep ship track that ballast water exchange is conducted, north of about 62°N latitude, the more likely discharged particles are to be dispersed into shallower waters along the Greenland coast. Likewise, the farther west of the coastal track that ballast water exchange is conducted, south of about 60°N, the more likely particles are to disperse into shallower waters along the Labrador coast. Along-shore currents (i.e., West Greenland Current and Labrador Current) offer both coasts some protection from offshore particle dispersal. In both areas relative risk could increase substantially as the discharge tracks approach the 300 m depth contour or enter these currents, which would tend to disperse them over the respective coastal shelves.

The CECOM results suggest that the areas of least risk are bounded approximately by the 1000 m depth contour. Given the relatively steep shelf breaks this depth is not far offshore from the 300 m depth contour in the western Labrador Sea and much of western Baffin Bay. This depth would allow ample distance (>400 km) for discharge to occur within the EEZ when approaching Hudson Strait from the Labrador Sea and Lancaster Sound from Baffin Bay.

ABSOLUTE RISK

> *"The mid-ocean exchange of ballast water and associated risk of invasion is a complicated problem combining ocean physics and biology. The model computes the risk relative to the population of possible outcomes, allowing a decision to be made regarding the safest region in which to exchange ballast water. We are still a long way from determining the absolute risk associated with this process." Brickman (2006:2758).*

This elegant summary for the Atlantic coast also applies to the eastern Canadian Arctic, where less is known of the oceanography, greater seasonal changes occur, and the ice environment is in flux. Until these absolute risks are better understood it is essential to take a precautionary approach to ballast water discharges, offshore and in ports.

RECOMMENDATIONS

1) For vessels enroute westward into the eastern Canadian Arctic, the existing ABWEZs in Lancaster Sound and Hudson Strait are among the areas of highest relative risk for introductions of NIS via ballast water.
2) To reduce risk, it is recommended that ABWEZs within the eastern Arctic be situated offshore of the 1000 m depth contour in waters between latitudes 57° and 75°N, and longitudes 56° and 73°W (Figure 25).
3) Vessels entering waters under Canadian jurisdiction from outside the EEZ should use an ABWEZ as a last resort.
4) To further mitigate risks from organisms in the ballast sediment, it is recommended that vessels entering Canadian Eastern Arctic from beyond the EEZ not in ballast flush their residuals from the ballast tanks prior to entering waters under Canadian jurisdiction. An ABWEZ should be used as a last resort.
5) There are currently no regulations for ballast water exchange for vessels operating within the EEZ. Given the potential for transfer of both indigenous and established NIS from southern Canada (and northeastern United States) by these vessels, the recommended ABWEZs would also be appropriate for ballast water exchange and flushing for vessels arriving from southern Canada regardless of whether they have taken on fresh- or marine ballast water. Recognizing operational constraints of vessels coming from southern Canada, further research is needed to assess options for exchange zones closer to shore that could be used by these vessels.
6) Under the current regulations Canada does not require the reporting of the origin of ballast water for vessels operating within the EEZ. Such knowledge would improve our abilities to understand ballast mediated NIS introductions. It is recommended that reporting of these data be a mandatory requirement for vessels operating within the EEZ.

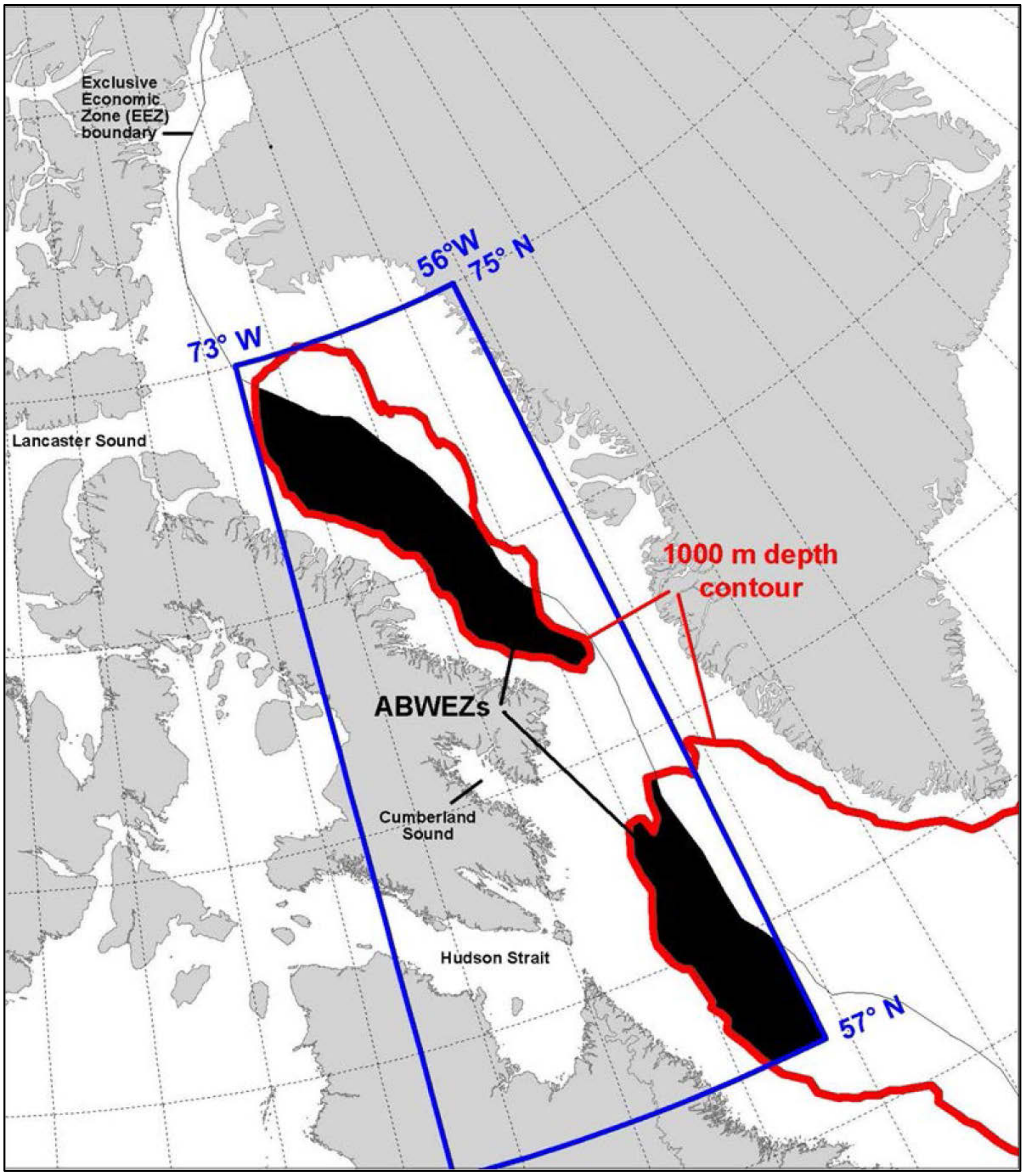

Figure 25. Recommended ABWEZs for the eastern Canadian Arctic are shaded in black.

7) We have a limited understanding of the species found in the ballast of vessels travelling into the Arctic, their interactions with native fauna, their ability to establish in the Arctic and their impacts. Research regarding these knowledge gaps is needed to improve our abilities to understand ballast mediated NIS introductions.

8) Research on content of ballast water tanks is needed to evaluate survival of propagules (species and numbers) prior to exchange and prior to release in port.

9) Research is needed to assess propagule pressures[9] at release and the ability of live species to survive under conditions found in eastern Arctic waters.

[9] 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.

10) Research is also needed to assess the effectiveness of ballast water treatment options under Arctic winter conditions to determine whether they offer a viable alternative to exchange. Research is needed to test environmental effects of ballast water treatment options (discharge) on Arctic environment/native biota.

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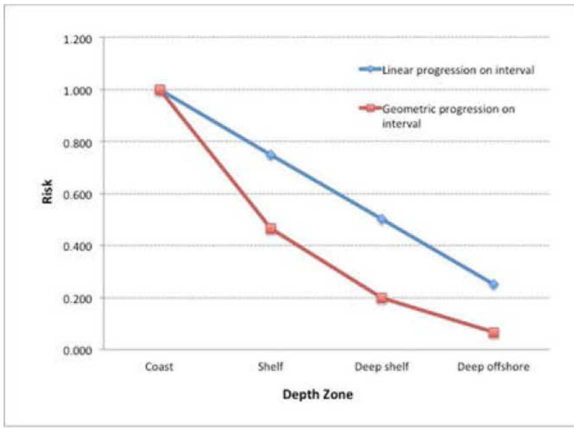
APPENDIX 1. WEIGHTING SCHEMES



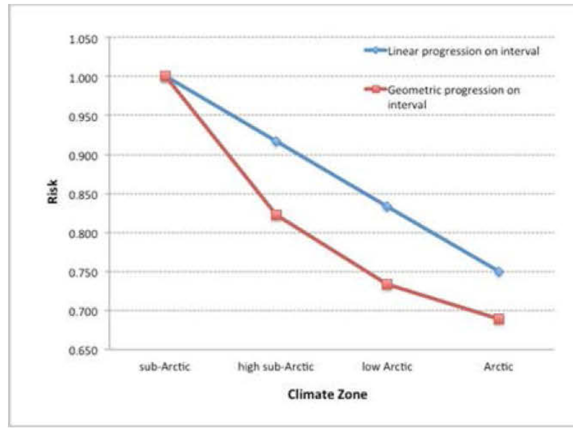


Figure A1-1 (above) and Table A1-1a (below). Climate category weightings extend over a scale from 1 (high) to 0.667 (low) and depth weightings over a scale of 1 (high) to 0 (low) (see Figures A1-2 and A1-3). The Y-axes have different scales to show the similar patterns of decline in risk weightings over both ranges. The geometric intervals double with each progression from low to high (i.e., 0.667 to 1; or 0 to 1). The upper limit of each bin is used to avoid null weightings.

	upper limit	Geometric progressions in bin size							lower limit			
		8x		4x		2x		x				
Geometric progression on intervals depth (1-0)	1.0000		0.4667		0.2000		0.0667		0.0000	**where x = (1-0)/15**	**or**	0.0667
		0.5333		0.2667		0.1333		0.0667		**sum of the progressions**	=	1.0000
Geometric progression on intervals climate (1-0.667)	1.0000		0.8224		0.7336		0.6892		0.6670	**where x = (1-0.667)/15**	**or**	0.0222
		0.1776		0.0888		0.0444		0.0222		**sum of the progressions**	=	0.3330

Table A1-1b. Depth and climate category weightings (linear, geometric) for comparing relative likelihood of establishment (see Figures A1-2 and A1-3).

Depth suitability:	**Coast**	**Shelf**	**Deep shelf**	**Deep offshore**
Linear interval depth	1.000	0.750	0.500	0.250
Geometric interval depth	1.000	0.467	0.200	0.067
Climate suitability:	**sub-Arctic**	**high sub-Arctic**	**low Arctic**	**Arctic**
Linear interval climate	1.000	0.917	0.834	0.750
Geometric interval climate	1.000	0.822	0.734	0.689

Table A1-2. Relative likelihood of establishment weighting for each depth x climate category combination under different weighting schemes (linear, geometric) (see Figure A1-4).

Depth category	**Climate category**			
(Weighting scheme)	**sub-Arctic**	**high sub-Arctic**	**low Arctic**	**Arctic**
Coast				
Case 1: linear depth-linear climate	1.000	0.917	0.834	0.750
Case 2: linear depth-geometric climate	1.000	0.822	0.734	0.689
Case 3: geometric depth-linear climate	1.000	0.917	0.834	0.750
Case 4: geometric depth-geometric climate	1.000	0.822	0.734	0.689
Shelf				
Case 1: linear depth-linear climate	0.750	0.688	0.625	0.563
Case 2: linear depth-geometric climate	0.750	0.617	0.550	0.517
Case 3: geometric depth-linear climate	0.467	0.428	0.389	0.350
Case 4: geometric depth-geometric climate	0.467	0.384	0.342	0.322
Deep Shelf				
Case 1: linear depth-linear climate	0.500	0.458	0.417	0.375
Case 2: linear depth-geometric climate	0.500	0.411	0.367	0.345
Case 3: geometric depth-linear climate	0.200	0.183	0.167	0.150
Case 4: geometric depth-geometric climate	0.200	0.164	0.147	0.138
Deep Offshore				
Case 1: linear depth-linear climate	0.250	0.229	0.208	0.188
Case 2: linear depth-geometric climate	0.250	0.206	0.183	0.172
Case 3: geometric depth-linear climate	0.067	0.061	0.056	0.050
Case 4: geometric depth-geometric climate	0.067	0.055	0.049	0.046

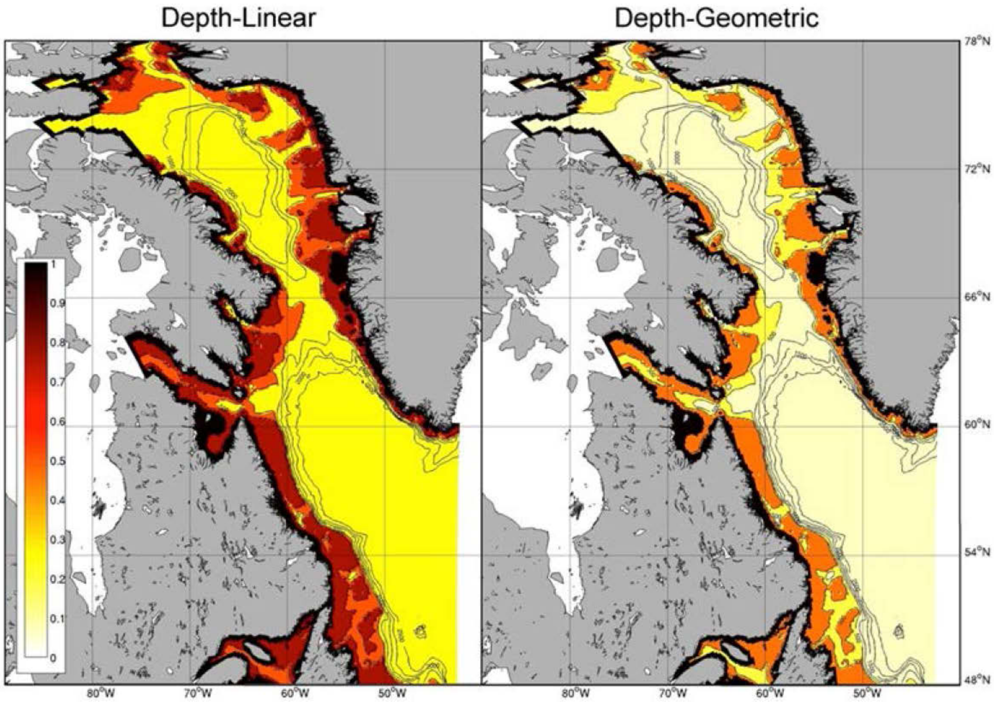


Figure A1-2. Depth category weightings under the linear and geometric weighting schemes (see Tables A1-1a and A1-1b).

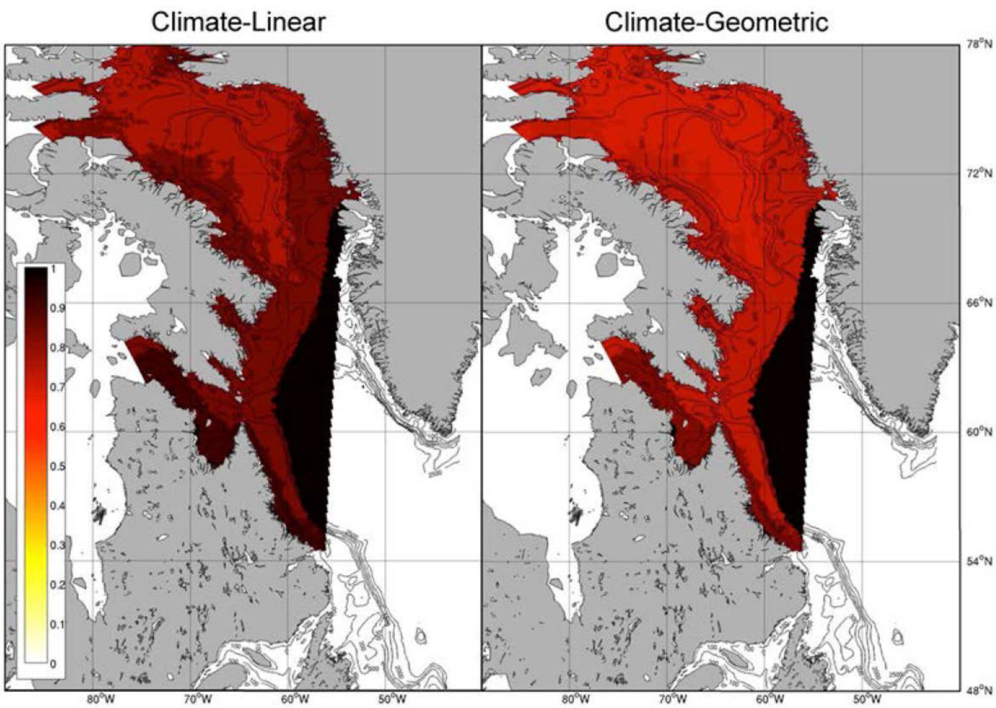


Figure A1-3. Climate category weightings under the linear and geometric weighting schemes (see Tables A1-1a and A1-1b).

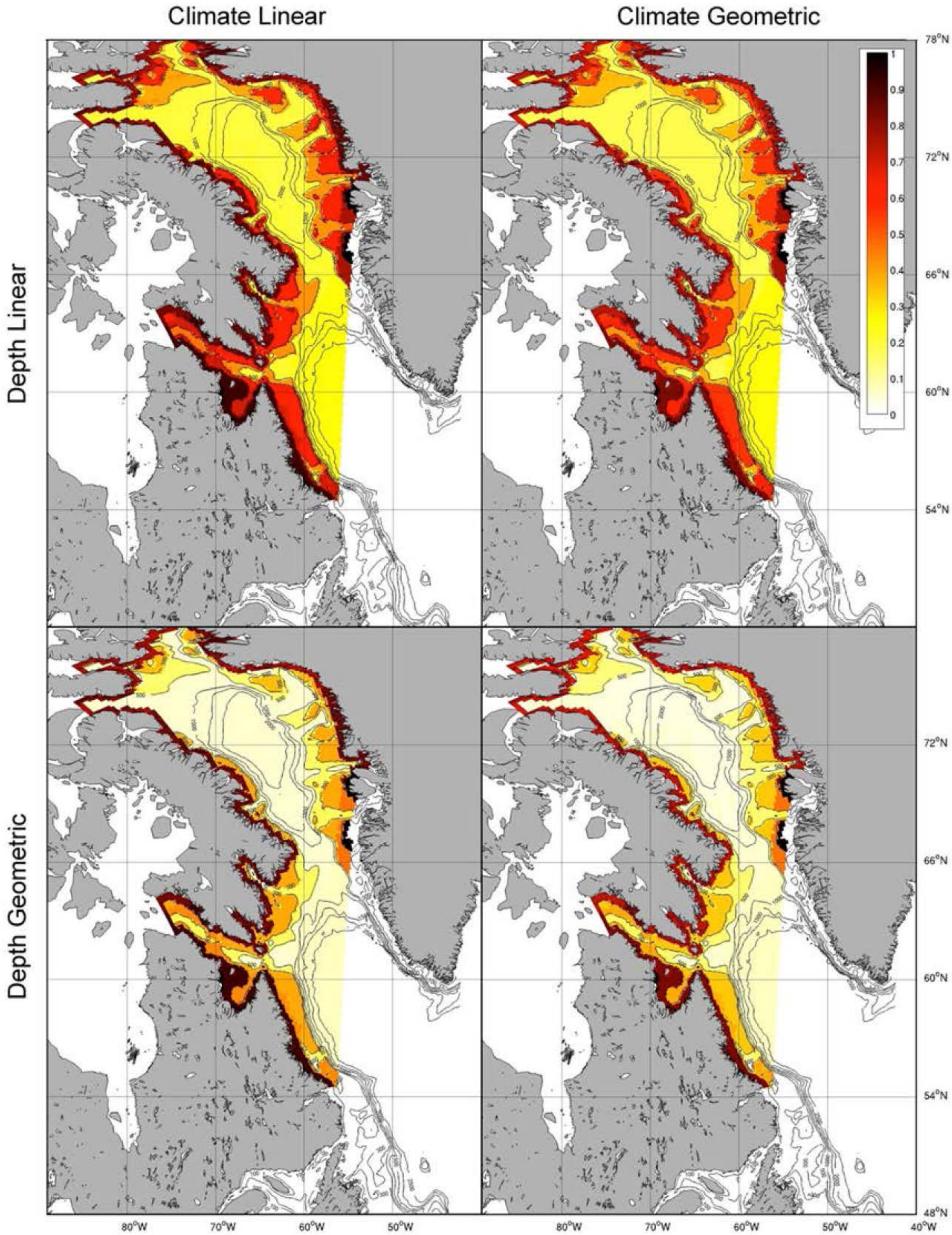


Figure A1-4. Weightings used to model relative likelihood of establishment under different linear and geometric weighting combinations for the depth and climate categories (see Table A1-2).

Table A1-3. Metric category weightings (linear, geometric) for comparing relative risk associated with ballast water release (see Figures A1-2, A1-3, and A1-5).

Depth suitability:	**Coast**	**Shelf**	**Deep shelf**	**Deep offshore**
Linear interval depth	1.000	0.750	0.500	0.250
Geometric interval depth	1.000	0.467	0.200	0.067
Climate suitability:	**sub-Arctic**	**high sub-Arctic**	**low Arctic**	**Arctic**
Linear interval climate	1.000	0.917	0.834	0.750
Geometric interval climate	1.000	0.822	0.734	0.689
Habitat sensitivity:	**High**	**Moderate**	**Fair**	**Low**
Linear interval relative habitat sensitivity	1.000	0.750	0.500	0.250

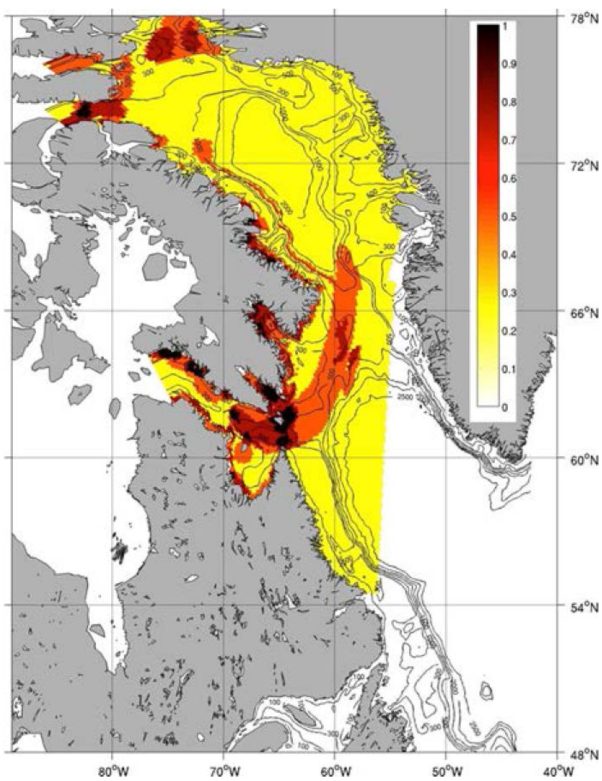


Figure A1-5. Weightings used to model relative habitat sensitivity (see Table A1-3).

Table A1-4. Relative risk weighting for each depth x climate x habitat sensitivity category combination under different weighting schemes (linear, geometric) (see Figure A1-6).

Depth category (Weighting scheme)	**Climate category** (Relative Habitat Sensitivity)															
	sub-Arctic				**high sub-Arctic**				**low Arctic**				**Arctic**			
	High	Moderate	Fair	Low	High	Moderate	Fair	Low	High	Moderate	Fair	Low	High	Moderate	Fair	Low
Coast																
Case 1: linear depth-linear climate	1.000	0.750	0.500	0.250	0.917	0.688	0.458	0.229	0.834	0.625	0.417	0.208	0.750	0.563	0.375	0.188
Case 2: linear depth-geometric climate	1.000	0.750	0.500	0.250	0.822	0.617	0.411	0.206	0.734	0.550	0.367	0.183	0.689	0.517	0.345	0.172
Case 3: geometric depth-linear climate	1.000	0.750	0.500	0.250	0.917	0.688	0.458	0.229	0.834	0.625	0.417	0.208	0.750	0.563	0.375	0.188
Case 4: geometric depth-geometric climate	1.000	0.750	0.500	0.250	0.822	0.617	0.411	0.206	0.734	0.550	0.367	0.183	0.689	0.517	0.345	0.172
Shelf																
Case 1: linear depth-linear climate	0.750	0.563	0.375	0.188	0.688	0.516	0.344	0.172	0.625	0.469	0.313	0.156	0.563	0.422	0.281	0.141
Case 2: linear depth-geometric climate	0.750	0.563	0.375	0.188	0.617	0.463	0.308	0.154	0.550	0.413	0.275	0.138	0.517	0.388	0.258	0.129
Case 3: geometric depth-linear climate	0.467	0.350	0.233	0.117	0.428	0.321	0.214	0.107	0.389	0.292	0.194	0.097	0.350	0.263	0.175	0.088
Case 4: geometric depth-geometric climate	0.467	0.350	0.233	0.117	0.384	0.288	0.192	0.096	0.342	0.257	0.171	0.086	0.322	0.241	0.161	0.080
Deep Shelf																
Case 1: linear depth-linear climate	0.500	0.375	0.250	0.125	0.458	0.344	0.229	0.115	0.417	0.313	0.208	0.104	0.375	0.281	0.188	0.094
Case 2: linear depth-geometric climate	0.500	0.375	0.250	0.125	0.411	0.308	0.206	0.103	0.367	0.275	0.183	0.092	0.345	0.258	0.172	0.086
Case 3: geometric depth-linear climate	0.200	0.150	0.100	0.050	0.183	0.138	0.092	0.046	0.167	0.125	0.083	0.042	0.150	0.113	0.075	0.038
Case 4: geometric depth-geometric climate	0.200	0.150	0.100	0.050	0.164	0.123	0.082	0.041	0.147	0.110	0.073	0.037	0.138	0.103	0.069	0.034
Deep Offshore																
Case 1: linear depth-linear climate	0.250	0.188	0.125	0.063	0.229	0.172	0.115	0.057	0.208	0.156	0.104	0.052	0.188	0.141	0.094	0.047
Case 2: linear depth-geometric climate	0.250	0.188	0.125	0.063	0.206	0.154	0.103	0.051	0.183	0.138	0.092	0.046	0.172	0.129	0.086	0.043
Case 3: geometric depth-linear climate	0.067	0.050	0.033	0.017	0.061	0.046	0.031	0.015	0.056	0.042	0.028	0.014	0.050	0.038	0.025	0.013
Case 4: geometric depth-geometric climate	0.067	0.050	0.033	0.017	0.055	0.041	0.027	0.014	0.049	0.037	0.024	0.012	0.046	0.034	0.023	0.011

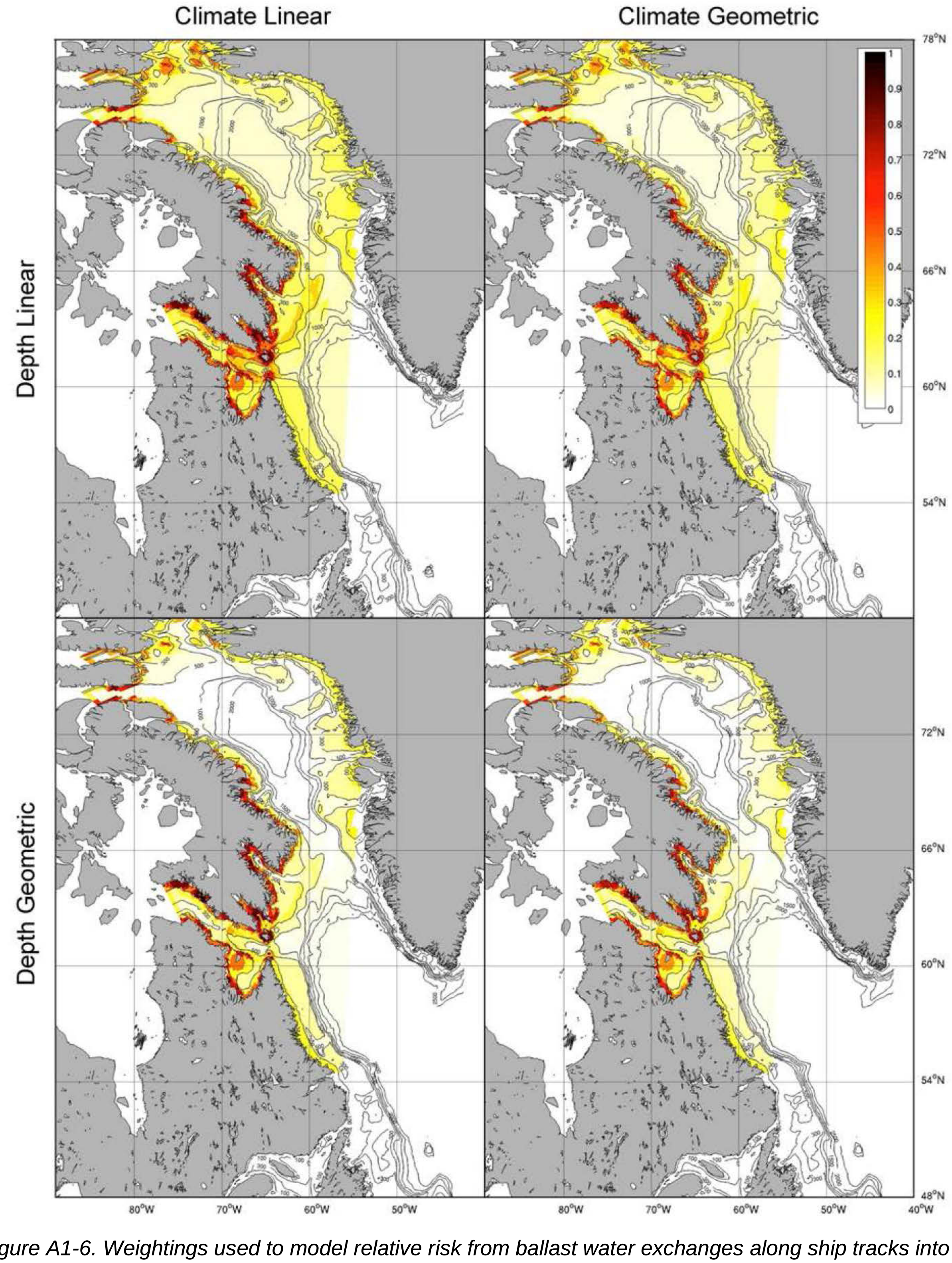


Figure A1-6. Weightings used to model relative risk from ballast water exchanges along ship tracks into the eastern Canadian Arctic based on different linear and geometric weighting combinations for the depth and climate categories in combination with weightings for relative habitat sensitivity (see Table A1-4).

APPENDIX 2. SENSITIVITY TESTING

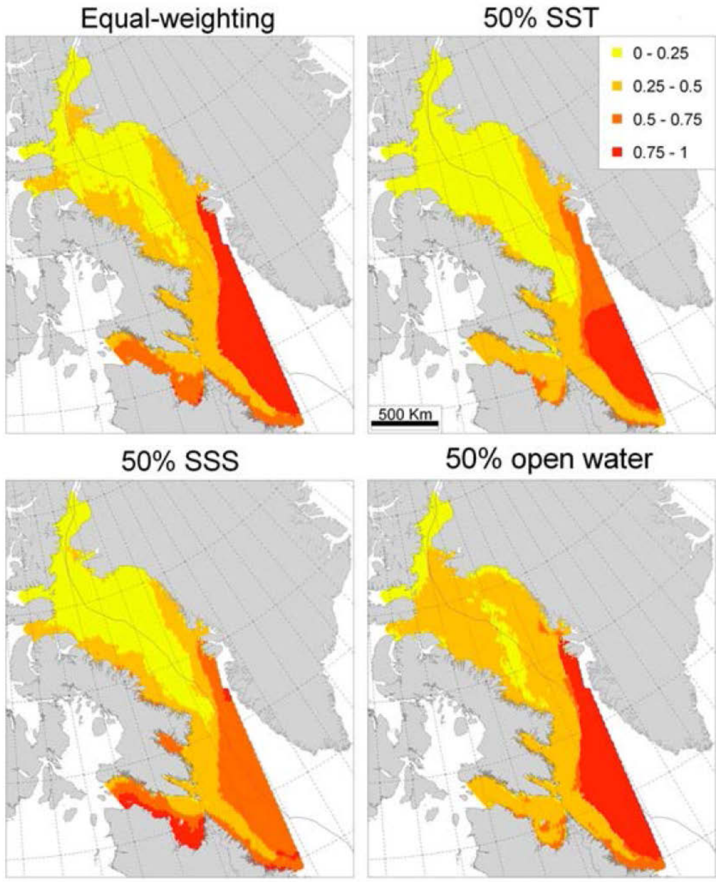


Figure A2-1. Comparison of four different weighting schemes for the climate risk index: equal weighting (all three variables weighted equally [33.33% each) and three formulations with each variable (SST, SSS, open water length) weighted 50% and the other two weighted 25%. All four of the index formulations are significantly correlated (r = 0.746-0.985, lowest for 50% SSS and 50% open water, highest for equal weighting and 50% SST, n = 11,924).

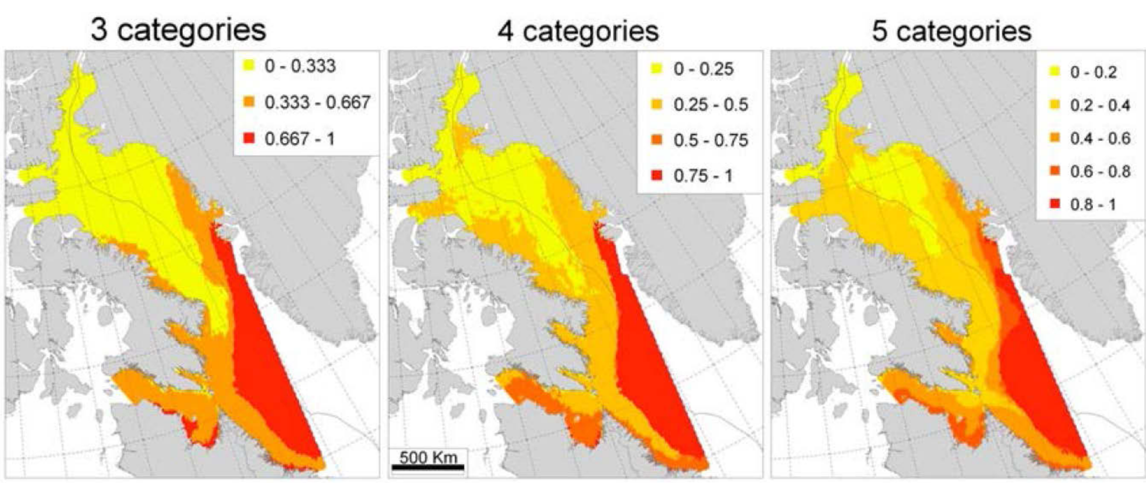


Figure A2-2. Comparison of climate index values (equal-weighting) presented using three, four and five ranges.

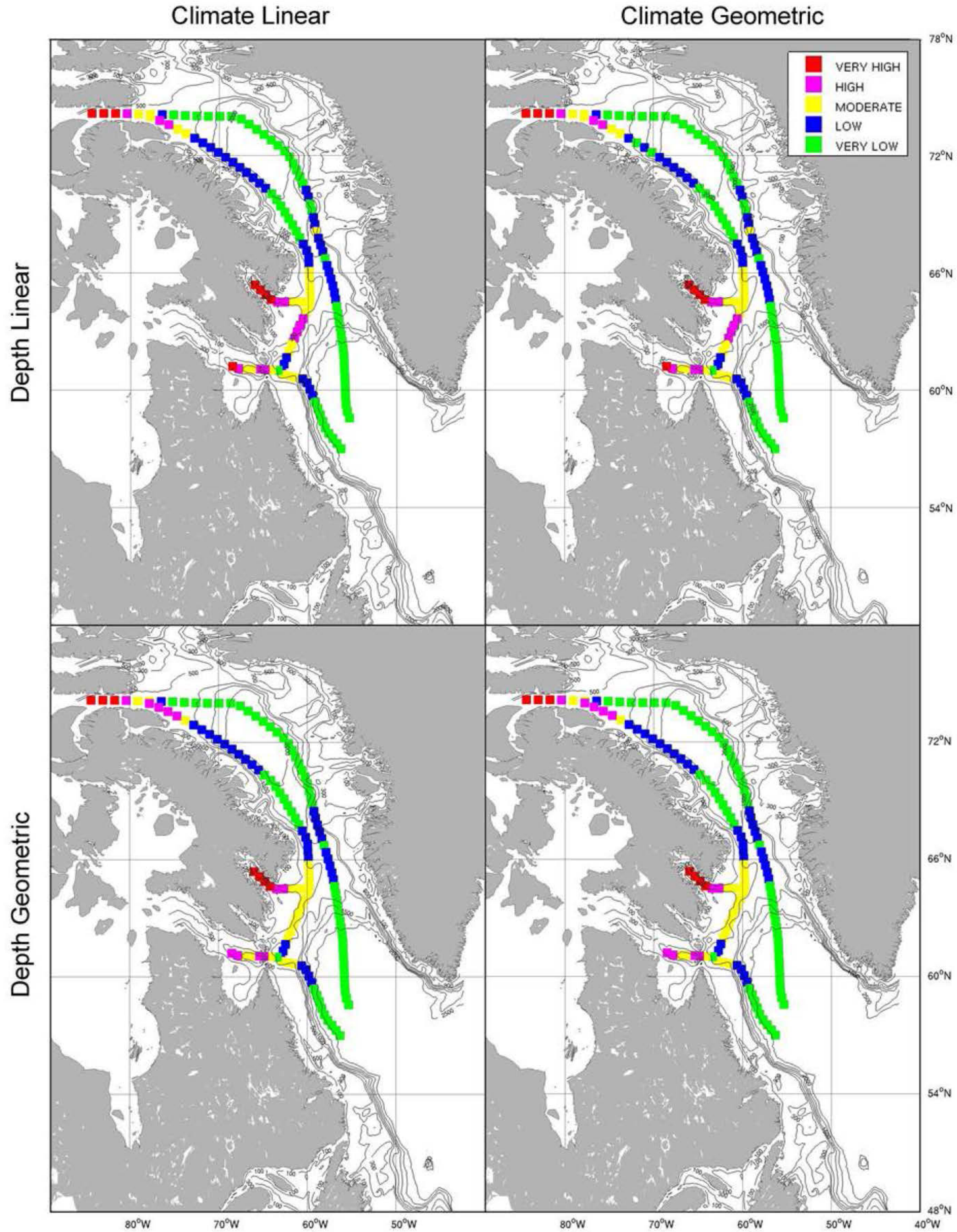


Figure A2-3. Relative likelihood of establishment from ballast water exchanges along ship tracks into the eastern Canadian Arctic based on modelling (CECOM) using different linear and geometric weighting combinations for the depth and climate metrics.

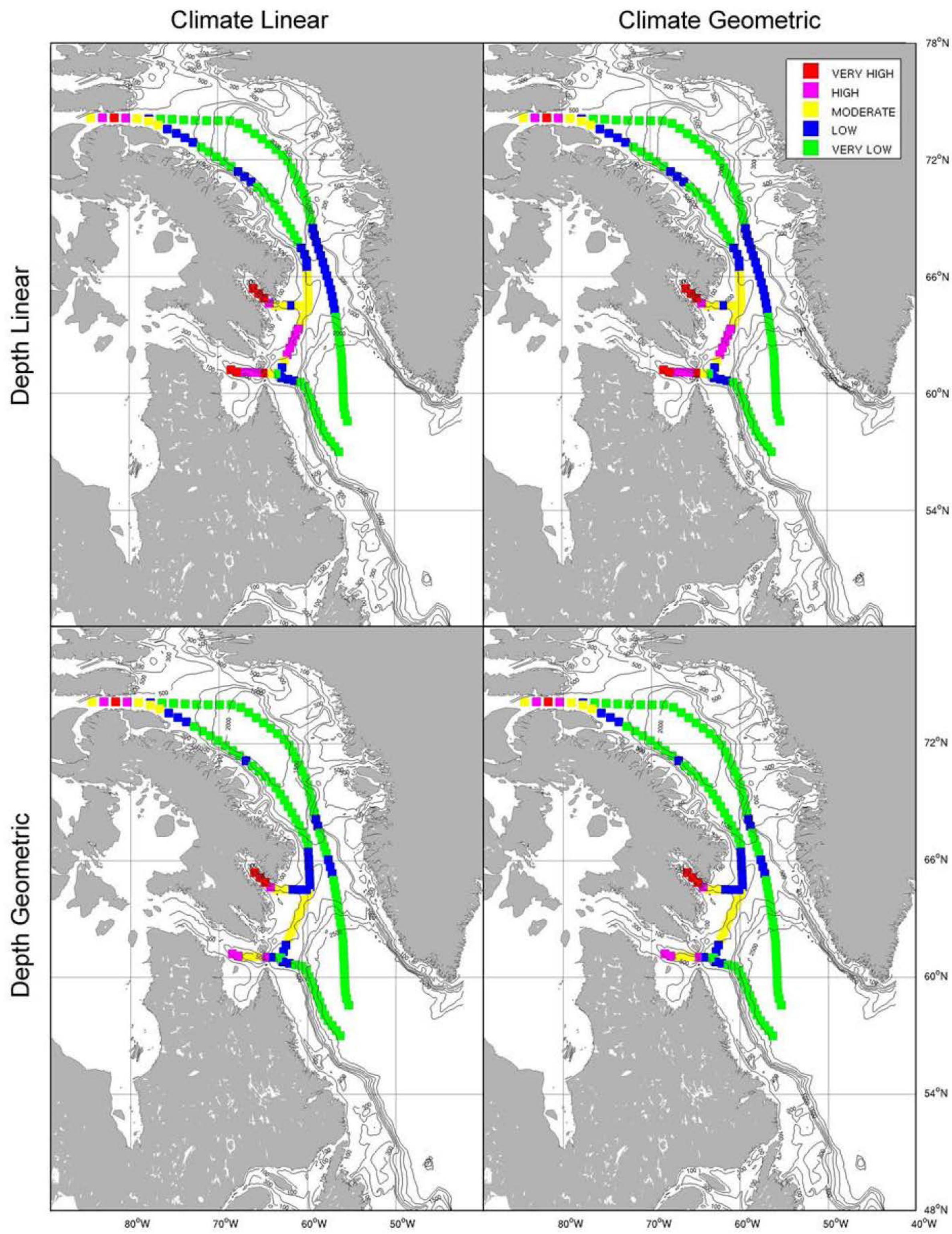


Figure A2-4. Relative risk from ballast water exchanges along ship tracks into the eastern Canadian Arctic based on modelling (CECOM) using different weighting schemes (linear, geometric) for the relative likelihood of establishment metrics (depth, climate).

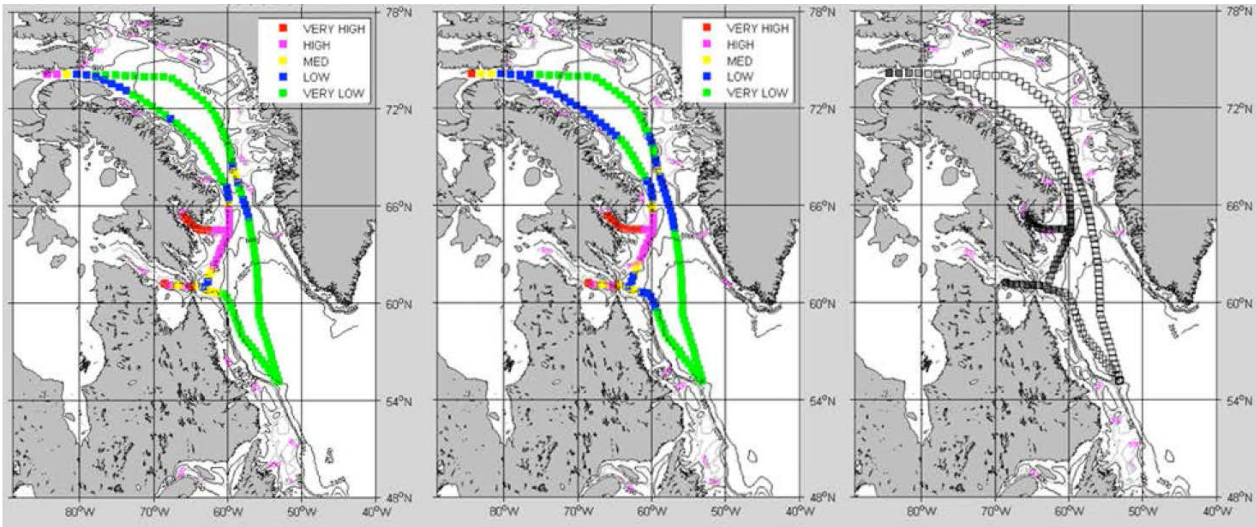


Figure A2-5. Depiction of risk rankings based on a linear scale (left), natural breaks in the data (center), and monochromatic shading (right). The linear and natural breaks both consist of 5 categories, while the monochromatic shading is a continuous sequence from low (white) to high (black).