SEA AROUND US PROJECT

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

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# 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).

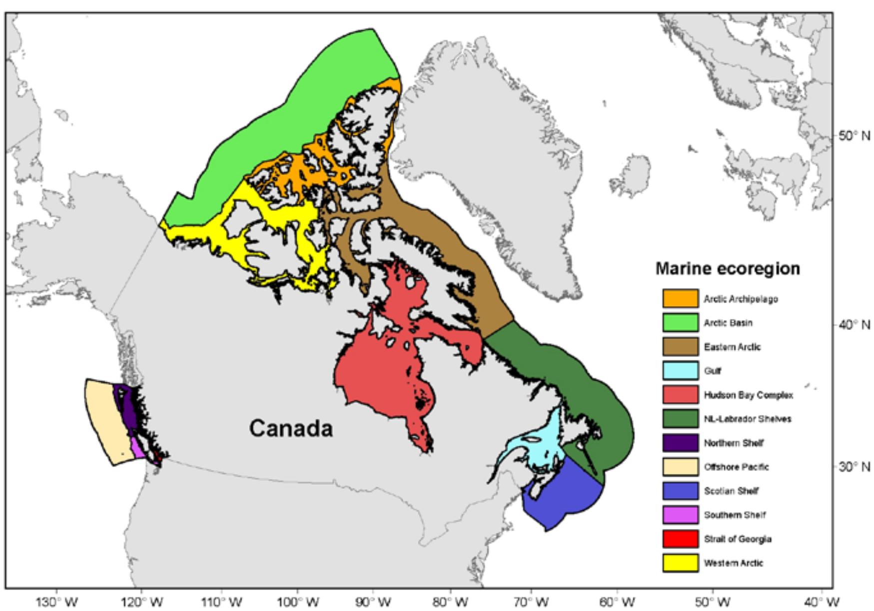


**Figure 1.** Canadian marine ecoregions (source: Fisheries and Oceans Canada 2009)

[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).

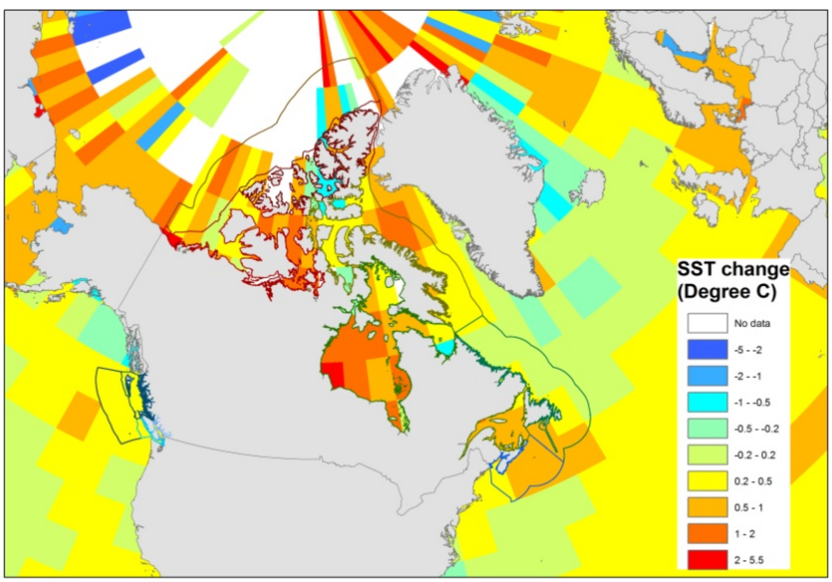


**Figure 2.** Changes in sea surface temperature (SST) between the 1960s (average 1950-1969) and 2000s (1988-2007), with Canadian marine ecoregions outlined (Rayner *et al.* 2006; source: Met. Office Hadley Centre; http://hadobs.metoffice.com/hadsst2/data/download.html).

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:

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

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.

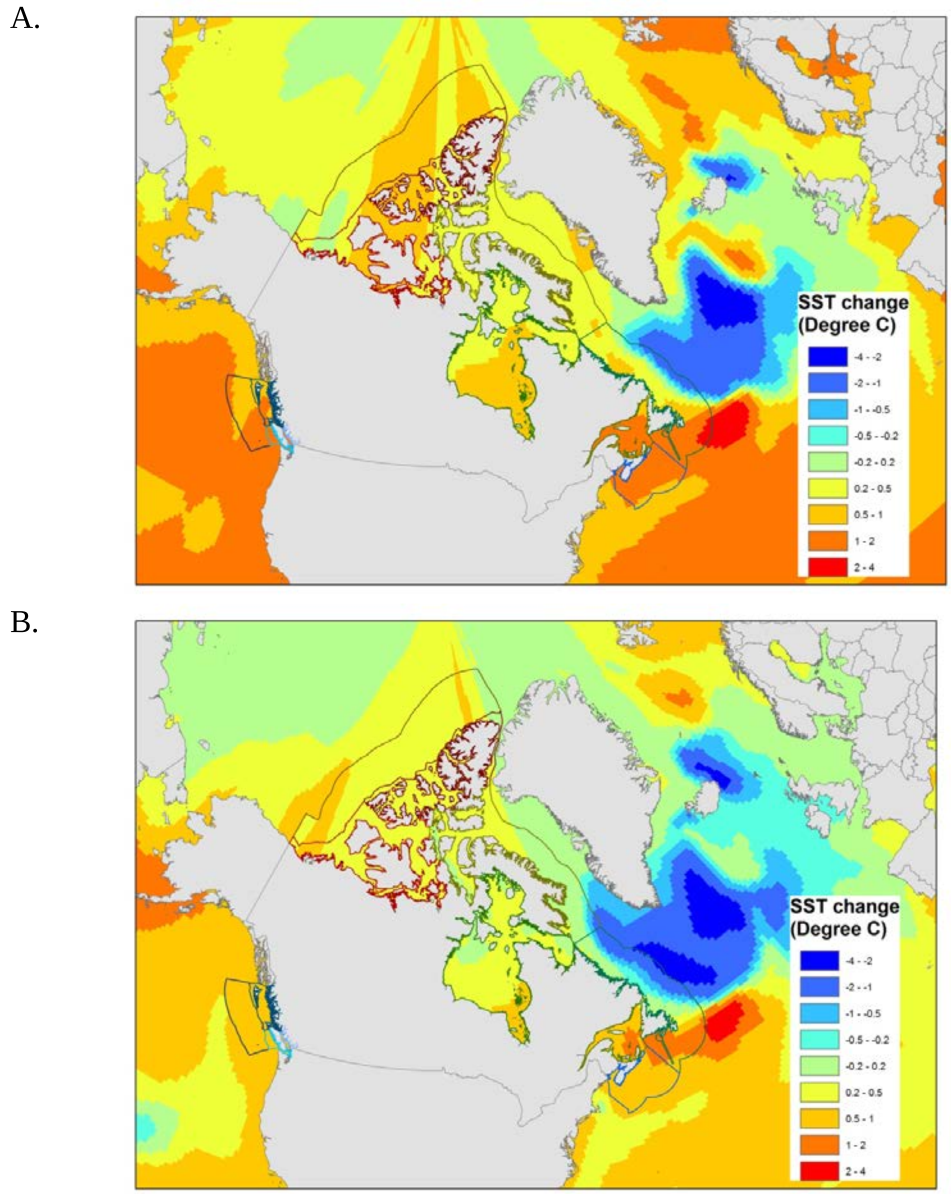


**Figure 3.** Projected change in sea surface temperature (SST, top 50 m) between the mid 2000s (average 2001 – 2010) and the 2050s (average 2046 – 2055) from the NOAA's GFDL CM2.1 under two IPCC scenarios: (A) SRES A1B; (B) SRES B1. Model outputs were interpolated onto a 0.5$^{o}$ latitude x 0.5$^{o}$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

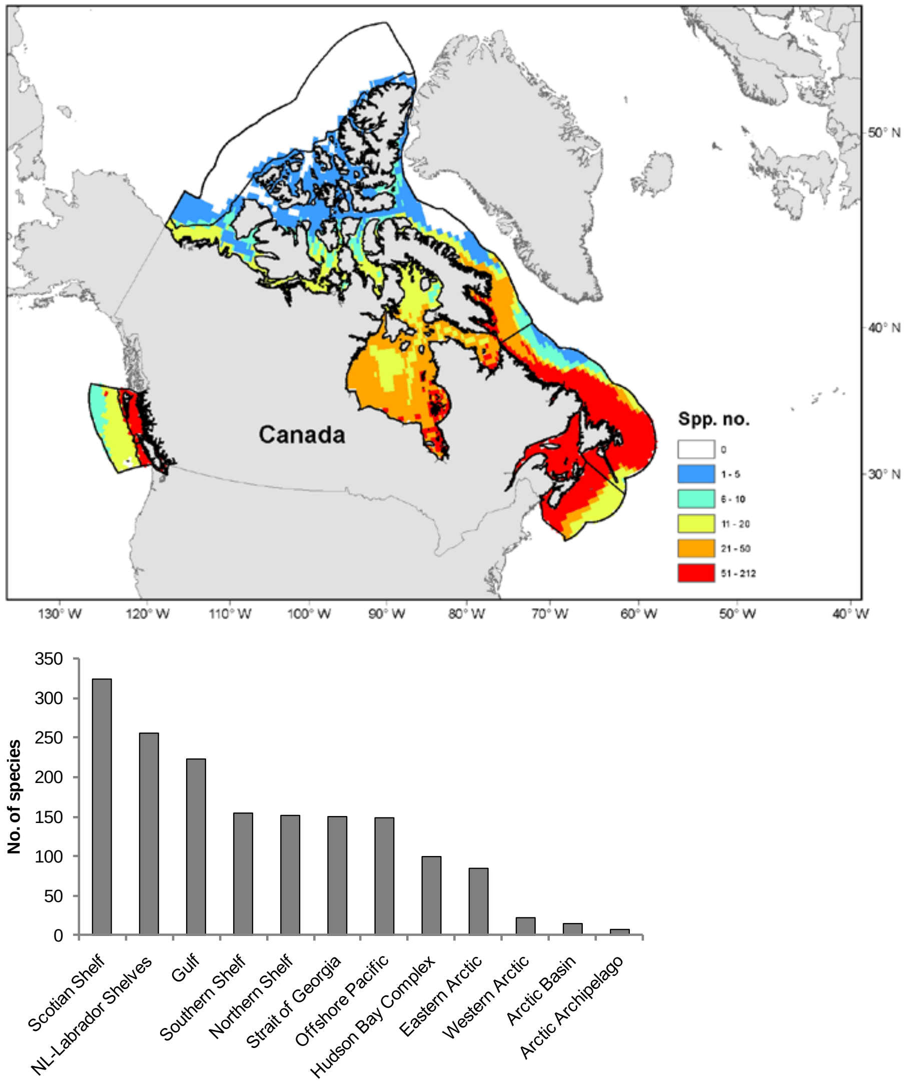


**Figure 4.** Estimated number of commercial species in the marine ecoregions based on predicted current (1980-2000) distribution (A) on 0.5$^o$ x 0.5$^o$ grid and (B) by marine ecoregions.

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.

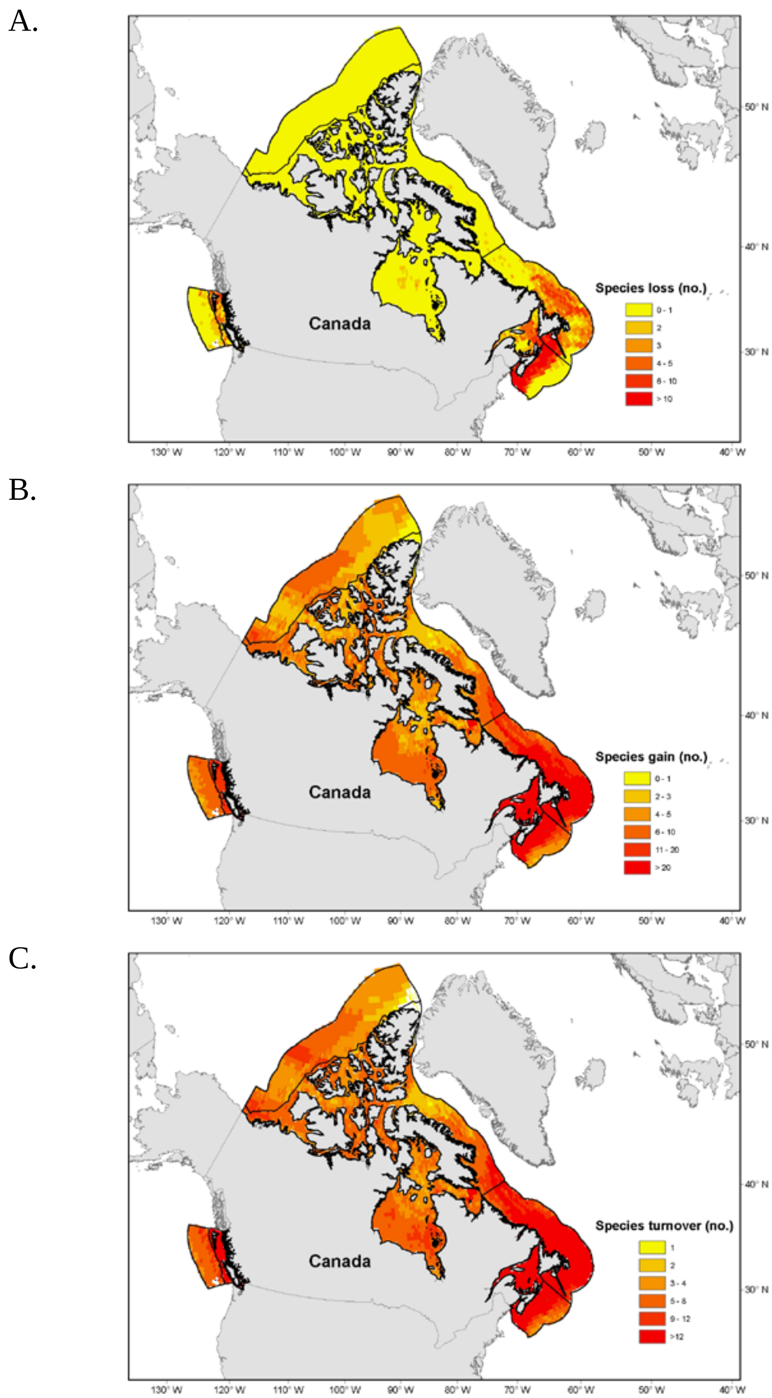


**Figure 5**. Projected number of (A) species loss, (B) gain and (C) turnover by 2050 relative to the original species richness in the 2000s under the SRES A1B scenario. For ecoregions see Figure 1.

A.

B.

C.

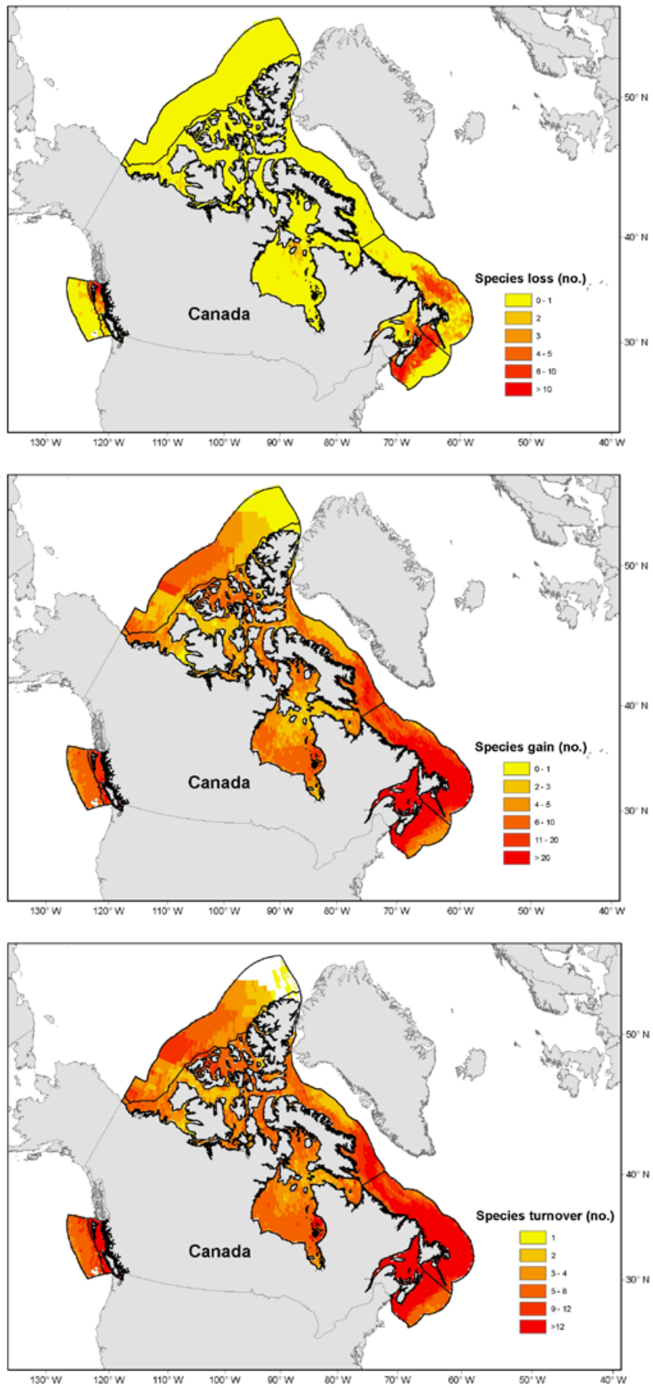


**Figure 6.** Projected number of (A) species loss, (B) gain and (C) turnover by 2050 relative to the original species richness in the 2000s under the SRES B1 scenario. For ecoregions see Figure 1.

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.

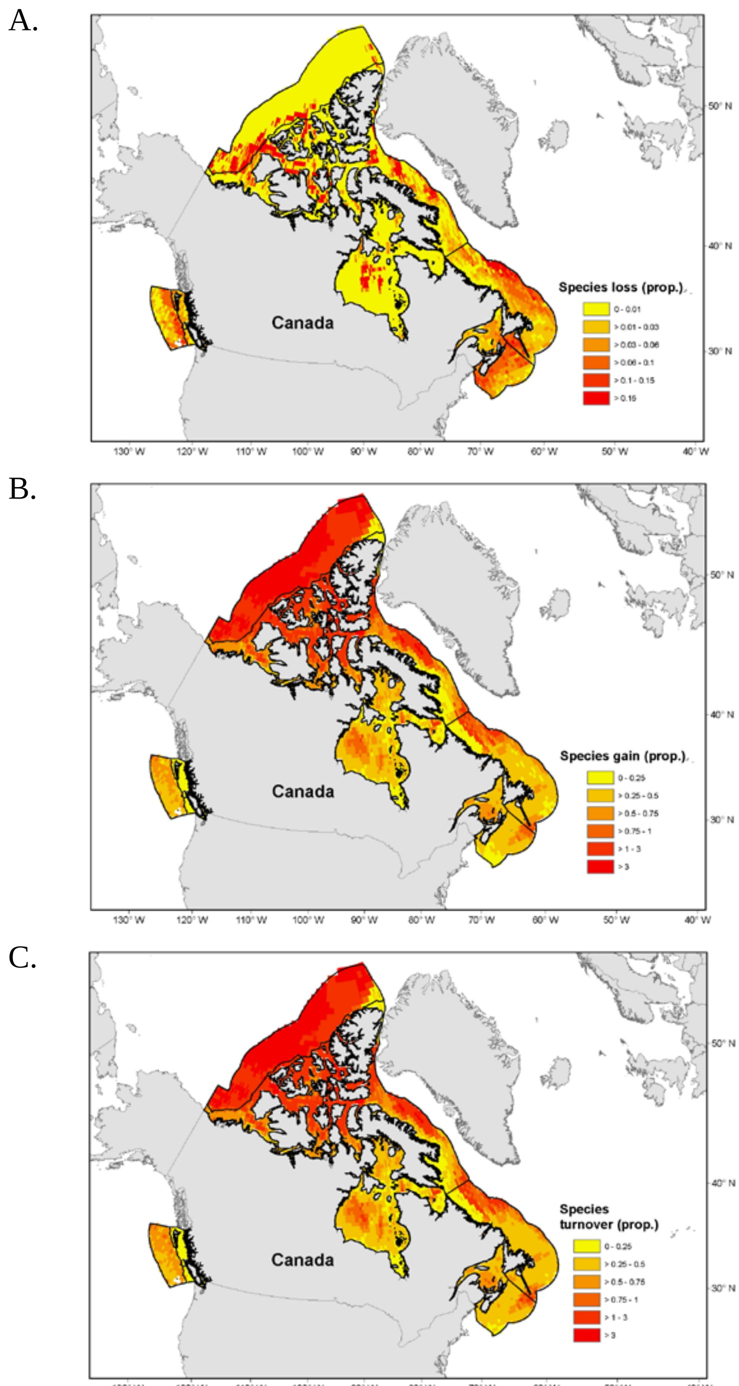


**Figure 7.** Projected proportion of (A) species loss, (B) gain and (C) turnover by 2050 relative to the species richness in the 2000s under the SRES A1B scenario. For ecoregions see Figure 1.

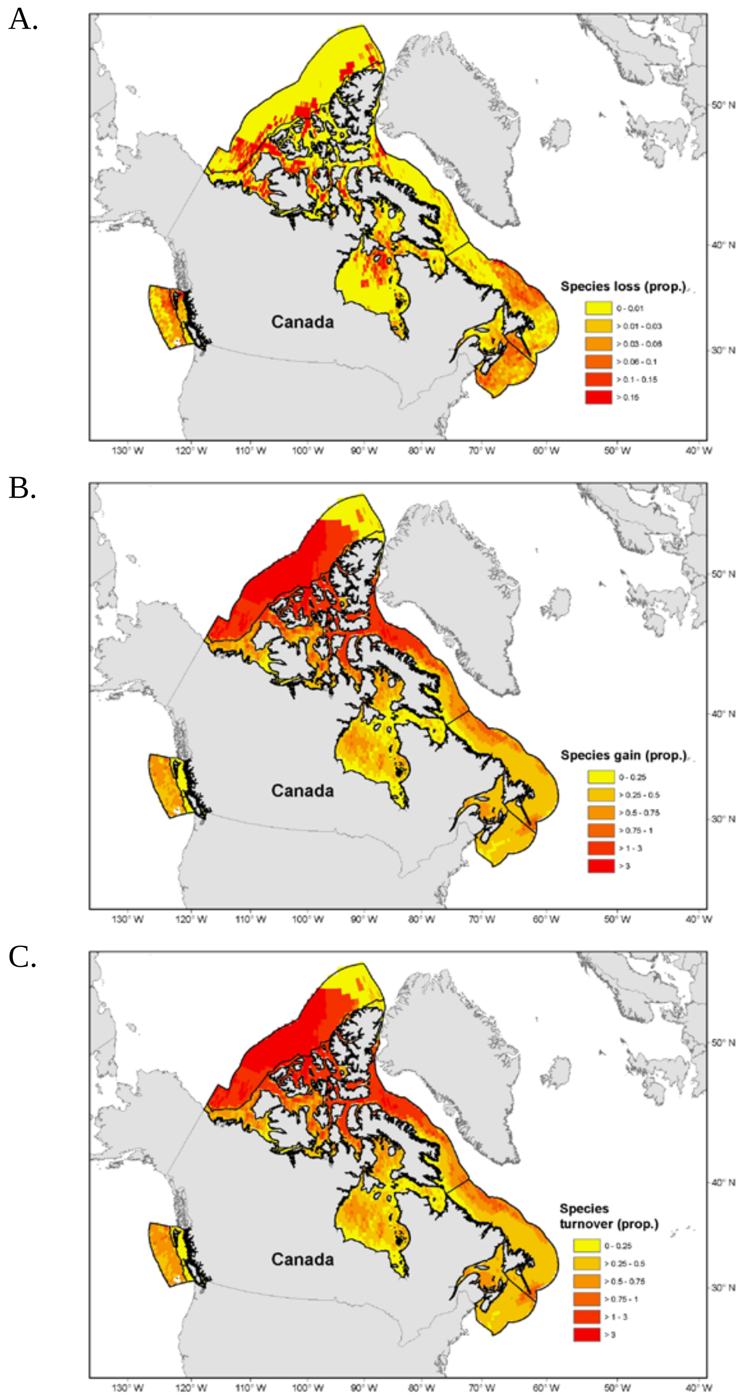


**Figure 8.** Projected proportion of (A) species loss, (B) gains and (C) turnover by 2050 relative to the species richness in the 2000s under the SRES B1 scenario. For ecoregions see Figure 1.

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.

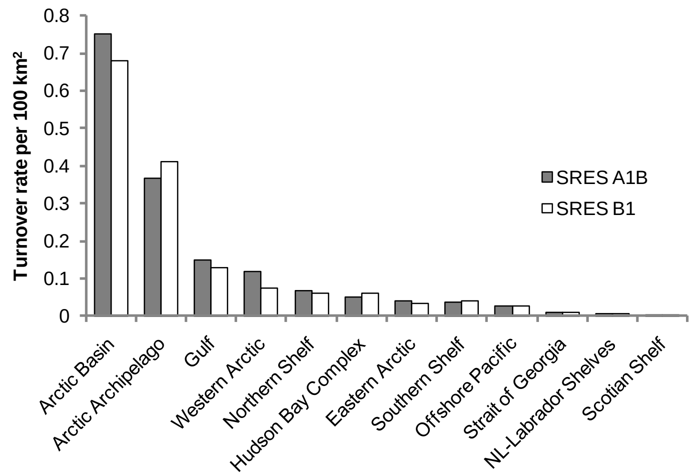


**Figure 9.** Species turnover per unit of area in each marine ecoregion under the two climate change scenarios SRES A1B (grey bars) and B1 (open bars).

## 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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