Projected species shifts due to climate change in the Canadian Marine Ecoregions

A report to Environment Canada prepared by

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Abstract

Anthropogenic climate change is expected to alter oceanographic conditions in the next decades, and also affect marine biodiversity, notably by affecting the distribution of marine species. Such changes will affect the effectiveness of existing conservation and ecosystem management measures. The Department of Fisheries and Oceans classified the Canadian Exclusive Economic Zones into a system of 'marine ecoregions' based on the biophysical characteristics of each area, allowing for region-specific integrated ecosystem management. However, the potential effects of climate change on the biotic characteristics in these ecoregions have so far not been considered. Such information would be important to assess the current and future ecosystem management and conservation planning in these ecoregions. This study aims to assess the potential changes in composition of marine fishes and invertebrates in the Canadian marine ecoregions likely to result from climate change-induced shifts in species distributions. Using a published dynamic bioclimate envelope model, we simulated shifts in distribution of 475 marine fishes and invertebrates that are currently occurring or potentially moving into the marine ecoregions from 2000 to 2050 under the IPCC's Special Report on Emission Scenario A1B and B1, with an emission pathway of approximately tripling and doubling the atmospheric CO_2 concentration, respectively, by 2100 relative to pre-industrial level, which may be considered conservative under current trends of greenhouse gas emissions. The model projected high rates of species gain in the Arctic marine ecoregions, and patches of high rates of species loss occurred throughout the Pacific, Atlantic and Arctic marine ecoregions. The pattern of species turnover (gain + loss relative to current) is dominated by species gain, and the overall patterns of rates of species gain, loss and turnover were similar between the two climate change scenarios, although the magnitude was greater under the SRES A1B scenario. Projections from this study provide spatially-explicit hypotheses of potential effects of climate change on the distributions and biodiversity of marine fishes and invertebrates in the Canadian marine ecoregions by 2050. Biodiversity and ecosystem structure in the Arctic ecoregions are likely to be particular hotspots of climate change impacts. However, the potential ecological risk of climate change impacts at lower latitudes should not be overlooked, given their high number of species and turnover. Although the fine-scale projections remain uncertain, the broad-scale changes projected from the model are likely to be robust. Also included in the present report is a summary of available data on the occurrence and abundance of Canadian seabirds by ecoregion. Although climate change impacts on seabird populations were not modelled here, the data presented by ecoregion can serve as a baseline for future comparison of changes in seabird occurrence and abundance in Canada. The results from this study should be useful in adapting and designing integrated ecosystem management and inform ecoregional planning for networks of marine protected areas.

Introduction

Fisheries and Oceans Canada (DFO) defines 12 marine ecoregions[1] in the Canadian Exclusive Economic Zone (EEZ), based on the geographical, physical and biological properties of these regions (Figure 1) (Powles *et al.* 2004; Fisheries and Oceans Canada, 2009). These ecoregions are defined as continental shelf-scale areas that are characterized by regional variations in salinity, marine flora and fauna, and productivity (Harper *et al.* 1993; Fisheries and Oceans Canada, 2009). An application of the ecoregion classification is to set more region-specific integrated ecosystem management objectives. Thus, there is a need to develop scenarios of how climate change may affect the faunal characteristics in these ecoregions, to assess the need to adjust current integrated ecosystem management objectives. Such need is recognized in a recent review on climate change and adaptation in relation to protected areas in Canada that highlights the importance in developing strategies to consider the changing climate in protected area design (Lemieux *et al.* 2010), and in recent analyses for terrestrial conservation areas (Lindsay *et al.* 2011).

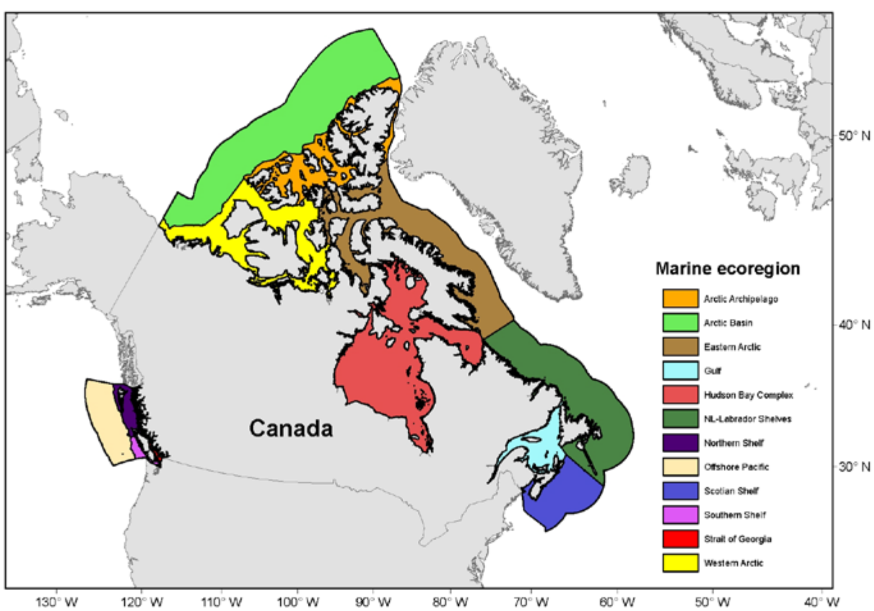


Figure 1. Canadian marine ecoregions (source: Fisheries and Oceans Canada 2009)

[1] The term "*ecoregion*" is used in the reports documenting the development of this bioregionalization approach (Powles *et al.* 2004; Fisheries and Oceans Canada, 2009). However, "*bioregion*" is used in a document for the National Framework for Canada's Network of Marine Protected Areas (2010). This report follows the original terminology of "*ecoregion*".

In the National Framework for Canada's Network of Marine Protected Areas (Fisheries and Oceans Canada 2010), mitigation and adaptation of climate change is stated explicitly as a goal of Marine Protected Areas (MPAs) in Canada. Specifically, the Framework states that, as an environmental benefit, a network of Marine Protected Areas in Canada should contribute to climate change mitigation and adaptation by, amongst various contributions, "*provision of refuge for marine species displaced by habitat change (i.e., access to similar habitat in new areas)*". Moreover, ecoregions are adopted as a framework to develop Canada's MPAs.

Anthropogenic climate change is causing alterations in ocean conditions occurring at rates much higher than those that occurred previously under natural conditions (Brierley and Kingsford 2009; Hoegh-Guldberg and Bruno 2010). These changes include physical (e.g., temperature, ocean current patterns) and chemical (e.g., acidity, oxygen content) modifications in oceanographic conditions. In waters adjacent to the Canadian coast, sea surface temperature (SST) generally increased by 0.2 – 2^{o} C between the 1960s (average 1950-1969) and 2000s (1988-2007) (Figure 2).

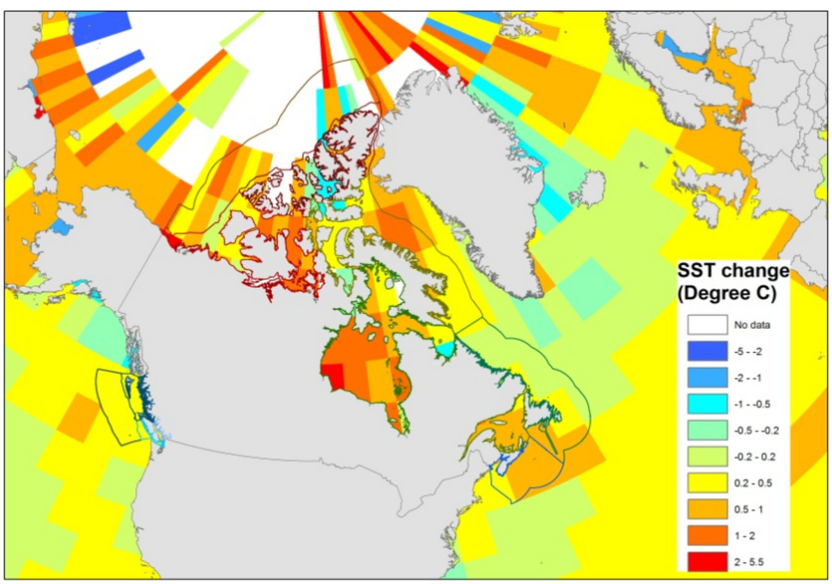


Figure 2. Changes in sea surface temperature (SST) between the 1960s (average 1950-1969) and 2000s (1988-2007), with Canadian marine ecoregions outlined (Rayner *et al.* 2006; source: Met. Office Hadley Centre; http://hadobs.metoffice.com/hadsst2/data/download.html).

Long-term changes in environmental conditions affect distributions of marine species and community structure (e.g., Perry *et al.* 2005; Hiddink and Hofstede 2007; Dulvy *et al.* 2008; Nye *et al.* 2009). Amongst these changes, shifts in distributions of marine fishes and invertebrates are the most commonly observed features that are related to long-term oceanographic changes. For example, off the coast of North America, Nye *et al.* (2009) showed that 26 (of 36) fish stocks significantly shifted the centres of their biomass distribution poleward and increased their mean depths of occurrence in the Northeast United States continental shelf from 1968 to 2007, due to changes in oceanographic conditions in the region. The invasion of the Humboldt squid (*Dosidicus gigas*) along the west coast of North America from Central and South America is also likely to be linked to changes in oceanographic conditions, themselves linked to climate change (Brodeur *et al.* 2006; Zeidberg and Robison 2007).

Shifts in species distributions of marine fishes and invertebrates are expected to intensify in the future, given the projected changes in ocean conditions (IPCC 2007). Using a dynamic bioclimate envelope model (Cheung *et al.* 2008), Cheung *et al.* (2009) examined the potential global shift in distribution of 1,066 exploited marine fish and invertebrates. The dynamic bioclimate envelope model simulates changes in habitat suitability, larval transport, adult migration and population growth of marine animals as modified by the ocean conditions predicted by a global circulation model (see Cheung *et al.* 2008 for details). Cheung *et al.* (2009) found that species distributions are projected to shift towards the poles at an average rate of around 40 km per decade. The projected shifts in distributions would result in high rates of species invasion (gain) in high latitude regions and local extinctions (loss) in the intertropical belt and semi-enclosed seas.

Such changes in species distributions and composition are likely to have considerable implications for conservation planning (Olson and Lindsay 2009). In particular, the design of spatial management plans or marine protected areas (MPA) for conservation of biodiversity largely relies on current species distributions, i.e., they do not incorporate the long-term effects of global climate changes (Hole *et al.* 2009; Prowse *et al.* 2009). As species distributions are expected to shift in the future, it is important to assess how and to what extent the effectiveness of existing spatial management planning or MPA design may be affected by climate change. Results from such assessments could be used to improve conservation planning, and ensure that it is adaptive to climate change (Olson and Lindsay 2009; Hole *et al.* 2009). For example, using a dataset for 150 bird species in the eastern USA, Olson and Lindsay (2009) found that reserve networks designed using the current species distributions were likely to lose 21-32% of species in two climate-change futures as a result of projected species shift. In addition, shifts in the geography of conservation priority from the present to the climate-change futures resulted in a spatial mismatch with the existing system of protected areas.

However, while similar studies have not been conducted for marine species, the potential impacts of climate change on Canadian marine ecosystems have been recognized. For example, a review by Prowse *et al.* (2009) discusses the various threats to marine ecosystems in Northern Canada. Particularly, they highlighted the effects of large projected changes of the Arctic environment on the survival and reproduction of mammals such as polar bear and ringed seal. They also point out the need to design protected areas that consider the effects of climate change. To date, most studies on climate change implications for the Canadian marine ecosystems focus on the Arctic and marine mammals (e.g., Stirling *et al.* 1999; Barber and Iacozza 2004; Ferguson *et al.* 2005).

This study aims to assess the potential changes in composition of marine fishes and invertebrates in the Canadian marine ecoregions likely to result from climate change-induced shifts in species distributions. We use the dynamic bioclimatic envelope model developed by Cheung *et al.* (2008) to simulate changes in distributions of commercially exploited marine fishes and invertebrates under two climate change scenarios. We project the magnitude of species gain, loss and turnover in the ecoregions by the 2050s relative to the 2000s, and discuss the robustness of such projections and their implications for conservation planning for these ecoregions.

Methods

Sample of species and their current distributions

This study is derived from a larger global study that included 1,066 species of commercially exploited marine fishes and invertebrates that are reported worldwide as species-level taxa by the United Nations Food and Agriculture Organization landings statistics (see www.seaaroundus.org for list of species). The current distributions of these species, representing the average pattern of relative abundance in recent decades (i.e., 1980-2000), were produced using an algorithm developed by the *Sea Around Us* Project (see Close *et al.* 2006; Cheung *et al.* 2008; www.seaaroundus.org). The algorithm predicts the probability of occurrence of a species on a 30' latitude x 30' longitude grid based on each species' depth range, latitudinal range, and polygons encompassing its known areas of occurrence. The resulting distribution maps were further refined by assigning habitat preferences to each species, such as affinity to shelf (inner, outer), estuaries and rocky reef habitats, and accounting for low-latitude 'submergence' (Ekman 1967; Pauly 2010). The required information was obtained from FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.org), which contains key information on the distribution of the species in question, and on their known occurrence area.

Projecting future distributions under climate change

Using the dynamic bioclimate envelope model described in Cheung *et al.* (2008, 2009), we projected shifts in distributions of the 1,066 species under different climate change scenarios. The model identified species' preference to environmental conditions that are defined by sea surface temperature, salinity, distance from sea-ice, and habitat types (e.g., estuaries, seamounts). Suitability, represented by the relative density of the species under environmental conditions and by habitat type, was calculated by overlaying environmental data with maps of relative abundance of the species. We calculated the temperature preference profile of each species by overlaying the predicted species distribution with observed annual sea surface temperature (10-year climatology) representing the 1991-2000 period.

Species' environmental preferences were then linked to the expected carrying capacity in a population dynamic model in which growth, mortality, and spatial dynamics of adult movement and larval dispersal along ocean currents were explicitly represented (Cheung *et al.* 2008, 2009). The model simulated changes in relative abundance of a species by:

$$\frac{dA_i}{dt} = \sum_{j=1}^{N} G_i + L_{ji} + I_{ji} \qquad \text{eq. 1}$$

where A_i is the relative abundance of a 30' x 30' cell i, G is the intrinsic population growth and L_{ji} and I_{ji} are settled larvae and net migrated adults from surrounding cells j, respectively.

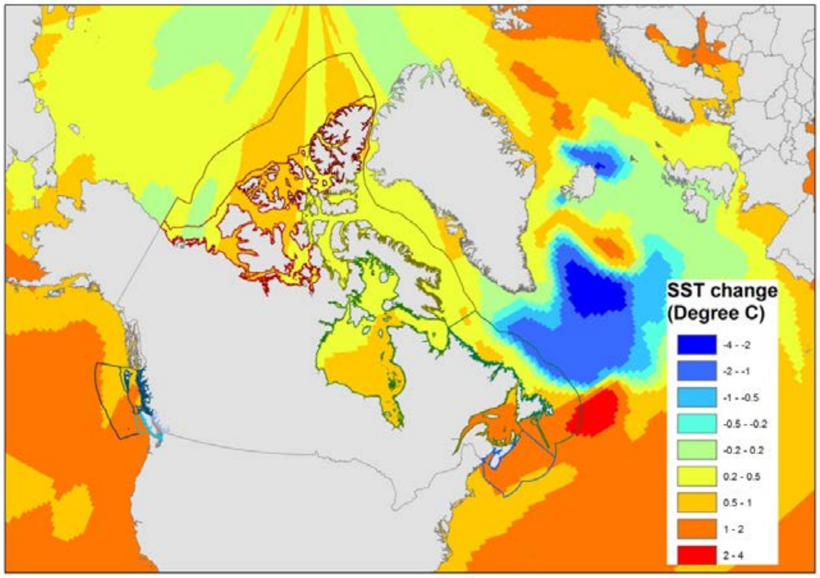
Population growth was modelled by a logistic equation:

$$G_i = r \cdot A_i \cdot \left(1 - \frac{A_i}{KC_i}\right) \qquad \text{eq. 2}$$

where r is the intrinsic rate of population increase, A_i and KC_i are the relative abundance and population carrying capacity at cell i, respectively. The model assumes that carrying capacity varies positively with habitat suitability of each spatial cell, and habitat suitability is dependent on the species' preference profiles to the environmental conditions (e.g., temperature, ice-coverage) in each cell. Estimates of r were obtained from the published literature and from FishBase. The distance and direction of larval dispersal as a function of the predicted pelagic larval duration was estimated based on an empirical equation (O'Connor *et al.* 2007). In addition, animals are assumed to migrate along the calculated gradient of habitat suitability. Thus, changes in habitat suitability in each cell, determined by ocean conditions, lead to changes in the species' carrying capacity, population growth, net migration, and thus relative abundance in each cell. The details of the model are documented in Cheung *et al.* (2008, 2009).

The model is driven by changes in ocean conditions and advection fields from projection from the NOAA's Geophysical Fluid Dynamic Laboratory (GFDL) ocean-atmosphere-coupled global circulation model (CM 2.1) (Delworth *et al.* 2006). Projected physical variables include sea temperature (surface and bottom), sea ice coverage, salinity, and advection under different climate change scenarios from 2000 to 2060 under two scenarios: (1) Special Report on Emission Scenarios (SRES) A1B in which CO_2 concentration is 720 ppm by 2100 and (2) SRES B1 in which CO_2 concentration is 550 ppm by 2100 (Figure 3). Note that these scenarios may now be considered conservative given the current trends of greenhouse gas emissions (New *et al.* 2011). We re-gridded the original oceanographic outputs from the NOAA's GFDL CM2.1 onto a 30' lat. x 30' long. grid using a bilinear interpolation method.

A.



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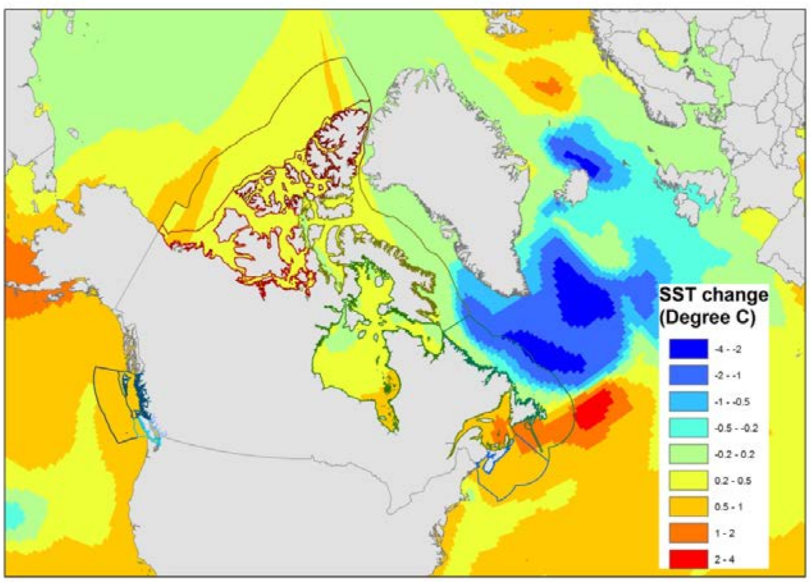


Figure 3. Projected change in sea surface temperature (SST, top 50 m) between the mid 2000s (average 2001 – 2010) and the 2050s (average 2046 – 2055) from the NOAA's GFDL CM2.1 under two IPCC scenarios: (A) SRES A1B; (B) SRES B1. Model outputs were interpolated onto a 0.5^{o} latitude x 0.5^{o} longitude cell grid using a bilinear interpolation method.

Using the projected changes in species distributions, we estimated the average changes in species number (gain, loss, and turnover) within each marine ecoregion. For each 30' x 30' cell and marine ecoregion, we calculated the number of species newly occurring (gain), disappeared (loss) and turnover (gain + loss) by 2050 (average of 2046 – 2055) relative to the 2000s. We also calculated the proportion of gain, loss and turnover by dividing the number of species gain, loss and turnover by the predicted number of species occurring in the 2000s. For areas where none of the species in our sample occur at present, a value of 1 is used as the denominator. We also calculated the per area species turnover based on species turnover in each 30’ x 30’ cell averaged overall all cells in each marine ecoregion.

Results

A total of 475 species (of 1066 globally) fishes and invertebrates were deemed to occur or modeled to occur in the Canadian EEZ waters and hence marine ecoregions (see Appendix I; Figure 4). The Scotian Shelf had the largest number of species (324), followed by the Newfoundland-Labrador Shelves (255), the Gulf (223), the Southern Shelf (155), the Northern Shelf (152.) and the Strait of Georgia (150). These are followed by the Offshore Pacific (149), the Hudson Bay Complex (100) and Eastern Arctic (85), while the Arctic Basin (15) and the Arctic Archipelago (8) had a much smaller number of taxa, strongly impacting the basis from which inference could be drawn.

A.

B.

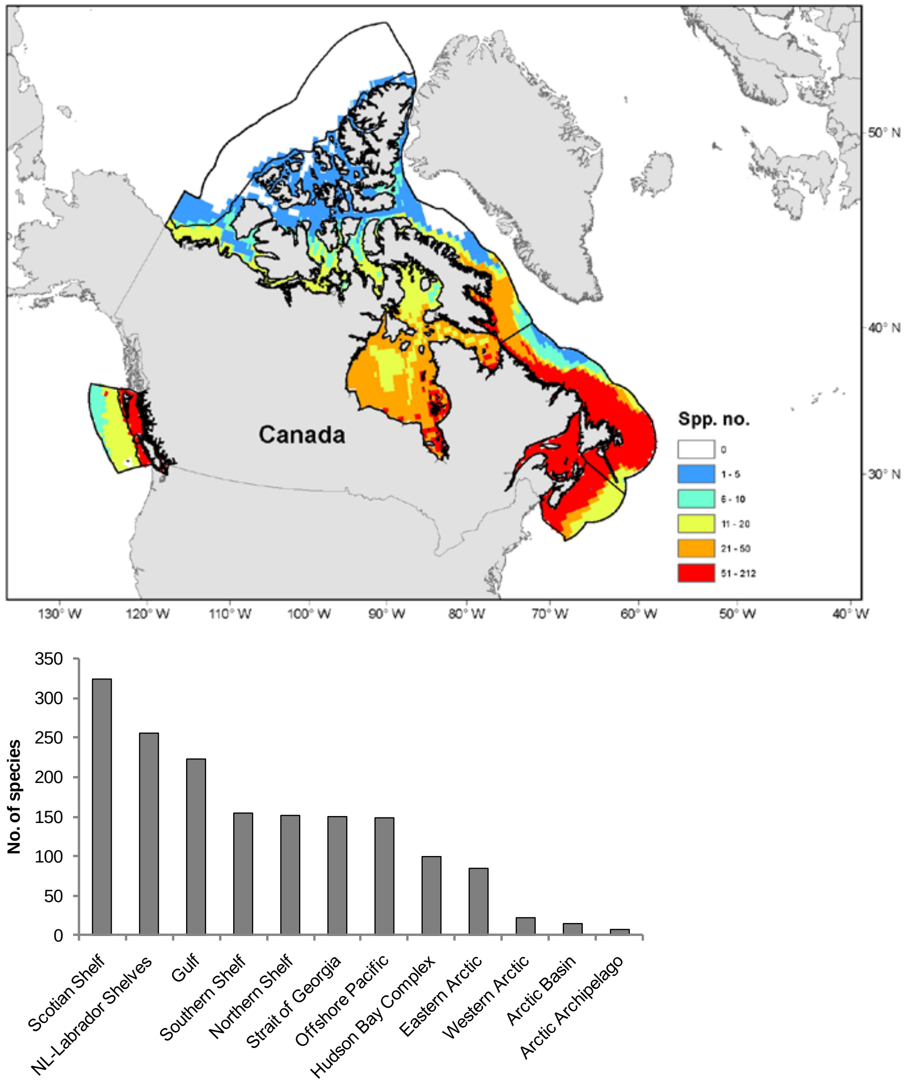


Figure 4. Estimated number of commercial species in the marine ecoregions based on predicted current (1980-2000) distribution (A) on 0.5° x 0.5° grid and (B) by marine ecoregions.

Under the two scenarios considered, the marine ecoregions at relatively lower latitude have larger numbers of species gain, loss and turnover (Figure 5 and 6). This is particular the case for species loss, of which the highest value occurred in the Northern and Southern Shelf, Scotian and Newfoundland-Labrador marine ecoregions. Overall, the total number of species in the system of Canadian marine ecoregions is projected to increase by up to 10% by 2050 relative to the 2000s.

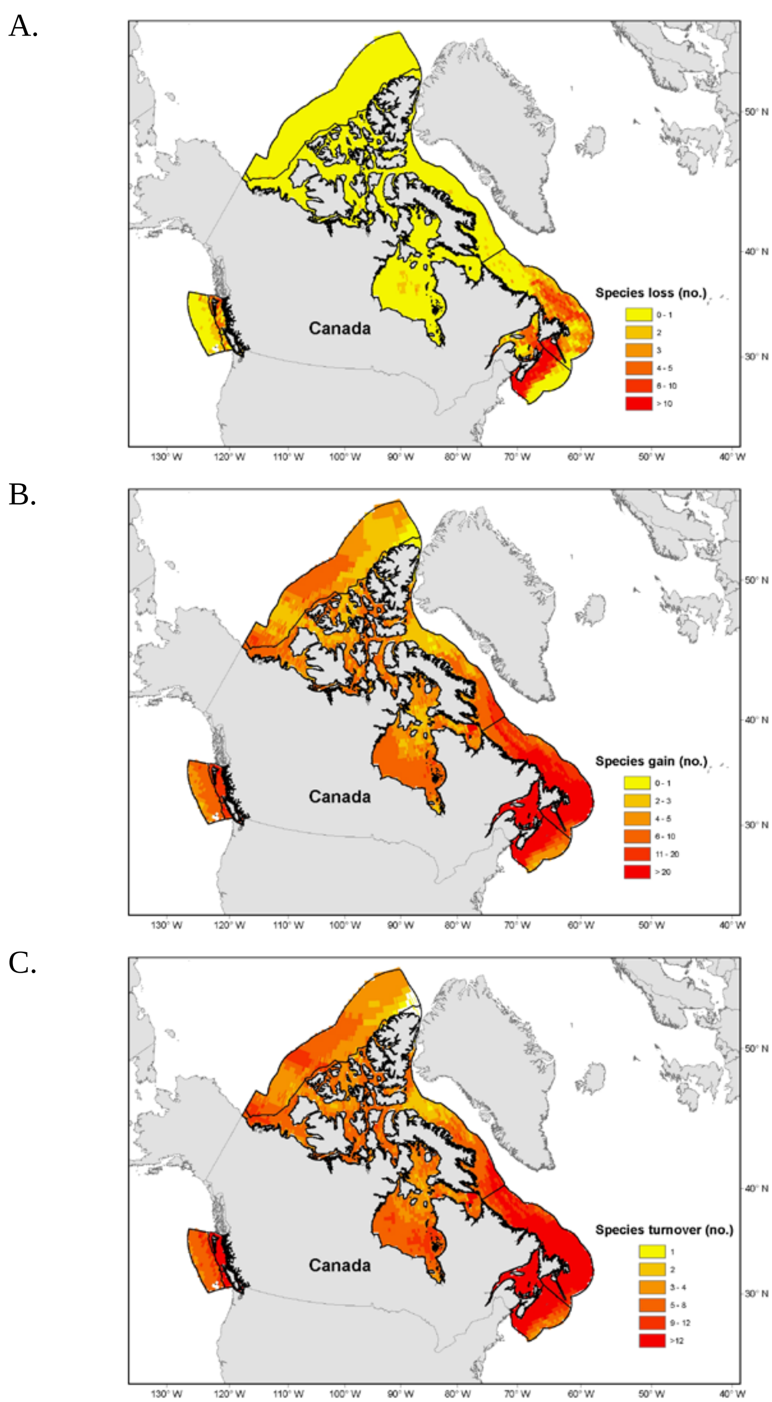
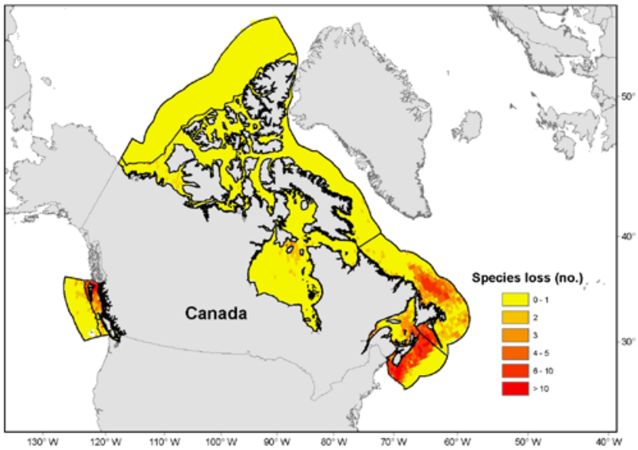


Figure 5. Projected number of (A) species loss, (B) gain and (C) turnover by 2050 relative to the original species richness in the 2000s under the SRES A1B scenario. For ecoregions see Figure 1.

A.



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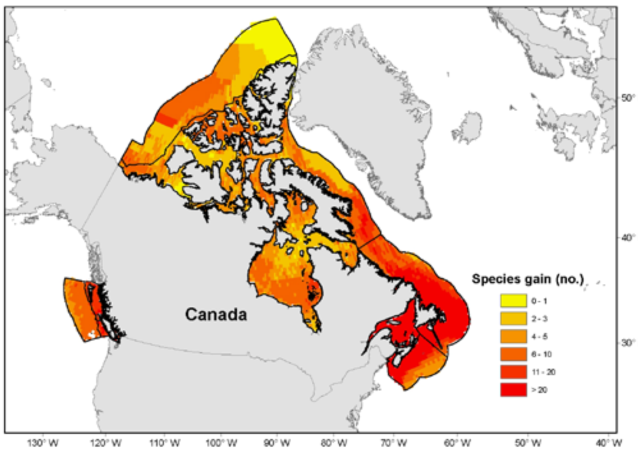


C.

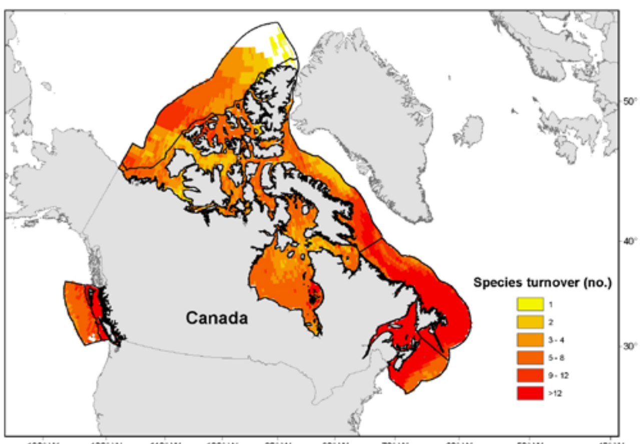


Figure 6. Projected number of (A) species loss, (B) gain and (C) turnover by 2050 relative to the original species richness in the 2000s under the SRES B1 scenario. For ecoregions see Figure 1.

Our model projected species loss, gain and turnover, expressed as proportions relative to original species richness, in all the ecoregions under the SRES A1B scenario (Figure 7).

Areas with high proportion of species loss are more widespread at lower latitudes, including the marine ecoregions of the Pacific, Atlantic (especially the Scotian Shelf and Newfoundland-Labrador Shelf) and Arctic coasts (including parts of the Hudson Bay complex). However, areas with high proportion of species loss are much patchier in the Arctic. In contrast, a higher proportion of species gain in the higher latitude marine ecoregions can be expected. The proportion of species gain was projected to be highest in the Eastern and Western Arctic and the Northern boundary of the Newfoundland-Labrador Shelves marine ecoregions. These are followed by the Offshore Pacific and the Hudson Bay Complex. Overall, the pattern of species turnover is dominated by the pattern of species gain.

The overall patterns of proportion of species gain, loss and turnover are similar between the two climate change scenarios, although the magnitude is smaller under the SRES B1 scenario (Figure 8). Particularly, species gain and turnover were notably lower in the northern boundary of the Arctic Basin.

A.

B.

C.

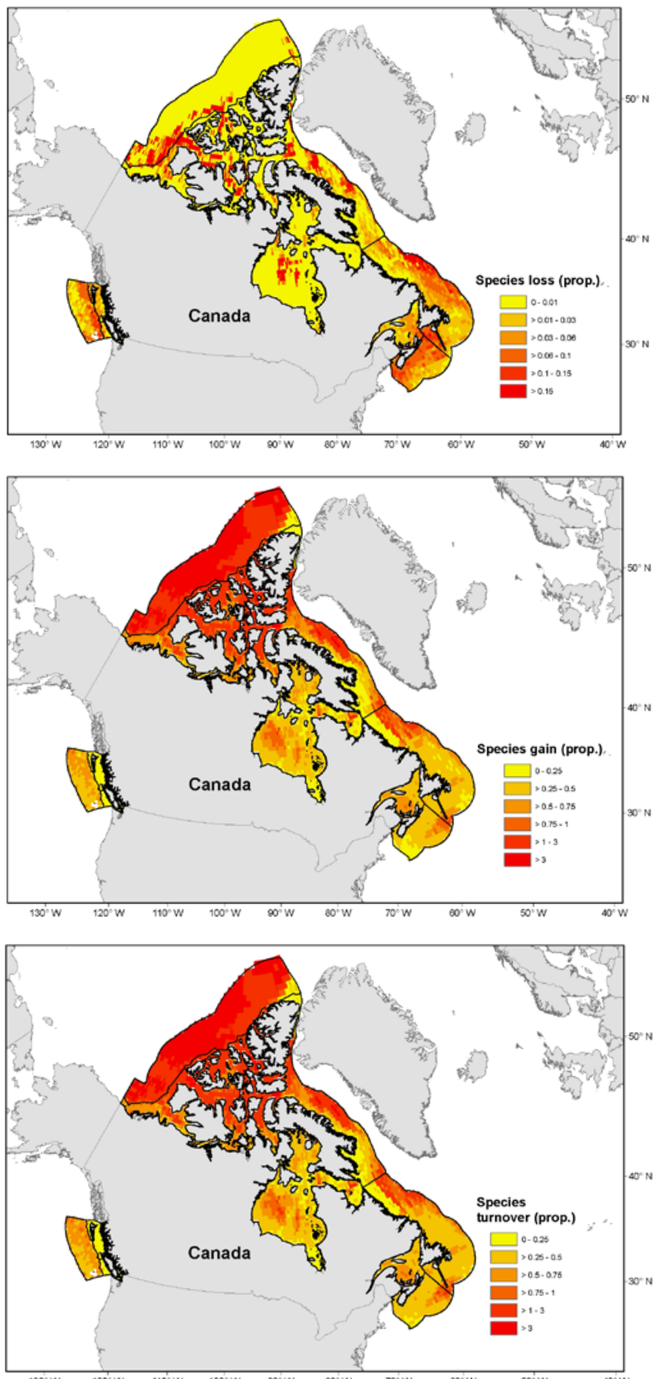
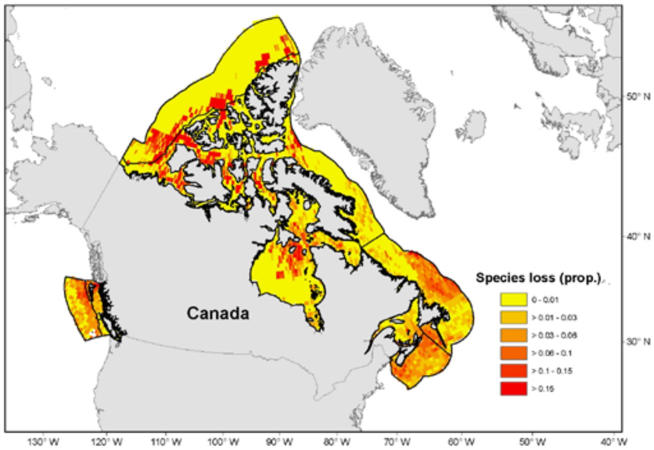


Figure 7. Projected proportion of (A) species loss, (B) gain and (C) turnover by 2050 relative to the species richness in the 2000s under the SRES A1B scenario. For ecoregions see Figure 1.

A.



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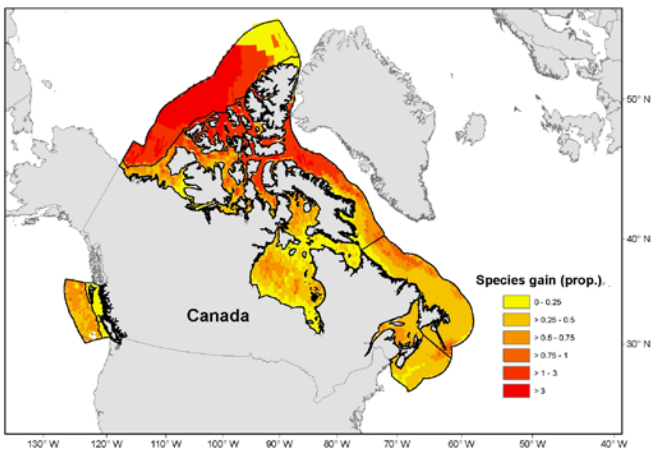

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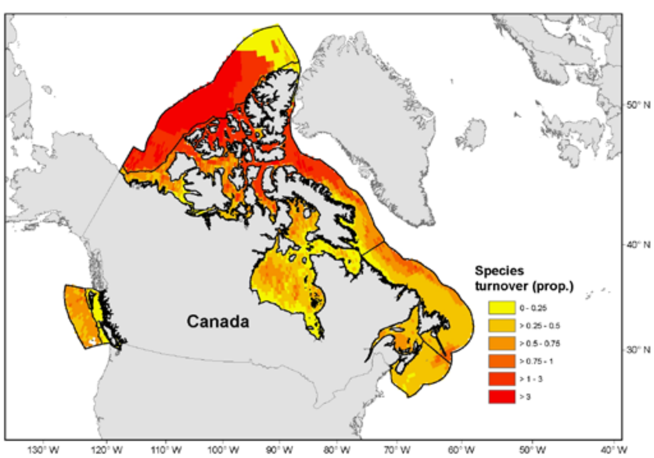

Figure 8. Projected proportion of (A) species loss, (B) gains and (C) turnover by 2050 relative to the species richness in the 2000s under the SRES B1 scenario. For ecoregions see Figure 1.

In terms of per unit area changes, the Arctic ecoregions have the highest estimated proportion of turnover (Figure 9). The rates of species turnover in the Arctic Basin and Arctic Archipelago are projected to be more than double the rates in other marine ecoregions under both scenarios of climate change. This is followed by the Gulf and Western Arctic. Turnover rates in the Hudson Bay Complex, Eastern Arctic, Southern Shelf and Offshore Pacific are approximately similar while the Strait of Georgia, NL-Labrador Shelves and Scotian Shelf have lower turnover rates.

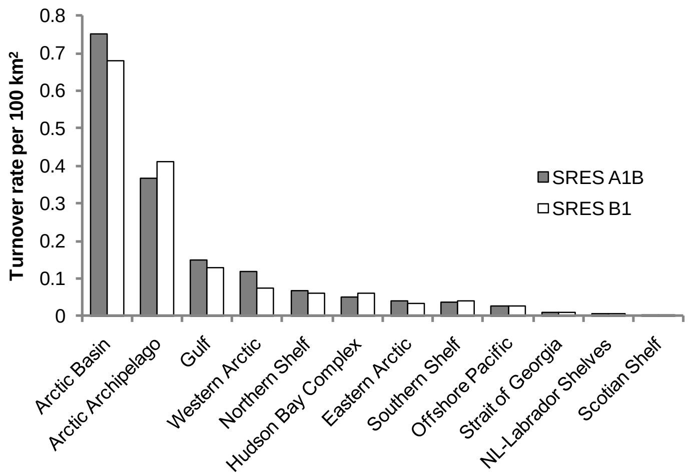

Figure 9. Species turnover per unit of area in each marine ecoregion under the two climate change scenarios SRES A1B (grey bars) and B1 (open bars).

Discussion

Projections from this study provide spatially-explicit hypotheses of potential effects of climate change on the distributions and biodiversity of marine fishes and invertebrates in the Canadian marine ecoregions by 2050. Firstly, there will be a net gain in total number of species in the Canadian system of marine ecoregions. Secondly, the Arctic marine ecoregions are expected to experience a high proportion of species gain and turnover, while patches of area with higher proportion of species loss are widespread in the Pacific and Atlantic marine ecoregions. In addition, the total number of species turnover will be high in the Pacific and Atlantic ecoregions.

The general pattern of distribution shifts and assemblage changes is likely to be robust, although the magnitude and fine-scale projections of such changes are uncertain. The first source of uncertainty is the projections of oceanographic conditions. These oceanographic projections were generated from a global atmospheric-oceanographic coupled model with a resolution of around 100 km (Stock *et al.* 2010). Such models generally have poor representation on the finer-scale coastal and shelf sea processes. Thus, the fine scale (within ecoregion) patterning of our model results is highly uncertain and should only be used to explore the potential level of variability in patterns of species turnover, particularly for small marine ecoregions such as the Strait of Georgia. There are also other inherent model and parameter uncertainties associated with the climate model. Regional oceanographic models (ROMs) may provide finer-scale projections that are more representative of the regions. However, at the time of this study, we did not have access to outputs from ROMs. The analysis presented here could be repeated when outputs from ROMs become available and sensitivity to different model outputs could be evaluated. On the other hand, since the model underlying this study was global, its outputs provided a more comprehensive picture of species movement as the immigrations of species currently occurring from outside of the Canadian marine ecoregions were considered in our analysis. Also, coarse comparisons of projected rates of range shift (in terms of latitudinal and bathymetric centroids shifts per decade) from the dynamic bioclimatic envelope model with observations suggest that the projected trends are robust (Cheung *et al.* 2009).

There are other known uncertainties regarding the dynamic bioclimatic envelope modelling approach used in this study. The modelling approach attempts to capture key physiological preferences and population dynamics that affect species distribution, although it did not consider factors such as biogeochemistry of the seas (e.g., pH, oxygen content) and species interactions, which are likely important factors affecting species distributions (Pörtner and Farrell 2008; Pörtner 2010). Recent analysis for the Northeast Atlantic that incorporated ocean chemistry into the dynamic bioclimatic envelope model shows that ocean acidification and reduced oxygen level would further increase the rate of range shift (Cheung *et al.* 2011). Also, some species may adapt to changing ocean conditions, although the scope for marine fishes and invertebrates to adapt without shifting their distribution range is not clear. Evidence from studies of terrestrial animals suggests that species may adapt to climate change through the natural selection of individuals that have greater dispersal ability (Thomas *et al.* 2001). In either case, the degree of adaptation to the changing ocean conditions would depend on the generation time of the species in question, and the diversity of life history traits and environmental tolerance in their gene pool. Currently, we have little empirical knowledge of the rate of adaptation to climate change in fish and invertebrates, which precludes incorporating this factor into our model. Also, the model used in our study does not account for effects of fishing and/or other human activities, which may have non-linear interactions with ecological impacts of climate change. In addition, our sample of species focused on commercially exploited species, which generally have high abundance in the area. For conservation planning, rare and/or non-fishery species are also of concern. The under-representation of Arctic species also increases the uncertainty in the pattern of species turnover projected for the Arctic ecoregions. Future studies should increase the coverage of such species. Overall, projections in this study may be considered as a set of null hypotheses that could be tested with data collected in the future.

Overall, these projected changes in species distributions and composition may have substantial ecological implications. The turnover of species in each area may have consequences for the food web and biodiversity. For example, the distribution extension of predatory species may increase the predation mortality of some prey species or competition with other predatory species in the area. Although our understanding of the potential trophic interactions implied by different species' distributions is limited, evidence from elsewhere suggests that such ecological impacts could be large. For example, the northward expansion of the distribution of predatory Humboldt squid (*Dosidicus gigas*), may have impacted groundfish species such as Pacific hake (*Merluccius productus*) (Zeidberg and Robison 2007). The explosion of jellyfish populations have been suggested to greatly reduce recruitment of commercially important fish species as their larvae are preyed on by the jellyfish (Purcell 1985; Brodeur *et al.* 2002). Although the direct causes of these changes are still being studied, these observations give us a preview of the potential ecological impacts of species distribution shifts. Moreover, in areas with high proportion of species loss, organisms that are dependent on these lost species may be affected. It is uncertain whether the ecological niche that these species vacate will be filled by other species. Such ecological consequences of species distribution shifts should be a focus of future research.

Biodiversity and ecosystem structure in the Arctic ecoregions are likely to be particularly sensitivity to species range-shifts. Given the relatively low species richness in the Arctic marine ecoregions, the gain or loss of relatively small numbers of species may lead to large changes in the overall community structure. Overall, our analysis suggests that Arctic species are likely to move further poleward following the sea-ice retraction, while species in the southern regions will move in. Cold-water associated species in these ecoregions generally have a narrower temperature preference range relative to warm-water species, rendering them more sensitive to ocean warming. Moreover, the extent of Arctic sea ice has been declining since 1980, and is projected to continue doing so under all emission scenarios (IPCC 2007; Stroeve *et al.* 2007). Changes in sea-ice extent cause large transformations of physical and biological oceanographic conditions of the habitat (Post *et al.* 2009). Although the mechanisms of ecosystem changes following sea-ice retraction are not explicitly represented in our model, the relationship between sea-ice and distribution of polar fishes and invertebrates is relatively well-known (Longhurst 1981) and is incorporated in our model. The large changes in faunal composition in the Arctic ecoregions may have large implications for ecosystem structure and functions; making these ecoregions likely hotspots of ecological impacts of climate change. This is further complicated by the lack of comprehensive accounting for total fisheries catches taken, especially by the small-scale fisheries (both artisanal and subsistence) that will be most affected by climate change impacts in Canadian arctic communities (Zeller *et al.* 2011). However, the small number of species in our sample that occurred in the Canadian Arctic, several of which are diadromous species, prevents us from providing more details at this point. Future study should increase the number of Arctic species included in the analysis.

The potential ecological risk of climate change impacts on the Atlantic and Pacific should not be overlooked. The Atlantic and Pacific coasts marine ecoregions are also expected to have more species turnover (in terms of number of species) caused by the immigration of southern, warmer-water species and loss of northern species. However, the relatively higher number of current species richness in some of the Atlantic and Pacific coast marine ecoregions leads to a lower rate of species turnover in these regions. In other words, high species richness may help buffer the effects of changes in species composition. However, this remains an important ecological question to address in future studies. Particularly, if species turnover involves ecologically important species, it may cause considerable ecosystem impacts. Immigration could fill the niches vacated by the species that move further north, or they will otherwise change community and ecosystem structure and function through exotic competition, predation, and generalized disturbance. Cases of negative effects of human-induced marine species invasions, e.g., jellyfish in the Black Sea (Kideys 2002) provide some insights into the potential impacts of species turnover, even in relatively species rich ecosystems.

The results of this study may be useful in adapting and designing integrated ecosystem management. Particularly, our analysis suggests that objectives and targets for indicators of ecosystem quality which assume constant environment conditions may not be suitable in the medium to long term. Output from this modelling study could be used to test the performance of these objectives and targets in accurately reflecting ecosystem status, pressures and trends. Also, it would help inform the design of protected areas that would be adaptive to expected changes in fauna and flora in these regions (Olson and Lindsay 2009). Moreover, it could be used to help adapt/design existing and future monitoring programmes to collect data that could be used to test the hypotheses of climate change impacts on marine species and communities in the Canadian marine ecoregions. Specifically, we have identified ecoregions where fish and invertebrate communities are expected to be particularly sensitive to climate change. Monitoring changes in distribution and relative abundance of selected ‘sentinel’ species in these ecoregions may help track climate change effects on these marine ecosystems. These species could be identified by including a sample of species in each ecoregion that have relatively more specific preferences for temperature and other environmental conditions, represent a range of eco-types, e.g., from polar to temperate, and ideally, include species that are already included in existing monitoring programmes and have historical data.

Although not explicitly modelled for the likely effects of climate change, the summary data on distribution and breeding abundance of the 38 seabird species (out of a global total of 334 species) recorded from the Canadian ecoregions can serve as a baseline for future comparisons (see Appendix II). While the overall increase in seabird abundance within Canada of around 10 million individuals seems positive, regional comparisons suggest that arctic areas (Western and Eastern Arctic, and Hudson Bay complex) are showing a decline in seabird abundance. To what extent this pattern is a result of climate change effects having occurred over the past decades or a sampling effect is at present not certain.

Conclusion

This study developed scenarios of projected future changes of fish and invertebrate communities in the Canadian marine ecoregions. Overall, these projected changes in species distributions and community structure should have substantial ecological implications. Biodiversity and ecosystem structure in the Arctic ecoregions are likely to be particularly sensitivity to species' range-shifts. The Atlantic and Pacific coast marine ecoregions are also expected to have high species turnover, although the magnitude of change relative to the original species richness may be smaller. Despite uncertainties associated with the modelling analysis, the general pattern of distribution shifts and assemblage changes is likely to be robust; it is the magnitude and fine-scale properties of the changes which are uncertain. The results from this study should be useful in adapting and designing integrated ecosystem management, designing networks of protected areas and monitoring programmes for detecting climate change impacts on Canadian marine ecosystems.

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Appendix I: Species list

List of commercial species (a) projected to occur during 1980-2000 in Canadian EEZ waters (n= 151) using the distribution projection method described in Close *et al.* (2006); (b) whose distributions (n= 288) are projected to be suitable for the survival of the species and is connected to the original distribution by larval dispersal or adult migration by 2010; and (c) with projected distributions (n= 36) within Canadian waters by 2050.

(Table 1a)

Scientific name	Common name
Acipenser medirostris	Green sturgeon
Acipenser sturio	Sturgeon
Alepocephalus bairdii	Bairds smooth-head
Amblyraja hyperborea	Arctic skate
Anarhichas denticulatus	Northern wolffish
Anarhichas lupus	Wolf-fish
Anarhichas minor	Spotted wolffish
Anguilla rostrata	American eel
Antimora rostrata	Blue antimora
Aphanopus carbo	Black scabbardfish
Arctica islandica	Ocean quahog
Argentina silus	Greater argentine
Artemia salina	Brine shrimp
Atheresthes stomias	Arrowtooth flounder
Belone belone	Garpike
Beryx decadactylus	Alfonsino
Boreogadus saida	Polar cod
Borostomias antarcticus	Borostomias antarcticus
Brama brama	Atlantic pomfret
Brosme brosme	Tusk
Carcharodon carcharias	Great white shark
Centrolophus niger	Blackfish
Centroscyllium fabricii	Black dogfish
Centroscymnus coelolepis	Portuguese dogfish
Centroscymnus crepidater	Longnose velvet dogfish
Cetorhinus maximus	Basking shark
Chelidonichthys gurnardus	Grey gurnard
Chelidonichthys lucerna	Tub gurnard
Chimaera monstrosa	Rabbit fish
Chionoecetes opilio	Queen crab

Scientific name	Common name
Chlamys islandica	Iceland scallop
Ciliata mustela	Fivebeard rockling
Clupea harengus	Atlantic herring
Clupea pallasii	Pacific herring
Cololabis saira	Pacific saury
Conger conger	European conger
Coryphaenoides rupestris	Roundnose grenadier
Cyclopterus lumpus	Lumpsucker
Dipturus batis	Blue skate
Dipturus linteus	Sailray
Echinus esculentus	European edible sea urchin
Eleginus navaga	Navaga
Enchelyopus cimbrius	Fourbeard rockling
Epigonus telescopus	Bulls-eye
Etmopterus spinax	Velvet belly lantern shark
Gadus morhua	Atlantic cod
Gadus ogac	Greenland cod
Galeocerdo cuvier	Tiger shark
Galeorhinus galeus	Tope shark
Galeus melastomus	Blackmouth catshark
Gasterosteus aculeatus	Three-spined stickleback
Glyptocephalus cynoglossus	Witch
Gobius niger	Black goby
Halargyreus johnsonii	Slender codling
Helicolenus dactylopterus	Blackbelly rosefish
Hexanchus griseus	Bluntnose sixgill shark
Hippoglossoides elassodon	Flathead sole
Hippoglossoides platessoides	American plaice
Hippoglossus hippoglossus	Atlantic halibut
Hoplostethus atlanticus	Orange roughy
Hoplostethus mediterraneus mediterraneus	Mediterranean slimehead
Hydrolagus mirabilis	Large-eyed rabbitfish
Illex illecebrosus	Northern shortfin squid
Istiophorus platypterus	Indo-Pacific sailfish
Lamna nasus	Porbeagle
Lampris guttatus	Opah
Lepidopus caudatus	Silver scabbardfish
Lepidorhombus boscii	Fourspotted megrim
Leucoraja fullonica	Shagreen ray
Leucoraja naevus	Cuckoo ray
Limanda aspera	Yellowfin sole

Scientific name	Common name
Limanda limanda	Dab
Littorina littorea	Common periwinkle
Liza saliens	Leaping mullet
Loligo forbesii	Veined Squid
Lophius piscatorius	Angler
Macrourus berglax	Onion-eye grenadier
Mallotus villosus	Capelin
Maurolicus muelleri	Pearlsides
Meganyctiphanes norvegica	Norwegian krill
Melanogrammus aeglefinus	Haddock
Merlangius merlangus	Whiting
Merluccius merluccius	European hake
Microchirus variegatus	Thickback sole
Micromesistius poutassou	Blue whiting
Microstomus kitt	Lemon sole
Microstomus pacificus	Dover sole
Mola mola	Ocean sunfish
Molva dypterygia	Blue ling
Molva molva	Ling
Mora moro	Common mora
Mugil soiuy	So-iuy mullet
Mya arenaria	Sand gaper
Mytilus edulis	Blue mussel
Myxine glutinosa	Hagfish
Necora puber	Velvet swimcrab
Nephrops norvegicus	Norway lobster
Nezumia aequalis	Common Atlantic grenadier
Oncorhynchus gorbuscha	Pink salmon
Oncorhynchus nerka	Sockeye salmon
Ophiodon elongatus	Lingcod
Osmerus mordax	Atlantic rainbow smelt
Palinurus elephas	Common spiny lobster
Pandalus borealis	Northern prawn
Pandalus montagui	Aesop shrimp
Petromyzon marinus	Sea lamprey
Phycis blennoides	Greater forkbeard
Platichthys stellatus	Starry flounder
Pleuronectes platessus	European plaice
Pollachius virens	Saithe
Raja brachyura	Blonde ray
Raja montagui	Spotted ray

Scientific name	Common name
Regalecus glesne	King of herrings
Reinhardtius hippoglossoides	Greenland halibut
Rhinochimaera atlantica	Spearnose chimaera
Salmo salar	Atlantic salmon
Salvelinus alpinus	Charr
Sardina pilchardus	European pilchard
Scomber japonicus	Chub mackerel
Scomber scombrus	Atlantic mackerel
Scomberesox saurus	Atlantic saury
Scophthalmus rhombus	Brill
Scorpaena scrofa	Largescaled scorpionfish
Scyliorhinus canicula	Smallspotted catshark
Scyliorhinus stellaris	Nursehound
Scymnodon ringens	Knifetooth dogfish
Sebastes entomelas	Widow rockfish
Sebastes flavidus	Yellowtail rockfish
Sebastes marinus	Ocean perch
Sebastes mentella	Deepwater redfish
Solen vagina	European razor clam
Somniosus microcephalus	Greenland shark
Spisula ovalis	Venus clam
Spisula polynyma	Stimpsons surf clam
Spisula solida	Surf clam
Spondyliosoma cantharus	Black seabream
Sprattus sprattus balticus	Baltic sprat
Squalus acanthias	Piked dogfish
Symphodus melops	Corkwing wrasse
Thaleichthys pacificus	Eulachon
Thunnus thynnus	Northern bluefin tuna
Todarodes sagittatus	European flying squid
Trachinotus ovatus	Derbio
Trachinus draco	Greater weever
Trachurus symmetricus	Pacific jack mackerel
Trichiurus lepturus	Largehead hairtail
Trigla lyra	Piper gurnard
Trisopterus esmarkii	Norway pout
Trisopterus minutus	Poor cod
Urophycis tenuis	White hake
Xiphias gladius	Swordfish

(Table 1b)

Scientific name	Common name
Acipenser ruthenus	Sterlet
Acipenser stellatus	Starry sturgeon
Acipenser transmontanus	White sturgeon
Albula vulpes	Bonefish
Alopias superciliosus	Bigeye thresher
Alopias vulpinus	Thintail thresher
Alosa aestivalis	Blueback shad
Alosa mediocris	Hickory shad
Alosa pseudoharengus	Alewife
Alosa sapidissima	American shad
Ammodytes personatus	Pacific sandeel
Anadara ovalis	Blood arc clam
Anchoa hepsetus	Broad-striped anchovy
Anchoa mitchilli	Bay anchovy
Anoplopoma fimbria	Sablefish
Aphanopus intermedius	Intermediate scabbardfish
Archosargus probatocephalus	Sheepshead seabream
Archosargus rhomboidalis	Western Atlantic seabream
Arctoscopus japonicus	Sailfin sandfish
Argopecten gibbus	Calico scallop
Argopecten irradians	Atlantic bay scallop
Atractoscion nobilis	White weakfish
Auxis rochei	Bullet tuna
Auxis thazard	Frigate tuna
Balistes capriscus	Grey triggerfish
Beryx splendens	Splendid alfonsino
Boops boops	Bogue
Brevoortia tyrannus	Atlantic menhaden
Brotula barbata	Bearded brotula
Callinectes danae	Dana's swimming crab
Callinectes sapidus	Blue crab
Cancer borealis	Jonah crab
Cancer irroratus	Atlantic rock crab
Cancer magister	Dungeness crab
Cancer productus	Pacific rock crab
Carangoides ruber	Bar jack
Caranx crysos	Blue runner
Caranx hippos	Crevalle jack

Scientific name	Common name
Carcharhinus brachyurus	Copper shark
Carcharhinus falciformis	Silky shark
Carcharhinus limbatus	Blacktip shark
Carcharhinus longimanus	Oceanic whitetip shark
Carcharhinus obscurus	Dusky shark
Carcharhinus plumbeus	Sandbar shark
Carcharias taurus	Sand tiger shark
Carcinus maenas	Green crab
Caulolatilus chrysops	Atlantic goldeye tilefish
Caulolatilus princeps	Ocean whitefish
Centrophorus granulosus	Gulper shark
Centropristis striata	Black seabass
Cephalopholis fulva	Coney
Chloroscombrus chrysurus	Atlantic bumper
Citharichthys sordidus	Pacific sanddab
Clinocardium nuttallii	Nuttall cockle
Conger oceanicus	American conger
Coryphaena hippurus	Common dolphinfish
Crassostrea gigas	Pacific cupped oyster
Crassostrea virginica	American cupped oyster
Cynoscion nebulosus	Spotted weakfish
Cynoscion regalis	Gray weakfish
Dalatias licha	Kitefin shark
Dasyatis centroura	Roughtail stingray
Diplectrum formosum	Sand seabass
Dipturus laevis	Barndoor skate
Dorosoma cepedianum	American gizzard shad
Echinorhinus brucus	Bramble shark
Elagatis bipinnulata	Rainbow runner
Elops saurus	Ladyfish
Engraulis mordax	Californian anchovy
Ensis directus	Atlantic razor clam
Eopsetta jordani	Petrale sole
Epinephelus aeneus	White grouper
Epinephelus coioides	Orange-spotted grouper
Epinephelus flavolimbatus	Yellowedge grouper
Epinephelus guttatus	Red hind
Epinephelus morio	Red grouper
Epinephelus nigritus	Warsaw grouper
Epinephelus niveatus	Snowy grouper

Scientific name	Common name
Epinephelus striatus	Nassau grouper
Epinephelus tauvina	Greasy grouper
Erimacrus isenbeckii	Hair Crab
Etrumeus teres	Round herring
Euthynnus alletteratus	Little tunny
Fistularia tabacaria	Cornet fish
Gadus macrocephalus	Pacific cod
Galeichthys feliceps	White baggar
Genyonemus lineatus	White croaker
Geryon quinquedens	Red crab
Ginglymostoma cirratum	Nurse shark
Girella nigricans	Opaleye
Glyptocephalus zachirus	Rex sole
Gymnothorax unicolor	Brown moray
Gymnura altavela	Spiny butterfly ray
Haliotis midae	Perlemoen abalone
Halobatrachus didactylus	Lusitanian toadfish
Hemiramphus brasiliensis	Ballyhoo
Heptranchias perlo	Sharpnose sevengill shark
Hippoglossus stenolepis	Pacific halibut
Homarus americanus	American lobster
Hydrolagus colliei	Spotted ratfish
Hyperoglyphe bythites	Black driftfish
Hypomesus pretiosus	Surf smelt
Illex coindetii	Broadtail shortfin squid
Istiophorus albicans	Atlantic sailfish
Isurus oxyrinchus	Shortfin mako
Isurus paucus	Longfin mako
Joturus pichardi	Bobo mullet
Katsuwonus pelamis	Skipjack tuna
Kyphosus sectatrix	Bermuda sea chub
Labrus merula	Brown wrasse
Laemonema longipes	Longfin codling
Leiostomus xanthurus	Spot croaker
Lepidocybium flavobrunneum	Escolar
Lepidopsetta bilineata	Rock sole
Lepidotrigla cavillone	Large-scaled gurnard
Lethrinus nebulosus	Spangled emperor
Leucoraja circularis	Sandy ray
Leucoraja erinacea	Little skate

Scientific name	Common name
Lichia amia	Leerfish
Limanda ferruginea	Yellowtail flounder
Limulus polyphemus	Horseshoe crab
Lithodes aequispina	Same-spine stone crab
Lithodes maia	Stone king crab
Lobotes surinamensis	Atlantic tripletail
Loligo opalescens	California market squid
Loligo pealeii	Longfin squid
Lophius americanus	American angler
Lophius budegassa	Black-bellied angler
Lopholatilus chamaeleonticeps	Great northern tilefish
Lutjanus argentiventris	Yellow snapper
Lutjanus campechanus	Northern red snapper
Lutjanus synagris	Lane snapper
Macroramphosus scolopax	Longspine snipefish
Makaira nigricans	Atlantic blue marlin
Megalops atlanticus	Tarpon
Menidia menidia	Atlantic silverside
Menippe mercenaria	Black stone crab
Menticirrhus littoralis	Gulf kingcroaker
Menticirrhus saxatilis	Northern kingcroaker
Mercenaria mercenaria	Northern quahog
Merluccius albidus	Offshore hake
Merluccius bilinearis	Silver hake
Merluccius productus	North Pacific hake
Microgadus proximus	Pacific tomcod
Microgadus tomcod	Atlantic tomcod
Micropogonias undulatus	Atlantic croaker
Mobula mobular	Devil fish
Morone americana	White perch
Morone saxatilis	Striped sea-bass
Mugil cephalus	Flathead mullet
Mullus barbatus	Red mullet
Mullus surmuletus	Striped red mullet
Muraena helena	Mediterranean moray
Mustelus asterias	Starry smooth-hound
Mustelus canis	Dusky smooth-hound
Mustelus henlei	Brown smooth-hound
Mustelus mustelus	Smooth-hound
Mycteroperca bonaci	Black grouper

Scientific name	Common name
Mycteroperca microlepis	Gag
Mycteroperca phenax	Scamp
Mycteroperca venenosa	Yellowfin grouper
Mycteroperca xenarcha	Broomtail grouper
Myliobatis aquila	Common eagle ray
Negaprion brevirostris	Lemon shark
Nemipterus virgatus	Golden threadfin bream
Notorynchus cepedianus	Broadnose sevengill shark
Octopus vulgaris	Common octopus
Ocyurus chrysurus	Yellowtail snapper
Ommastrephes bartramii	Neon flying squid
Oncorhynchus keta	Chum salmon
Oncorhynchus kisutch	Coho salmon
Oncorhynchus mykiss	Rainbow trout
Oncorhynchus tshawytscha	Chinook salmon
Opisthonema oglinum	Atlantic thread herring
Orthopristis chrysoptera	Pigfish
Ostrea lurida	Olympia flat oyster
Oxynotus centrina	Angular roughshark
Pagrus pagrus	Common seabream
Pandalus goniurus	Humpy shrimp
Pandalus hypsinotus	Humpback shrimp
Panopea abrupta	Pacific geoduck
Panulirus argus	Caribbean spiny lobster
Paralichthys californicus	California flounder
Paralichthys dentatus	Summer flounder
Paralithodes brevipes	Spiny king crab
Paralithodes camtschaticus	Red king crab
Parapenaeus longirostris	Deepwater rose shrimp
Parapristipoma octolineatum	African striped grunt
Parophrys vetula	English sole
Patinopecten caurinus	Weathervane scallop
Pegusa lascaris	Sand sole
Penaeus aztecus	Northern brown shrimp
Penaeus brasiliensis	Redspotted shrimp
Penaeus duorarum	Northern pink shrimp
Penaeus setiferus	Northern white shrimp
Peprilus alepidotus	Harvestfish
Peprilus simillimus	Pacific pompano
Peprilus triacanthus	American butterfish

Scientific name	Common name
Placopecten magellanicus	American sea scallop
Pleoticus robustus	Royal red shrimp
Plesiopenaeus edwardsianus	Scarlet shrimp
Pleuroncodes planipes	Pelagic red crab
Pleuronectes quadrituberculatus	Alaska plaice
Pleuronichthys decurrens	Curlfin sole
Pogonias cromis	Black drum
Polyprion americanus	Wreckfish
Pomadasys incisus	Bastard grunt
Pomatomus saltator	Bluefish
Pontinus kuhlii	Offshore rockfish
Prionace glauca	Blue shark
Promethichthys prometheus	Roudi escolar
Protothaca staminea	Pacific littleneck clam
Psettichthys melanostictus	West American sand sole
Pseudopleuronectes americanus	Winter flounder
Pseudupeneus prayensis	West African goatfish
Rachycentron canadum	Cobia
Raja asterias	Starry ray
Raja stellulata	Starry skate
Raja undulata	Undulate ray
Reinhardtius evermanni	Kamchatka flounder
Rhomboplites aurorubens	Vermilion snapper
Ruvettus pretiosus	Oilfish
Sarda sarda	Atlantic bonito
Sardinella aurita	Round sardinella
Sardinella zunasi	Japanese sardinella
Sardinops sagax	South American pilchard
Saurida undosquamis	Brushtooth lizardfish
Saxidomus giganteus	Butter clam
Schedophilus ovalis	Imperial blackfish
Sciaena umbra	Brown meagre
Sciaenops ocellatus	Red drum
Scomberomorus cavalla	King mackerel
Scomberomorus maculatus	Spanish mackerel
Scomberomorus regalis	Cero
Scophthalmus aquosus	Windowpane
Scorpaenichthys marmoratus	Cabezon
Sebastes alutus	Pacific ocean perch
Sebastes goodei	Chilipepper

Scientific name	Common name
Sebastes melanops	Black rockfish
Sebastes paucispinis	Bocaccio
Sebastes pinniger	Canary rockfish
Sebastolobus alascanus	Shortspine thornyhead
Selar crumenophthalmus	Bigeye scad
Selene setapinnis	Atlantic moonfish
Semicossyphus pulcher	California sheephead
Seriola dumerili	Greater amberjack
Seriola lalandi	Yellowtail amberjack
Sicyonia brevirostris	Rock shrimp
Siliqua patula	Pacific razor clam
Sillago sihama	Silver sillago
Solea senegalensis	Senegalese sole
Somniosus pacificus	Pacific sleeper shark
Somniosus rostratus	Little sleeper shark
Sparisoma cretense	Parrotfish
Sparus auratus	Gilthead seabream
Spectrunculus grandis	Pudgy cuskeel
Sphoeroides maculatus	Northern puffer
Sphyraena barracuda	Great barracuda
Sphyrna lewini	Scalloped hammerhead
Sphyrna zygaena	Smooth hammerhead
Spicara maena	Blotched picarel
Spisula solidissima	Atlantic surf clam
Stenotomus chrysops	Scup
Stereolepis gigas	Giant sea-bass
Synagrops japonicus	Japanese splitfin
Tautoga onitis	Tautog
Tautogolabrus adspersus	Cunner
Tetrapturus albidus	Atlantic white marlin
Tetrapturus audax	Striped marlin
Tetrapturus pfluegeri	Longbill spearfish
Thais haemastoma	Hays rock-shell
Theragra chalcogramma	Alaska pollack
Thunnus alalunga	Albacore
Thunnus albacares	Yellowfin tuna
Thunnus atlanticus	Blackfin tuna
Thunnus obesus	Bigeye tuna
Thunnus orientalis	Pacific bluefin tuna
Todarodes pacificus	Japanese flying squid

Scientific name	Common name
Trachinotus carolinus	Florida pompano
Trachurus lathami	Rough scad
Trachyscorpia cristulata cristulata	Atlantic thornyhead
Umbrina canariensis	Canary drum
Umbrina cirrosa	Shi drum
Upogebia pugettensis	Blue mud shrimp
Urophycis chuss	Red hake
Xiphopenaeus kroyeri	Atlantic seabob
Zenopsis conchifer	Silvery John dory
Zoarces americanus	Ocean pout

(Table 1c)

Scientific name	Common name
Ablennes hians	Flat needlefish
Acanthocybium solandri	Wahoo
Argentina sphyraena	Argentine
Atule mate	Yellowtail scad
Caranx melampygus	Bluefin trevally
Caranx sexfasciatus	Bigeye trevally
Centropomus undecimalis	Common snook
Cetengraulis edentulus	Atlantic anchoveta
Crassostrea rhizophorae	Mangrove cupped oyster
Diplodus argenteus	South American silver porgy
Epinephelus analogus	Spotted grouper
Euthynnus lineatus	Black skipjack
Gerres oyena	Common silver-biddy
Kyphosus cinerascens	Blue seachub
Lepidorhombus whiffiagonis	Megrim
Lutjanus argentimaculatus	Mangrove red snapper
Lutjanus purpureus	Southern red snapper
Makaira indica	Black marlin
Mugil liza	Liza
Orcynopsis unicolor	Plain bonito
Osmerus eperlanus	European smelt
Penaeus notialis	Southern pink shrimp
Perna perna	South American rock mussel
Perna viridis	Brown mussel
Platycephalus indicus	Bartail flathead
Pseudocaranx dentex	White trevally

Scientific name	**Common name**
Raja clavata	Thornback ray
Salmo trutta	Sea trout
Scomberoides lysan	Doublespotted queenfish
Scomberoides tol	Needlescaled queenfish
Scomberomorus brasiliensis	Serra Spanish mackerel
Sebastes viviparus	Norway redfish
Sepia officinalis	Common cuttlefish
Sphyraena obtusata	Obtuse barracuda
Tetrapturus angustirostris	Shortbill spearfish
Tonna galea	Helmet ton

Appendix II: Seabirds in Canadian marine ecoregions

Seabirds in Canadian marine ecoregions:

Distribution and Abundance

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Introduction

The *Sea Around Us* project maintains a Global Seabird Database, containing data on distributions and breeding abundances of 334 seabird species worldwide, from 1950-2010. The following report is a summary from this database, by Canadian ecoregions, of the abundance and occurrence of the 38 seabird species breeding in Canada.

Part I: Seabird abundance in Canadian ecoregions

Methods

The *Sea Around Us* Global Seabird Database contains seabird breeding abundance data from 1950 to 2010, compiled from books, peer-reviewed journal articles, online databases and unpublished data.

The data were collected by *stretch* of coast. A *stretch* is a subdivision of coastline where seabird breeding occurs. A *stretch* may include more than one colony, but *stretches* were assigned based on regions used in seabird reporting. Thus, it is assumed that all colonies in a given *stretch* are counted. There are 27 *stretches* in Canada, and a*stretches* are contained entirely within individual Canadian ecoregions. The number of *stretches* per Canadian ecoregion varies (Table 1). Each seabird species within a *stretch* is assigned a unique *population* identifier, of which there are 171 in Canada.

Table 1. Canadian ecoregions and their associated coastal *stretches* as defined for the seabird database

Ecoregion	***Stretch***
Eastern Arctic	Bylot Island
-	Coburg Island
-	Prince Leopold Island
-	Queen Elizabeth Islands
Gulf of St Lawrence	Quebec
Hudson Bay Complex	Baffin Island E
-	Baffin Island SE
-	Baffin Island W
-	Coats Island
-	Digges Island
-	Hudson Bay
-	Southampton Island
Newfoundland-Labrador Shelves	Nain
-	Newfoundland-Labrador
North Shelf British Columbia	BC N coast
-	Graham Is W
-	Moresby Is E
-	Moresby Is W
-	Queen Charlotte Strait
-	Scott Islands
Scotian Shelf	Scotian Shelf
South Shelf British Columbia	Vancouver Is W
Strait of Georgia	Georgia Strait
-	Gulf Islands
Western Arctic	Banks Island
-	Northwest Territories
-	Victoria Island

Seabird breeding abundance records were collected for all years possible for each *population*. Where abundance was given as a range, we took the geometric mean. We included abundance records reported as either breeding pairs or population size. The analyses required all breeding abundance estimates be expressed in a common unit, thus we converted breeding pairs (BP) to population size (P) using the following definitions, which account for non-breeders and new fledglings:

P = BP*2 +BP*0.6 + BP*1, for species laying a multi-egg clutch; and

P = BP*2 + BP*0.6 + BP*0.7, for species laying a single-egg clutch.

The most recent breeding abundance of all seabird species, defined as the sum of the most recent population size records for all *populations*, was estimated by Canadian ecoregion. The change in breeding abundance, defined as most recent breeding abundance divided by the least recent breeding abundance, was estimated by Canadian ecoregion. Change could be calculated only for the 57% of the Canadian seabird *populations* that have been re-sampled (i.e., have at least two sampling events), which account for 86-90% of all seabirds breeding in Canada. For the remaining *populations* that have not been re-sampled, it was assumed that no change occurred.

Results and Discussion

The most recent breeding abundance estimates range from 3,000 individuals in the Western Arctic ecoregion to 16,695,000 individuals in the Newfoundland-Labrador Shelves ecoregion (Table 2). The total of most recent abundance of seabirds breeding in Canada is 36.27 million individuals.

Table 2. Most recent data on breeding abundance (total number of individuals) and percent change in abundance for seabirds in Canadian ecoregions (ratio of recent to oldest abundance estimate).

Ecoregion	**Recent abundance** (Nos. individuals)	**Change** (ratio recent to oldest abundance)
Strait of Georgia	85,000	0.43
South Shelf British Columbia	833,000	1.01
North Shelf British Columbia	7,513,000	1.00
Western Arctic	3,000	0.06
Hudson Bay Complex	3,486,000	0.49
Eastern Arctic	4,957,000	0.79
Newfoundland-Labrador Shelves	16,695,000	4.59
Gulf of St Lawrence	1,051,000	5.32
Scotian Shelf	1,652,000	1.46

The greatest positive change in seabird abundance occurred in the Gulf of St. Lawrence ecoregion, while the greatest negative change occurred in the Western Arctic ecoregion (Table 2). The total change between the oldest and most recent abundance estimates across all re-sampled *populations* in Canadian ecoregions is an increase by 10.13 million individuals.

The values reported here are best used for comparisons of relative abundance among Canadian ecoregions, as their accuracy in absolute terms is limited by various sources of error. Recent abundance estimates include the most recent records for all populations. However, in some cases the most recent population estimate was recorded as far back as 1975. Thus, truly recent changes occurring in such populations will not be captured in our estimate of recent abundance. Furthermore, change in abundance is determined by comparing between abundance records collected from different sources, potentially using different data collection methods (e.g., differing experimental design, sampling area, season, and estimation of population size from breeding pairs). Changes in abundance observed here may thus be influenced by changes of data collection methods.

Finally, accuracy of the estimate of change in abundance is influenced by the availability of data. Ideally, all *populations* in an ecoregion would have been re-sampled, allowing an estimate of change for all *populations*. However, the percent of *populations* that have been re-sampled ranged from 17% in the Scotian Shelf ecoregion to 88% in the Gulf of St. Lawrence ecoregion (Table 3). While not relevant to the calculation of change, the weighted average number of sampling events per *population*, which varied from 1.2 in the Scotian Shelf ecoregion to 4.8 in the Gulf of St. Lawrence ecoregion (Table 3), is also indicative of data availability.

Table 3. Availability of data used to estimated the change in seabird abundance: Percent of *populations* that have been sampled more than once, and weighted average number of sampling events per *population* by Canadian ecoregion

Ecoregion	**Percent of *populations* that have been re-sampled (%)**	**Weighted mean number of sampling events per *population***
Strait of Georgia	33	1.3
South Shelf British Columbia	57	1.8
North Shelf British Columbia	70	1.9
Western Arctic	25	1.3
Hudson Bay Complex	33	1.6
Eastern Arctic	57	1.8
Newfoundland-Labrador Shelves	75	3.6
Gulf of St. Lawrence	88	4.8
Scotian Shelf	17	1.2

Part II: Seabird occurrence in Canadian ecoregions

Methods

The *Sea Around Us* Global Seabird Database contains, for each seabird species, a geo-referenced database of coastal *stretches* where breeding occurs, and at-sea ranges, divided into breeding and non-breeding ranges for species that disperse or migrate after breeding. These data were compiled from books, journal articles, and online databases (e.g., Birds of North America, http://bna.birds.cornell.edu/bna/), and is part of the graduate research thesis of the senior author of the present report. The present report includes the breeding and non-breeding occurrence of all Canadian seabird species, by ecoregion.

Results and Discussion

The seabird species breeding and wintering occurrence in Canadian ecoregions is summarized in Table (4). Newfoundland-Labrador Shelves, Scotian Shelf, and the Gulf of St. Lawrence ecoregions have the largest number of breeding species, while Western Arctic, Eastern Arctic and Strait of Georgian ecoregions have the smallest number of breeding species. South Shelf British Columbia and North Shelf British Columbia ecoregions have the largest number of wintering species, while the Western Arctic, Eastern Arctic and Hudson Bay Complex ecoregions have the smallest number of wintering species.

Table 4. Occurrence of Canadian seabird species during the breeding season (b) and wintering season (w), by Canadian ecoregion (SoG= Strait of Georgia, SSBC= South Shelf British Columbia, NSBC= North Shelf British Columbia, WA= Western Arctic, HBC= Hudson's Bay Complex, EA= Eastern Arctic, NLS=Newfoundland-Labrador Shelves, G= Gulf of St. Lawrence, SS= Scotian Shelf).

Common name	Species name	**SoG**	**SSBC**	**NSBC**	**WA**	**HBC**	**EA**	**NLS**	**G**	**SS**
Ancient Murrelet	*Synthliboramphus antiquus*	w	w	bw						
Arctic Tern	*Sterna paradisaea*					b		b	b	b
Atlantic Puffin	*Fratercula arctica*					b		bw	bw	bw
Black Guillemot	*Cepphus grylle*					bw		bw	bw	bw
Black-legged Kittiwake	*Rissa tridactyla*		w	w		b	b	bw	bw	bw
Brandt's Cormorant	*Compsohalieus penicillatus*	bw	bw	bw						
Caspian Tern	*Sterna caspia*							b	b	b
Cassin's Auklet	*Ptychoramphus aleuticus*		bw	bw						
Common Black-headed Gull	*Larus ridibundus*							bw	bw	bw
Common Gull	*Larus canus*	bw	bw	w						
Common Murre	*Uria aalge*	w	bw	bw				bw	bw	bw
Common Tern	*Sterna hirundo*							b	b	b
Double-crested Cormorant	*Hypoleucos auritus*	bw	bw	w				b	b	b
Forked-tailed Storm Petrel	*Oceanodroma furcata*		bw	bw						
Glaucous Gull	*Larus hyperboreus*	w	w	w		bw	w	bw	w	w
Glaucous-winged Gull	*Larus glaucescens*	bw	bw	bw						
Great Black-backed Gull	*Larus marinus*							bw	bw	bw
Great Cormorant	*Phalacrocorax carbo*							bw	bw	bw
Herring Gull	*Larus argentatus*	w	w	w				b	b	b
Horned Puffin	*Fratercula corniculata*		bw	bw						
Iceland Gull	*Larus glaucoides*					b		w	w	w
Ivory Gull	*Pagophila eburnea*						bw	w		
Leach's Storm Petrel	*Oceanodroma leucorhoa*		b	b				b	b	b
Little Gull	*Larus minutus*					b				
Manx Shearwater	*Puffinus puffinus*							b		
Marbled Murrelet	*Brachyramphus marmoratus*	bw	bw	bw						
Northern Fulmar	*Fulmarus glacialis*		w	bw		bw	bw	bw		
Northern Gannet	*Morus bassanus*							b	b	b
Pelagic Cormorant	*Strictocarbo pelagicus*	bw	bw	bw						
Pigeon Guillemot	*Cepphus columba*	bw	bw	bw						
Razorbill	*Alca torda*				b			bw	b	bw
Rhinoceros Auklet	*Cerorhinca monocerata*	bw	bw	b						
Ring-billed Gull	*Larus delawarensis*	w	w					b	b	b
Roseate Tern	*Sterna dougallii*									b
Sabine's Gull	*Xema sabini*				b	b				
Thayer's Gull	*Larus thayeri*	w	w	w		b				
Thick-billed Murre	*Uria lomvia*		w	bw	b	bw	bw	bw	bw	bw
Tufted Puffin	*Fratercula cirrhata*	b	bw	bw						

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