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Prediction of the Suitable Habitat of the Northern Shrimp, *Pandalus borealis,* in the Estuary and Gulf of St. Lawrence

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Foreword

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

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ABSTRACT

The northern shrimp (*Pandalus borealis*) is a key species for the Estuary and Gulf of St. Lawrence (EGSL). Climate change is rapidly altering the conditions of this ecosystem, causing warming, deoxygenation, and acidification of its deep waters. These alterations, combined with a re-emergence of redfish predation, led to a diminution of the area occupied by shrimps and to the stocks' decline, many of which are now in the critical zone according to the precautionary approach. This study aims to characterize and model the evolution of the habitat suitable for the northern shrimp in the EGSL using data from the annual ecosystem survey conducted by Fisheries and Oceans Canada and a regional climate model. Our results show that the habitat suitable for the northern shrimp is characterized by temperatures between 1.9 and 5.7 °C, dissolved oxygen concentration greater than 77.8 mmol O_2/m^3, and total pH (pH_T) above 7.54. Using projections of physical (temperature) and chemical (pH_T, dissolved oxygen) conditions, changes in the suitable habitat area were characterized for the Estuary and the northern Gulf of St. Lawrence. The numerical model projects a gradual decline of 58% in habitat suitability between the 2011–2020 and 2041–2050 periods. This loss of suitable habitat is mainly due to an increase in temperature, except in the western part of the Sept-Iles stock assessment unit and in the Estuary assessment unit, where dissolved oxygen concentrations and pH_T also contribute to the habitat decline. Starting in 2050, the area of suitable habitat stabilizes in all stock assessment units.

INTRODUCTION

The northern shrimp (*Pandalus borealis,* hereafter called shrimp) is a cold-water species distributed in the northwest Atlantic from Davis Strait up north to the Gulf of Maine down south, including the Estuary and Gulf of St. Lawrence (EGSL). The adult stage is widespread on the EGSL seabed but found mainly below the cold intermediate layer (CIL), at depths ranging from 150 to 350 m (Bourdages et al., in preparation). This deep layer is also known as the Atlantic layer and is primarily composed of waters entering through Cabot Strait (Gilbert et al. 2005; Galbraith et al. 2025). The shrimp is affected by changing environmental and ecosystem conditions as a result of climate change. The deep layer is currently experiencing warming, oxygen depletion and acidification (Bernier et al. 2023; Blais et al. 2025; Galbraith et al. 2025; Lizotte et al. 2026). In response to these changes, a modification of the spatial distribution of the population has been observed at certain locations in the EGSL, associated with a decrease in the size of areas with high concentrations of shrimp. In addition, in recent years, the redfish (S*ebastes mentella*), a predator of shrimp, has made a strong comeback in the EGSL (DFO 2025a). The combined effect of environmental changes and increased predation pressure has been unfavorable for EGSL shrimp stocks in recent years. The EGSL shrimps are a separate population from the Scotian Shelf and Newfoundland/Labrador/Arctic populations (Bourret et al. 2024*).* The EGSL has four shrimp stock assessment units: the Estuary, Sept-Iles, Anticosti and Esquiman (Figure 1). The status of three of these stocks is currently in the critical zone of the precautionary approach (DFO 2025b).

Environmental changes are affecting the availability of the habitat suitable to the northern shrimp and stock productivity. Quantifying the availability of past, current and future shrimp's suitable habitat is essential in the context of climate change and would allow fishery management measures to be adjusted accordingly. To do this, it is first necessary to characterize the environmental conditions suitable for the northern shrimp in the EGSL ecosystem. The shrimp's habitat characteristics have been described in the literature (Koeller et al. 2009; Zabihi-Seissan et al. 2024). However, multiple regional factors, such as predation pressure (Richards and Hunter 2021; Zabihi-Seissan et al. 2024) and phenotypic plasticity of both individuals and populations of the EGSL (Leung et al. 2023) lead to the clearer observed distribution patterns of the shrimp relative to the observed physical and chemical conditions. Therefore, for this study, we investigated the environmental conditions promoting abundant northern shrimp stocks in the EGSL.

After empirically establishing the temperature, dissolved oxygen concentration and pH conditions suitable to the shrimp, we projected the evolution of this suitable habitat in the future using the Gulf of St. Lawrence regional climate model (Long et al. 2016; Lavoie et al. 2020; Lavoie et al. 2021). Connectivity between each of these units in the adult stage appears to be limited (Bourdages et al. 2023). The results of this work are therefore presented in terms of the boundaries of the four stock assessment units (Figure 1). Moreover, all results presented in this study will use data from the month of August of each year exclusively since the annual ecosystemic surveys made by DFO (Chamberland et al. 2025) are conducted in August.

METHODOLOGY

DESCRIPTION OF THE HABITAT SUITABLE FOR THE SHRIMP

Since 1990, a bottom trawl survey has been conducted annually in August in the EGSL to sample near-bottom fish and invertebrate species, including the northern shrimp (Chamberland et al. 2025). Annually, approximately 160 to 200 trawl tows are successfully completed. In

addition to monitoring shrimp abundance and biomass, oceanographic data are also generally collected at each station using a CTD SBE 19PlusTM device (temperature and salinity data, since 1990) and a dissolved oxygen sensor (SBE 63, since 2004) installed on the back of the trawl. This survey is therefore essential to monitor this population's dynamic. To determine the environmental conditions corresponding to the habitat suitable for the shrimp in the EGSL, we used data from 2006 to 2008 (shrimp catches, temperature and dissolved oxygen concentration, respectively Figure 2A, B and C). The period from 2006 to 2008 is associated with high productivity for EGSL shrimp stocks. Abundances were very high; the spatial distribution was at its maximum as were commercial fishery yields.

Since pH was not measured during the surveys, we used the total pH (pH_T) simulated by the regional climate model (Lavoie et al. 2021) for the same period (2006 to 2008, Figure 2E). The numerical model provides data for horizontal cells of approximately 6 km (see section below Description of the Regional Climate Model). Since the model determines the temperature at the center of the cells and the trawl data can be located between grid cell's middle positions, the simulated pH_T values were interpolated horizontally at the location of the survey stations (Figure 3).

The Perry and Smith's method (1994) implemented in the R package 'habitatCDF' (Isabel et al. 2025) was used to empirically determine the environmental conditions associated with shrimp catches in the survey. This method consists of cumulating catches based on the cumulative values of environmental variables measured in situ. Mean bottom temperature values corresponding to the 5th and 95th percentiles (90%) of cumulative shrimp catches in the survey define the suitable habitat with respect to temperature (Table 1).

Since the maximum dissolved oxygen and pH conditions are not limiting for the shrimp, only average values corresponding to the 5th percentile of catches are considered for these variables (Table 1). Note that these values correspond to the conditions measured or simulated near the bottom. For the Estuary, Sept-Iles, Anticosti and Esquiman assessment units, measurements were taken at depths of 49 m to 359 m, 41 m to 438 m, 46 m to 484 m and 41 m to 511 m, respectively (Figure 2D).

The exploitable shrimp population, i.e. aggregations dense enough to allow commercial fishing, is mostly found below the CIL since the latter is too cold to offer suitable environmental conditions for the shrimp. Coastal areas can be unsuitable because temperatures are too high in the summer (which, on average, have been above 9.8 °C from May to November since 2005 (Galbraith et al. 2025)) and the substrate is generally coarse and consisting mainly of gravel (Sklar et al. 2024), whereas shrimp are associated with fine sediments and muddy bottoms rich in organic matter (Krawczyk et al. 2022, 2024; Jónsdóttir et al. 2022). To take these factors into consideration and reject the coastal areas from the diagnosis of suitable habitat, a minimum depth constraint of 75 m was imposed. By excluding areas shallower than 75 m, 20% of the surface of the EGSL is dismissed.

REGIONAL CLIMATE MODEL DESCRIPTION

The regional climate model is based on an implementation of the NEMO model (Nucleus for European Modelling of the Ocean) in the Gulf of St. Lawrence. The model grid covers the EGSL, the Scotian Shelf and the Gulf of Maine, with a spatial resolution of 1/12th of a degree (approximately 6 km). The grid has 46 vertical layers of varying thickness (thinner at the surface, ~6 m, and thicker near the bottom). In this study, we use two versions of the regional climate model; a version that simulates past conditions, from 2005 to 2024 (called HIND for "hindcast"), using realistic atmospheric forcings from the Canadian Meteorological Centre (Pellerin et al. 2003), and a version that simulates future conditions (up to 2100, hereafter called

PROJ). Two projections are used (PROJ1 for temperature and pH_T, and PROJ2 for oxygen). To obtain the projections, we use downscaled atmospheric conditions provided by the global model of the Max-Plank Institute (MPI-ESM-LR (Ilyina et al. 2013)) for the CMIP5 exercise and the RCP 8.5 climate change scenario. In a regional model, the conditions at the open boundaries must be specified (e.g., currents, temperature, salinity, dissolved oxygen, nitrate, alkalinity, and dissolved inorganic carbon). In the first version of the model (HIND), open boundary conditions are represented by a climatology of the different physical and biogeochemical variables. This version of the model has proven effective in representing the system dynamics (Lavoie et al. 2016 and Lavoie et al. 2021) on a seasonal and interannual scale. However, since the mid-2010s, the influence of the Gulf Stream on the waters entering the deep layers of the EGSL has been more pronounced, leading to warming and deoxygenation of the deeper layers. The first step is to evaluate how well the numerical model (HIND) reproduces the environmental conditions measured during the shrimp surveys. Since the model uses climatological boundary conditions for the HIND simulation, it does not reproduce recent changes in temperature and dissolved oxygen in the deep layer. Therefore, we use the period from 2006 to 2008, which also corresponds to the period of high productivity of the above-mentioned stocks. To properly compare the observations with the model data, we selected the model cell closest to the sampling position, as well as the equivalent or closest day (the output frequency of the model results being 2 days). In addition, since the shrimp is found on the bottom at depths generally greater than 150 m and the model provides an average value for the entire cell, we extrapolated the temperature profiles to the bottom at each point to obtain values more representative of the value where the shrimps were caught.

As previously mentioned, since the annual ecosystem survey takes place in August, only the model outputs for the month of August were used. Figures 4 and 5 compare, respectively, the temperatures and dissolved oxygen concentrations measured in the different stock assessment areas with those simulated by the model at the same location and time. The temperatures and dissolved oxygen concentrations simulated by the model generally match well with the concentrations measured during the DFO survey. However, the model underestimates the temperature in the Estuary assessment unit. Overall, the HIND model provides a good representation of the biogeochemical conditions of the EGSL between 2006 and 2008.

The boundary conditions for the second version of the model, which simulates future conditions, are obtained by applying trends in oceanographic conditions from the global MPI-ESM-LR model to the climatology of oceanographic conditions used in the first version of the model (see Lavoie et al. 2020 for a full description of the method). The boundary conditions for this version of the model therefore take into account all changes occurring outside the Estuary and Gulf of St. Lawrence (EGSL), including the increased influence of Gulf Stream waters, climate warming, deoxygenation, and acidification (Lavoie et al. 2019). However, the representation of historical and current conditions is generally less accurate than with the previous version of the model (HIND), since the goal of global models is to represent major climate trends.

SUITABLE HABITAT PROJECTION

To estimate future changes in the suitable habitat of the shrimp, we used projections of physical (temperature) and chemical (pH_T) conditions from Lavoie et al. (2020) (PROJ1) and from Mei et al. (2024) (PROJ2) for dissolved oxygen. We determined the regions that meet the thresholds determined using the Perry and Smith method (1994) under these new conditions. In both cases, the simulations use dynamically downscaled atmospheric forcing based on the global model MPI-ESM-LR.

The simulated average temperature for the month of August (Figure 6) in the assessment units is very similar across the three simulations (HIND, PROJ1, and PROJ2) during the historical

period as well as in the future for PROJ1 and PROJ2. Differences, however, are with dissolved oxygen and pH_T (Figures 7 and 8). In the simulations by Lavoie et al. (2020), an error crept into the nitrification equation, resulting in larger oxygen consumption by this process, which transforms ammonium into nitrate. As a result, dissolved oxygen projections were not included in their report. This error has been corrected in PROJ2. This simulation provides a good comparison with the results of the HIND simulation for some of the assessment areas, but in the Esquiman region, in particular, dissolved oxygen concentrations are higher. The concentrations obtained with PROJ2 were therefore adjusted to the climatology of the HIND simulation for the period 2006 to 2015 (Figure 7). Climatology and trends were calculated for each cell in the model. In doing so, we preserve the future trends of PROJ2 for each assessment area while bringing the baseline period in line with that simulated by HIND, which compares well with observations (Figure 5). The adjusted simulation is hereinafter referred to as PROJ2A. To correct the overestimation of the pH_T in PROJ1 compared to HIND (Figure8), we apply the same method. The new corrected simulation, PROJ1A, is used for the subsequent analysis.

RESULTS

AREA OF SUITABLE HABITAT

As described in the section Description of the habitat suitable to the shrimp, the environmental conditions corresponding to suitable habitat to the shrimp were determined using the method of Perry and Smith (1994) and are presented in Table 1. The concordance of these thresholds with those found in the literature is presented in the Discussion section in more detail, but generally the thresholds found in this study are consistent with the literature. We can now focus on the evolution of this habitat in the context of global warming.

Current and future trends in oceanographic conditions (Figures 6, 7, and 8) point to a decrease in suitable shrimp habitat in the EGSL. To quantify future shrimp habitat loss, we calculated the average area of suitable habitat in August between 1990 and 2085 for the entire EGSL and within each of the four assessment units. For the EGSL as a whole (Figure 9), the suitable area dropped by 58%, from 66,461 km^2 to 27,809 km^2, between the 2011–2020 and 2041–2050 periods and is constrained primarily by temperature (Figure 9B). The effects of dissolved oxygen concentration (Figure 9C) and pH_T (Figure 9D) are only slightly limiting, as illustrated by the slightly smaller area in Figure 9A compared to 9B for the 1990–2030 period. For Esquiman (Figure 10) and Anticosti (Figure 11), only temperature determines the area of suitable habitat. The Sept-Iles unit (Figure 12) is comparable to the EGSL as a whole, with temperature having the main influence on suitable habitat, but with contributions from oxygen and pH_T as well. The Estuary unit (Figure 13) stands out from the other regions. The impact of dissolved oxygen (Figure 13C) and pH_T (Figure 13D) was greater than the impact of temperature (Figure 13B) until the end of the 2030s. Subsequently, the three criteria have relatively similar importance. For Esquiman (Figure 10), Anticosti (Figure 11) and Sept-Iles (Figure 12) the suitable area loss is generally more pronounced between the 2011–2020 and 2041–2050 periods (decreases of 38%, 65% and 71% for each assessment unit, respectively) and remains relatively stable thereafter. The suitable areas thus decrease from 19,445 km^2 to 12,089 km^2 (Esquiman), from 16,401 km^2 to 5,659 km^2 (Anticosti) and from 29,128 km^2 to 8,519 km^2 (Sept-Iles). Lastly, for the Estuary Unit (Figure 13), the decrease in the suitable area is more gradual, reaching 20% between 2041 and 2050 and 2071 to 2080, from 1,542 km^2 to 1,229 km^2.

SPATIAL DISTRIBUTION OF THE SUITABLE HABITAT IN THE GULF OF ST. LAWRENCE

Changes in the distribution of areas meeting the suitable habitat criteria during the month of August were determined using PROJ1, PROJ1A and PROJ2A for the period from 1991 to 2080 (decadal means).

Figures 14 to 16 show the conditions for each criterion separately. Despite the presence of decadal variability, the Figure 14 shows that bottom temperatures were generally suitable for the shrimp in the Atlantic layer between 1991 and 2030. The deeper parts of the shelves (>75 m) are too cold (below the threshold of 1.9 °C) due to the presence of the CIL. Beginning in 2031–2040, the Atlantic layer warms and exceeds the upper threshold of 5.7 °C, leading to an expansion of unsuitable habitat in the deep channels (Laurentian, Anticosti and Esquiman). Only the channel heads remain suitable during this period (2031–2040) because of cooler temperatures, but these regions also become unsuitable from 2041–2050 onwards. However, the continental slope over the entire EGSL is favored by the increase in temperature, which also occurs in the CIL and whose temperature rises above the threshold of 1.92 °C. Warming continues from 2041 to 2080, and channel habitat loss caused by warming will continue at a more moderate rate since the deep waters are already unsuitable. The continental slope at a depth of >75 m remains suitable since warming is occurring mainly within the suitable temperature range, i.e., the cold waters have warmed but remain below 5.7 °C, which helps stabilize the area of suitable shrimp habitat. From 2040 to 2079, channel habitat loss caused by warming will continue.

In contrast to temperature, conditions unsuitable for the shrimp in terms of dissolved oxygen and pH_T are initially found in the eastern part of the domain and progress westward (Figures 15 and 16). Dissolved oxygen conditions falling below the threshold of 77.8 mmol/m^3 were simulated as early as 1991-2000 at the head of the Laurentian Channel (Figure 15) and spread to the northwestern Gulf of St. Lawrence (GSL) as early as 2001-2010. The unsuitable zone continued to extend along the slopes of the Laurentian Channel and eastward starting in 2041-2050 but did not extend beyond the Honguedo Strait (see Figure 1 for location). The evolution of unsuitable conditions for pH_T is similar to that of dissolved oxygen, but with a slightly more extensive unsuitable area (e.g., present in the northwestern GSL as early as 1991-2000, Figure 16).

Figure 17 illustrates the number of environmental conditions (between none (0) and 3) meeting the suitable habitat criteria for each cell of the model, for depths greater than 75 m (minimum depth criterion). A suitability index of 3 indicates that all criteria are met, i.e. for temperature, dissolved oxygen concentration and pH_T. From 1990 to 2029, the suitable habitat is found mostly in the Atlantic layer in the deep channels, where all the criteria are met, except in the Estuary unit where oxygen and pH_T are unsuitable. With the warming of the Atlantic layer starting in 2031-2040 (Figure 14), the Laurentian Channel becomes unsuitable since only two criteria are met. The expansion of unsuitable conditions in oxygen and pH_T westward and in temperature eastward leads to unsuitable conditions for the three criteria in the Estuary and in the northwestern GSL (eastern part of Sept-Iles) beginning in 2041–2050. Only the regions along the deep channels, corresponding to the CIL depth, and the deeper areas of the continental shelf (> 75 m) remain suitable for the shrimp (dark blue regions).

DISCUSSION

The habitat of the adult shrimp is affected by changes in all environmental conditions, including localized positive effects in the medium term (e.g., increase in CIL temperature) and widespread adverse effects in the short and long term (temperature increase above the upper threshold of

5.7 °C, decrease in dissolved oxygen concentrations and pH_T). These changes differ in intensity among stock assessment units because of differences in the hydrodynamics of the system. As early as 1990, the Estuary region and the western part of Sept-Iles experienced low dissolved oxygen and pH_T conditions, with an increase in temperature over time. Although the climate version of the model used to make the projections does represent the observed historical conditions as well as the hindcast version (the climate model reproduces broad trends and decadal variability), the results accurately reflect the shrimp migration to shallower areas observed in recent years. Indeed, Bourdages et al. (2023) noted a significant shift in the depth at which more than 95% of the shrimp biomass is found. Between 2008 and 2017, the biomass was distributed to depths of 100 to 320 m in the Estuary, whereas for the 2018–2023 period, it was found between depths 70 to 170 m, avoiding the unsuitable conditions of the Atlantic layer. Based on the shift in fishing efforts consistent with the displacement of high shrimp abundance regions, Bourdages et al. (2023) also suggested that future environmental pressure on shrimp would be more pronounced in the Estuary and western part of the GSL. This prediction is consistent with those of the model presented in this study, which indicates that for the western part of the Sept-Iles unit and for the Estuary unit, shrimp movement to shallower areas could be due to cumulative environmental stresses in the surrounding deeper areas. With the projected increase in stratification in the future (Mei et al. 2024), the decrease in oxygen concentration and acidification in the Atlantic layer will be exacerbated by the decrease in the ventilation of the deeper layers (i.e. reduced renewal of the deep layers through vertical mixing). These changes will lead to an expansion of the area unsuitable for the shrimp in the Estuary and Sept-Iles assessment units. However, this eastward expansion stops at the Honguedo Strait. The deep channels east of Honguedo Strait indeed benefits at depth from the inflow of more oxygenated and less acidic water from Cabot Strait, which limits the effects of eutrophication, as observed upstream in the Estuary and in the northwestern part of the GSL. The Anticosti and Esquiman stocks are only subject to the negative impact of warming since this deep water renewal occurs on a seasonal basis. This dynamic leads to a stabilization of the habitat suitable to the shrimp in all the assessment units starting in 2035, since the warming on the slopes takes place within the suitable temperature range, and the horizontal and vertical expansion of the area unsuitable for pH and oxygen stabilizes. Areas that are already unsuitable for the shrimp become even more so but they no longer affect the total area of suitable habitat.

Northern shrimp stocks in Atlantic Canada are generally associated with water depths greater than 100 m and temperature conditions between 1 °C and 6 °C (Chemel et al. 2020, Garcia 2007). Le Corre et al. (2021) defined favorable thermal habitat to the northern shrimp on the Labrador continental shelf at between 1 °C and 5 °C mean annual bottom temperature, values comparable to those used in our study for the month of August (1.9–5.7 °C). The available data on the species' sensitivity to pH and oxygen variations come mainly from laboratory studies (Bechmann et al. 2011; Arnberg et al. 2013; Hammer and Pedersen 2013; Dupont-Prinet et al. 2013; Pillet et al. 2016). Recent studies confirm that shrimp are more sensitive to warming than to acidification (Guscelli et al 2023), and that there is a negative effect on survival from concurrent exposure to warming, acidification and deoxygenation of waters (Guscelli et al. 2025).

Within the species' known spatial distribution, northern shrimp populations tend to acclimate and adapt to local or regional environmental conditions (Koeller et al. 2009, Ouellet et al. 2017). It was therefore relevant to define the suitable habitat for the shrimp at the adult stage in relation to the conditions observed in the EGSL. The empirical method used to define the suitable habitat in our study was able to identify and project local conditions associated with high stock abundance but fails to take into account the species' adaptive potential, the distinction between critical and marginal habitats, and the cumulative effects of predation on the past and future distribution of the shrimp in the ecosystem. The available evidence, including the demonstration

of a low potential for adaptation to temperature changes at the species level (Leung et al. 2023), nevertheless suggests that this approach is appropriate and informative in the short term.

The projections used in this study were based on the RCP8.5 scenario of CMIP5. This scenario projects greater warming than the other CMIP5 scenarios. This scenario evolved into the SSP5-8.5 scenario of CMIP6 which also results in an important warming on the global scale. The new high emission scenario developed for CMIP7 shows more moderated maximal greenhouse gases (GHGs) trajectories because of mitigation actions undertook to limit the rise of GHGs, which would lead to a decrease in warming starting in 2070 or 2100 depending on the scenario (van Vuuren et al. 2026). The accomplishment or non-accomplishment of these projections therefore depends on the undertaking (or not) of actions against climate changes. However, differences between the projections we used and the more recent scenarios generally occur after 2050, a period for which the changes in the suitable habitat of the shrimp already stabilized. Hence, the choice of scenarios only weakly influences our results, especially considering that many of the changes projected are already in progress.

The results of this study illustrate the complexity of ongoing and anticipated changes in the physical and chemical environments that determine the current and future availability of suitable habitats for demersal species in the EGSL. Upcoming steps will further improve our results and strengthen the conclusions of this study, such as: (1) increasing our knowledge of favorable conditions for different shrimp life stages, physical and chemical conditions in coastal environments, and predator abundance, (2) implement spatio-temporal modelling of shrimp densities as a function of the variables considered (temperature, oxygen and pH), and (3) update our projections using a numerical model with higher spatial resolution and forced with CMIP6 (and CMIP7 when available) global models.

CONCLUSION

After determining the environmental conditions of temperature, dissolved oxygen and pH_T corresponding to the suitable habitat for the adult shrimp in the EGSL during the 2006–2008 reference period, we used a regional climate model to project future environmental conditions in the EGSL in order to characterize the changes in the suitable habitat to the shrimp in a context of global warming. The model projects a decline of 58% in the shrimp's suitable habitat in the EGSL between the 2011–2020 and 2041–2050 periods. For the Esquiman and Anticosti assessment units and most of the Sept-Iles unit, temperature is the limiting factor and dictates the areas suitable to the northern shrimp. For the western part of the Sept-Iles Unit and the Estuary Unit, low oxygen concentrations and acidification are the main constraints of the suitable habitat, while temperatures eventually become unsuitable as well with the warming of the bottom waters. In general, for all assessment units, a shallowing of the suitable habitat is predicted, resulting in a significant decrease in its area.

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TABLE

Table 1: Average environmental conditions corresponding to 90% of cumulative northern shrimp catches in the Estuary and Gulf of St. Lawrence ecosystem-based survey between 2006 and 2008.

Temperature (°C)	$[O_2]$ (mmol/m^3)	Total pH (pH_T)
1.9 à 5.7	> 77.8	> 7.54

FIGURES

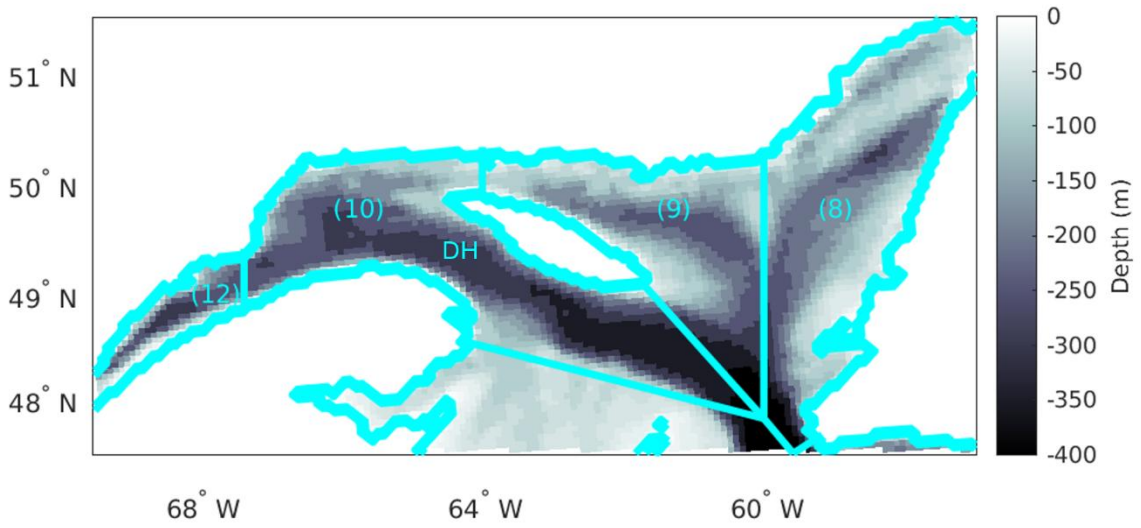


Figure 1. Bathymetry of the Estuary and Gulf of St. Lawrence from the biogeochemical model and northern shrimp stock assessment units. The units are (8) Esquiman, (9) Anticosti, (10) Sept-Iles and (12) Estuary. The Honguedo Strait is identified by the designation DH.

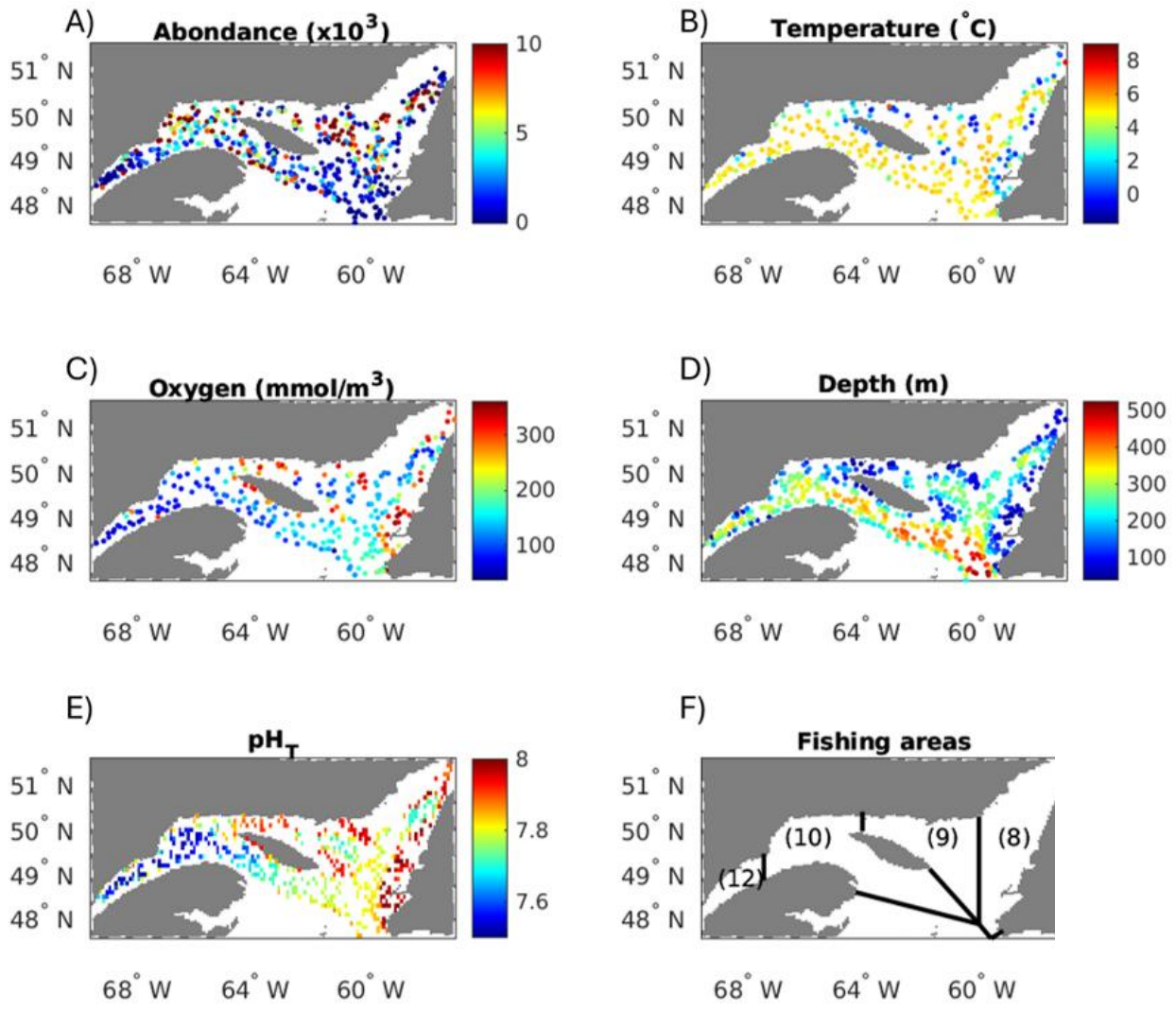


Figure 2. A) Shrimp abundance (number per station), B) temperature, C) dissolved oxygen concentration, D) depth, E) total pH (pH_T) simulated at stations sampled during the 2006–2008 DFO survey. The assessment units are (8) Esquiman, (9) Anticosti, (10) Sept-Iles and (12) Estuary.

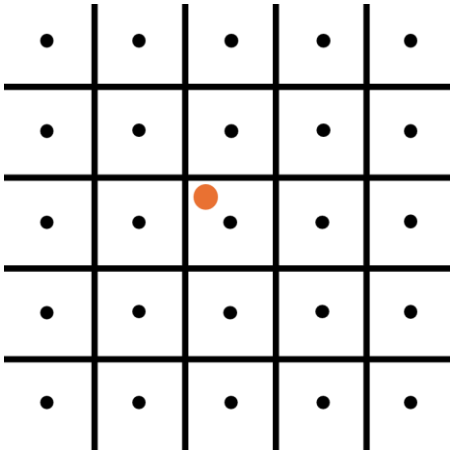


Figure 3. Representation of the grid of the numerical model used. The total pH values are given at the black dots. The orange dot represents the position of a survey station where the total pH is interpolated.

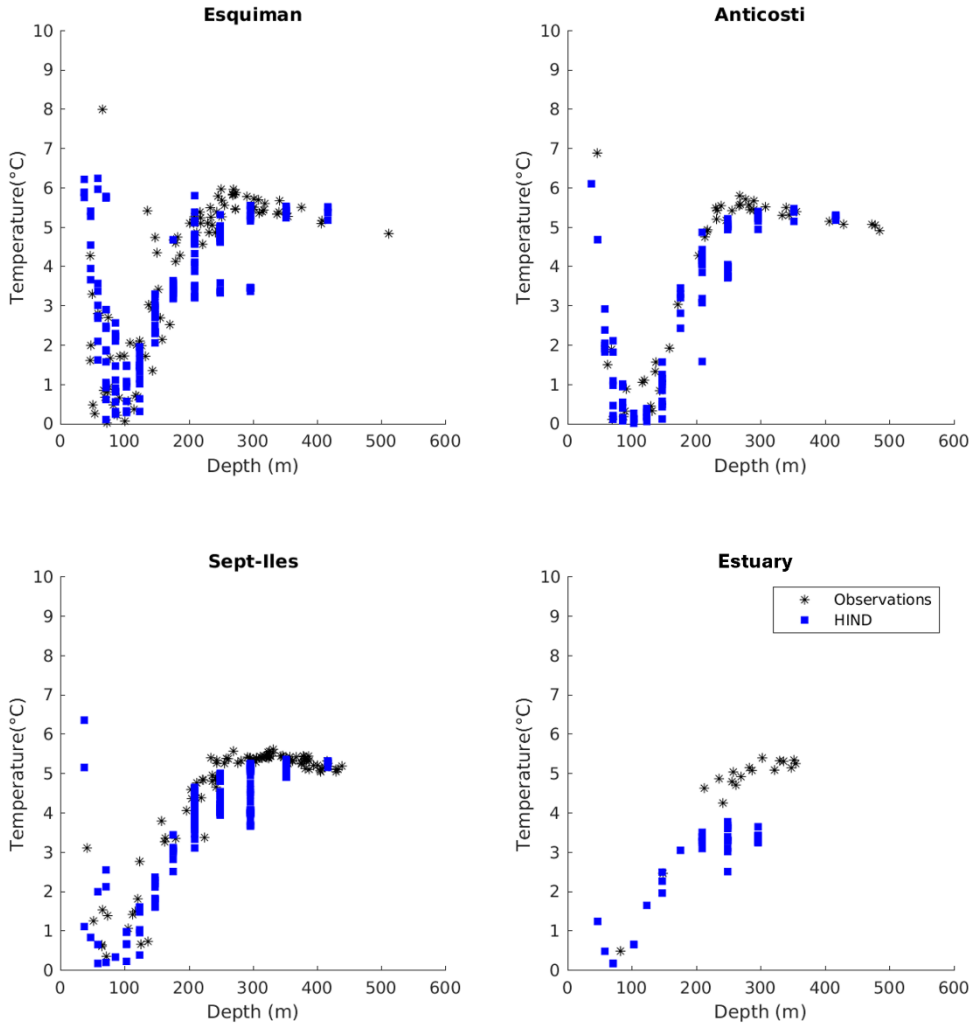


Figure 4. Comparison of temperature as a function of depth between the survey's observations (black) and the HIND simulation (blue) by stock assessment unit. The data presented covers the period from 2006 to 2008. Model data were taken at the points closest to the observations.

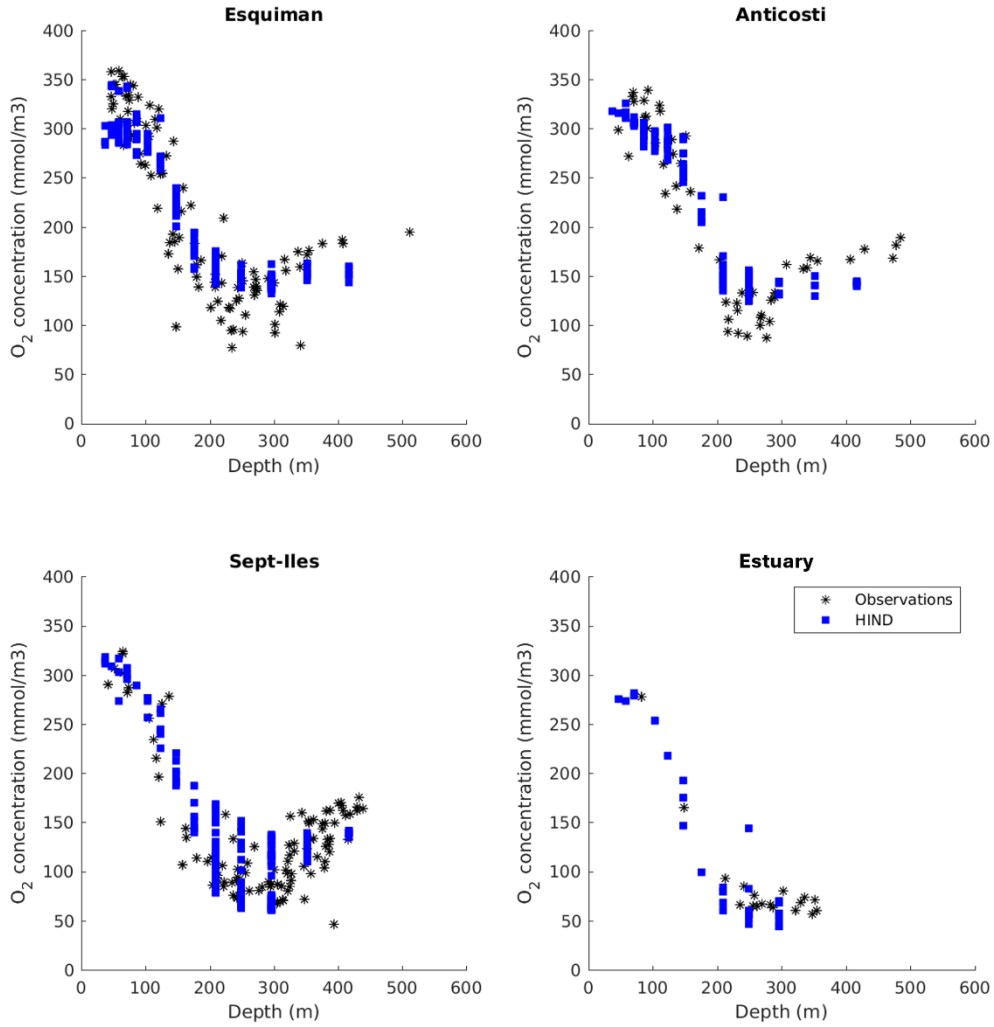


Figure 5. Comparison of dissolved oxygen concentration as a function of depth between the survey's observations (black) and the HIND simulation (blue) by stock assessment unit. The data presented covers the period from 2006 to 2008. Model data were taken at the points closest to the observations.

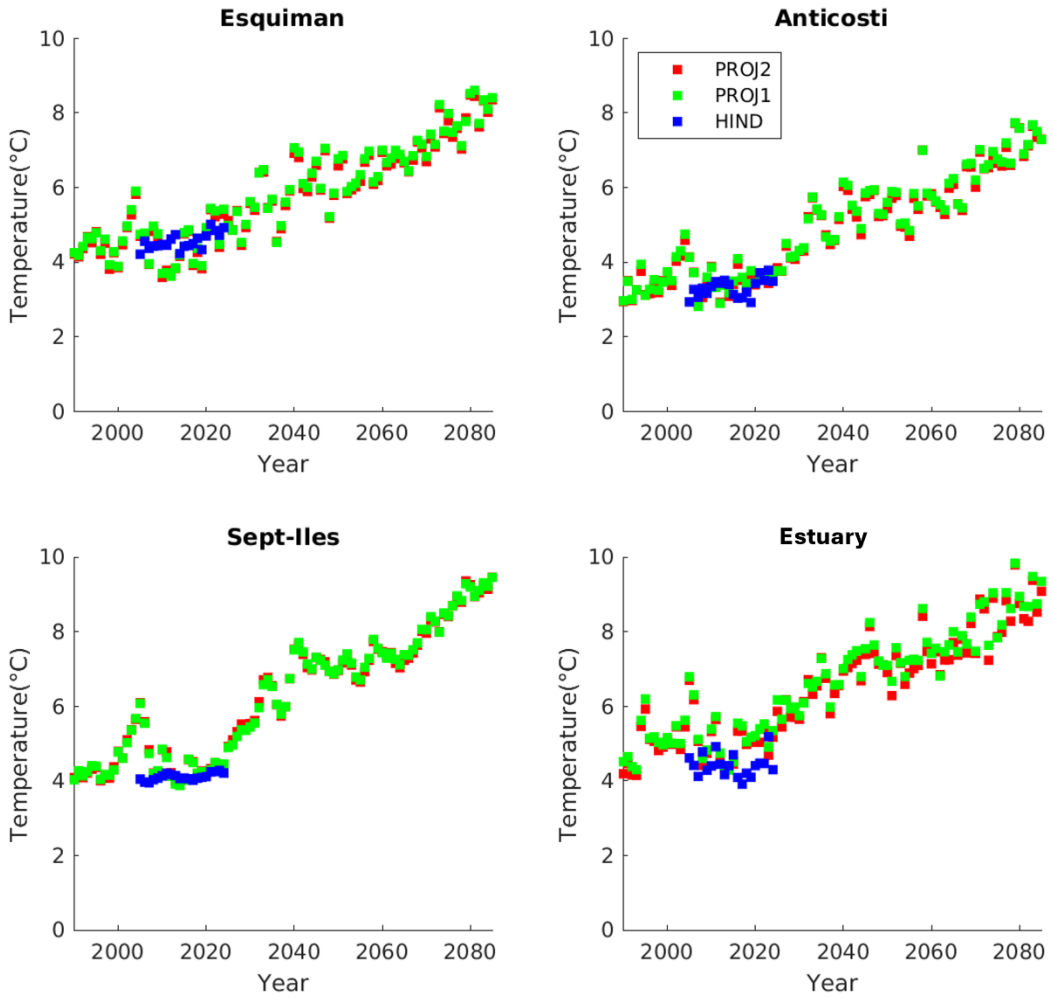


Figure 6. Average sea temperature in August for the HIND (dark blue), PROJ1 (green) and PROJ2 (red) simulations in each of the stock assessment units. For each model, all the bottom grid points found in the assessment units are included in the annual average.

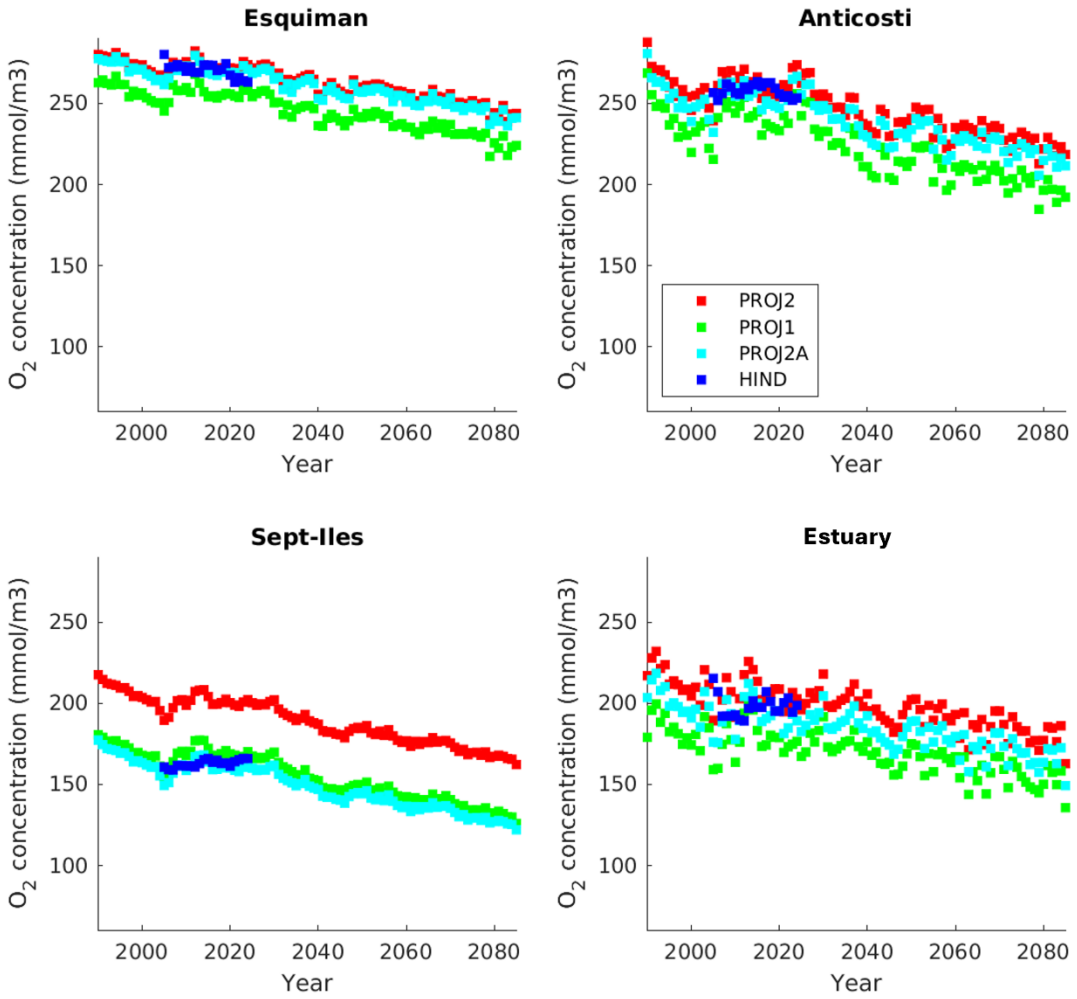


Figure 7. Average dissolved oxygen contraction in August for the HIND (dark blue), PROJ1 (green), PROJ2 (red) and adjusted PROJ2 (PROJ2A, cyan) simulations in each of the stock assessment unit. For each model, all the bottom grid points found in the assessment units are included in the annual average.

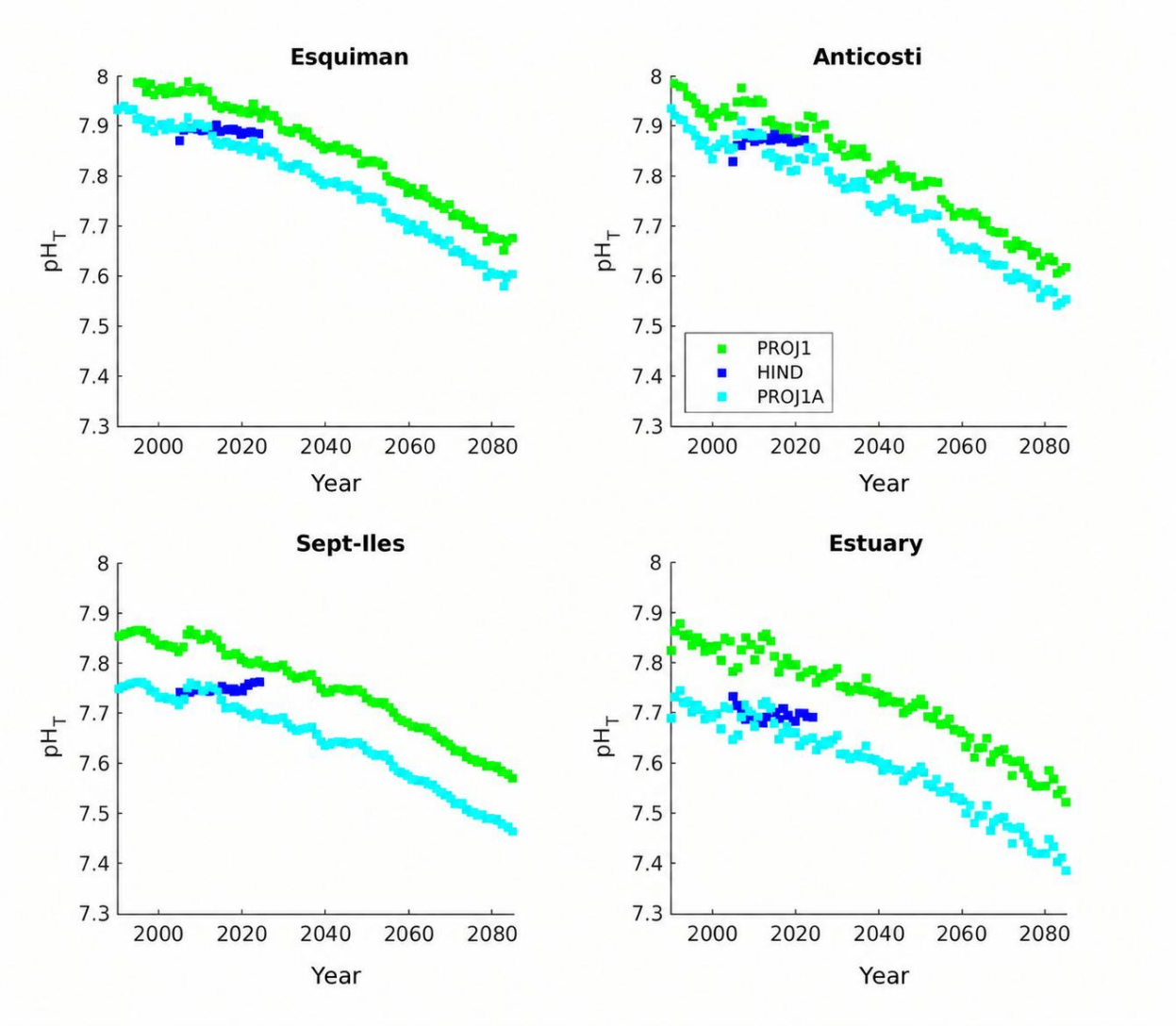


Figure 8. Average total pH (pH_T) in August for the HIND (dark blue), PROJ1 (green), and adjusted PROJ2 (PROJ1A, cyan) simulations in each of the stock assessment units. For each model, all the bottom grid points found in the assessment units are included in the annual average.

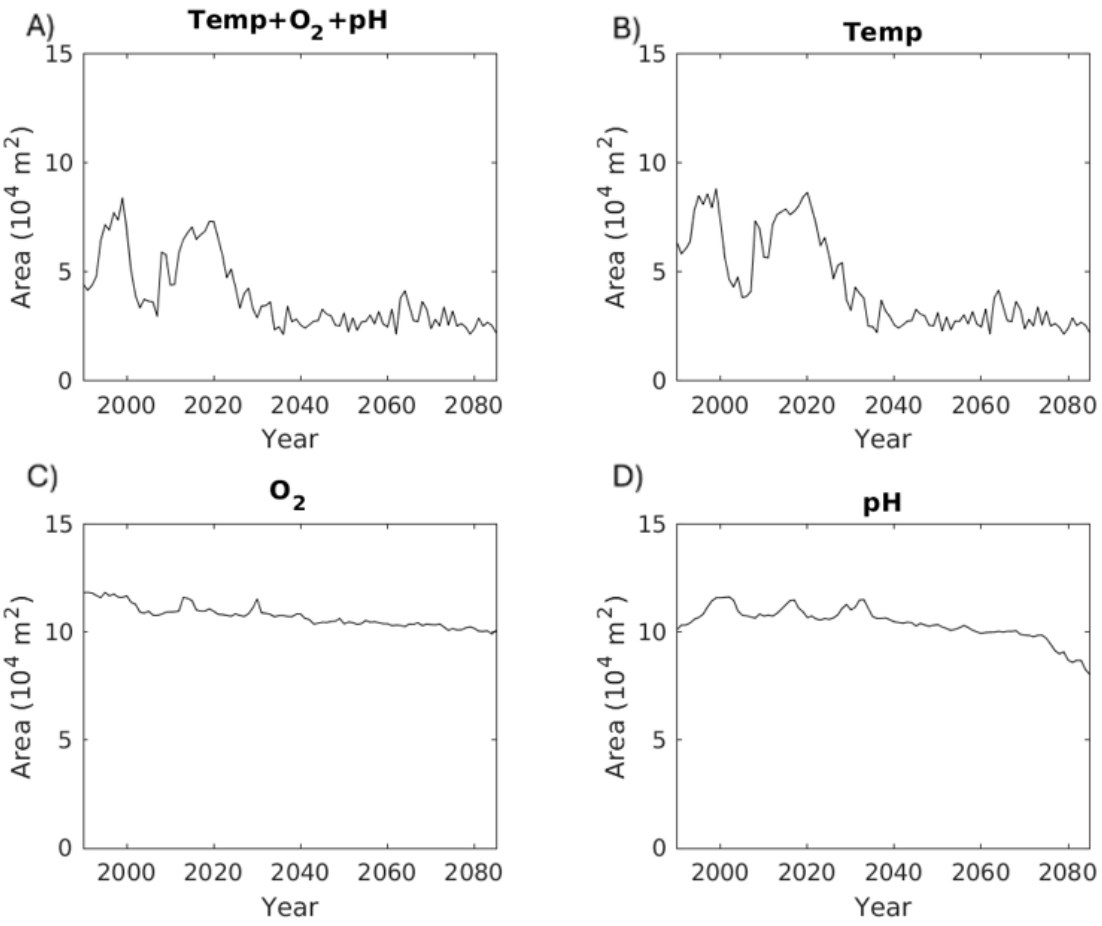


Figure 9. Average area of suitable habitat for the month of August across the Gulf of St. Lawrence. Panel A) considers all three environmental conditions. Panel B) corresponds to the area meeting the temperature criterion. Panels C) and D) meet the criteria for dissolved oxygen concentration and total pH, respectively. All panels also meet the criterion for a minimum depth of 75 m.

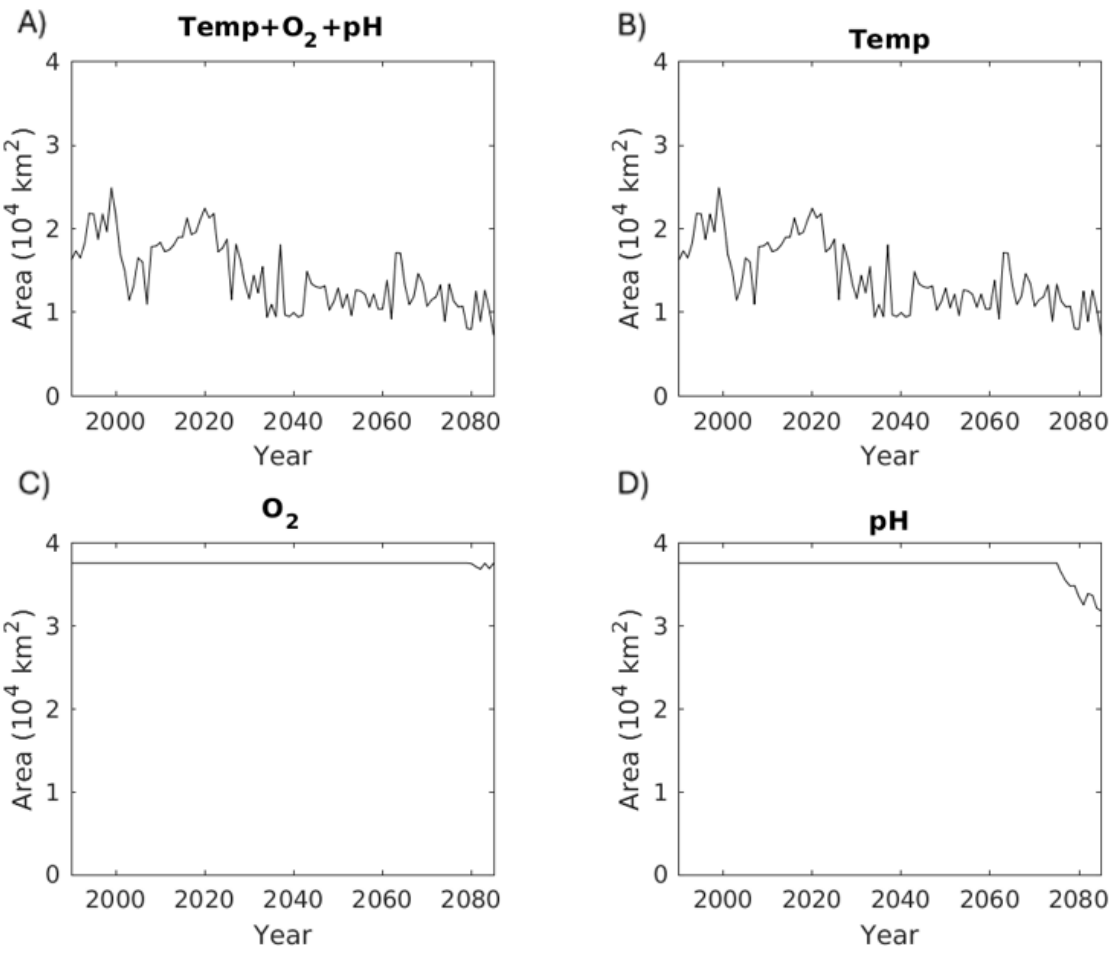


Figure 10. Average area of suitable habitat for August in the Esquiman assessment unit. Panel A) considers all three environmental conditions. Panel B) corresponds to the area meeting the temperature criterion. Panels C) and D) meet the criteria for dissolved oxygen concentration and total pH, respectively. All panels also meet the criterion for a minimum depth of 75 m.

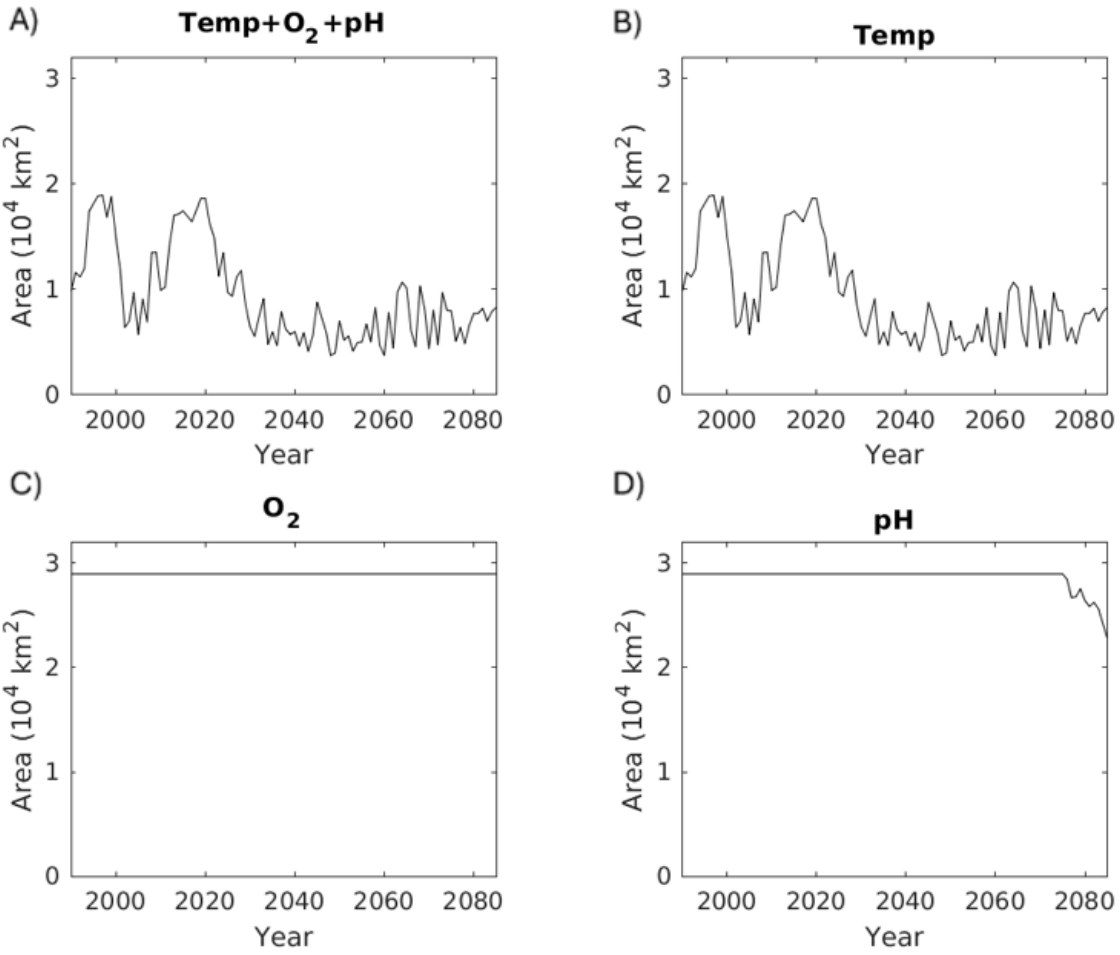


Figure 11. Average area of suitable habitat for August for the Anticosti assessment unit. Panel A) considers all three environmental conditions. Panel B) corresponds to the area meeting the temperature criterion. Panels C) and D) meet the criteria for dissolved oxygen concentration and total pH, respectively. All panels also meet the criterion for a minimum depth of 75 m.

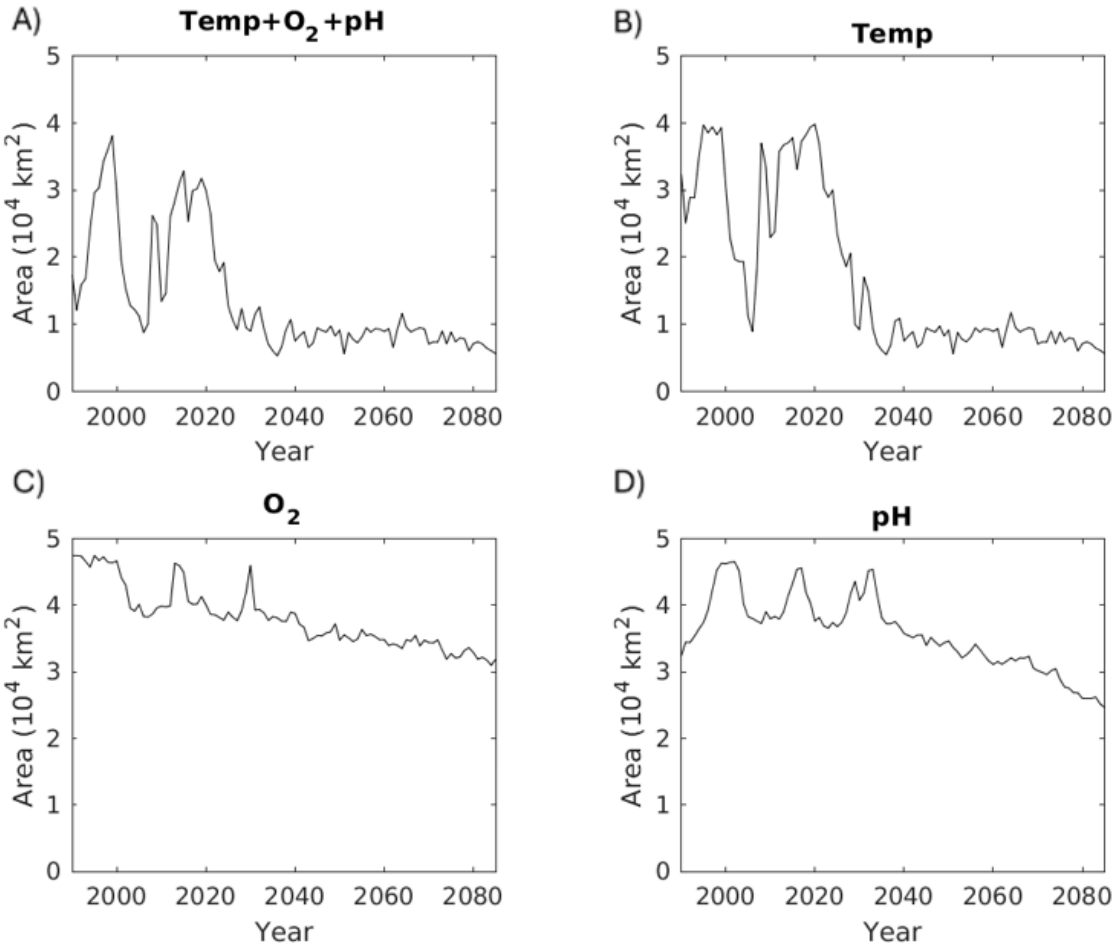


Figure 12. Average area of suitable habitat for August for the Sept-Iles assessment unit. Panel A) considers all three environmental conditions. Panel B) corresponds to the area meeting the temperature criterion. Panels C) and D) meet the criteria for dissolved oxygen concentration and total pH, respectively. All panels also meet the criterion for a minimum depth of 75 m.

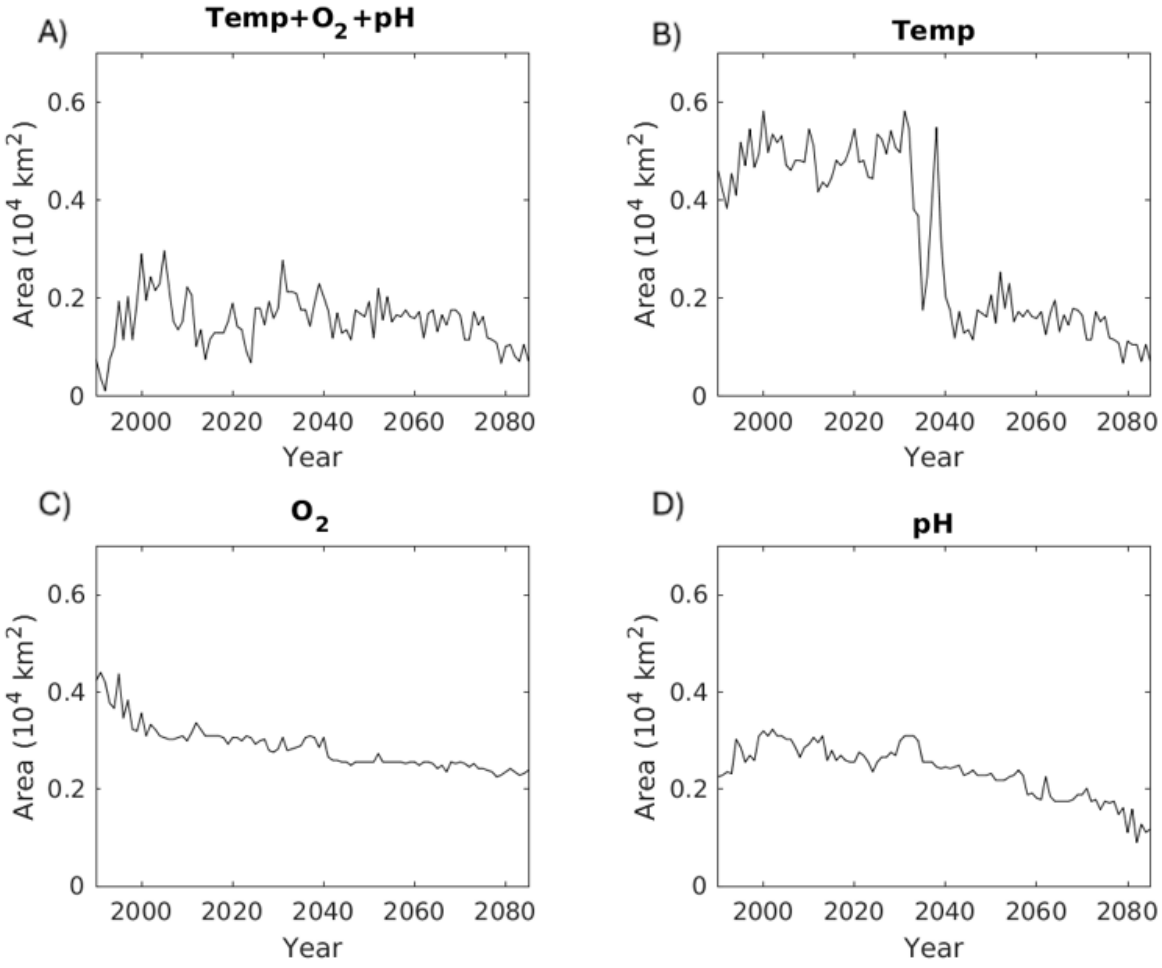


Figure 13. Average area for the month of August of suitable habitat for the Estuary assessment unit that satisfies the three criteria (A), the temperature only criterion (B), the dissolved oxygen concentration (C) and total pH (D) criteria. All panels also meet the criterion for a minimum depth of 75 m.

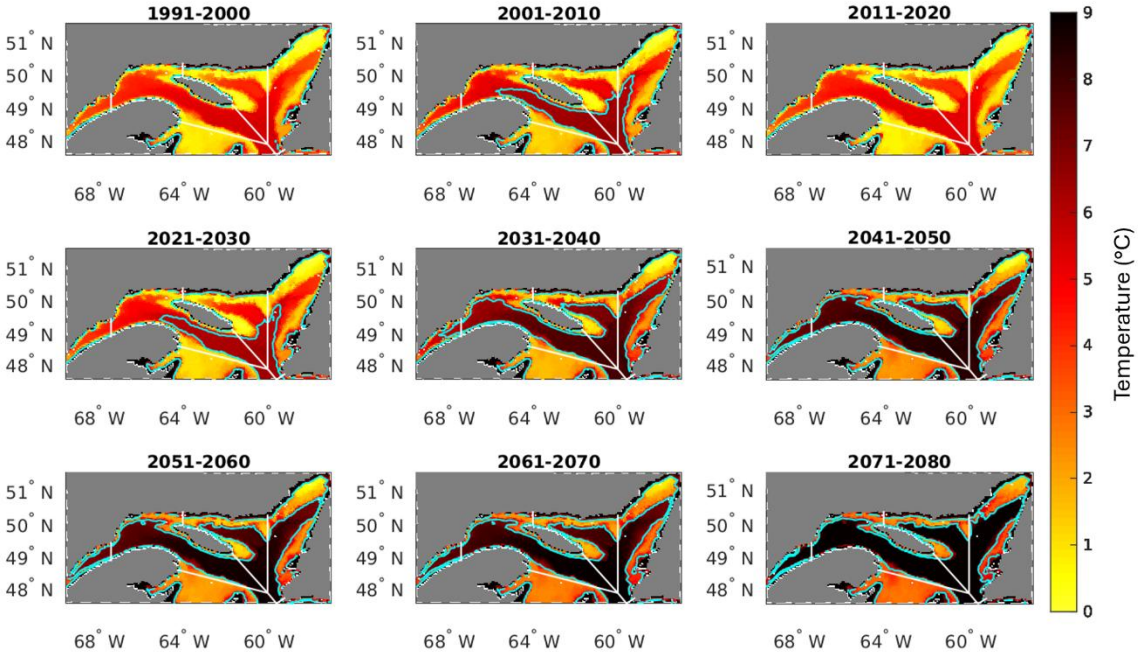


Figure 14. Past and future decadal bottom temperature averages for August obtained with simulation PROJ1. The cyan blue lines represent the upper limit (5.7 °C) of the temperature condition. The temperatures within the zone created by this boundary are therefore too warm for shrimp. Temperatures that are too cold (< 1.9 °C) are represented by the regions in yellow. The white lines are the boundaries of the units of assessment.

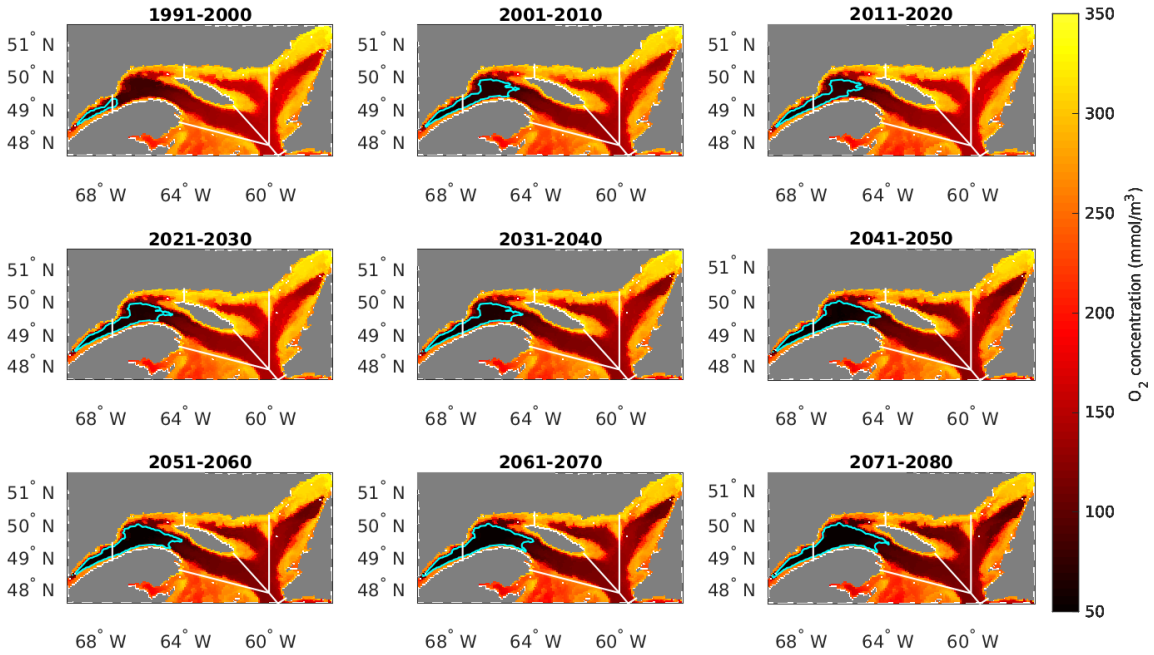


Figure 15. Past and future ten-year mean dissolved oxygen concentration on the seabed for the month of August obtained with the PROJ2A simulation. The cyan blue lines are the limit condition for dissolved oxygen concentration (77.8 mmol/m³). The white lines are the boundaries of the units of assessment
Figure 16. Past and future ten-year means of the total pH on the bottom for the month of August obtained with simulation PROJ1A. The cyan blue lines represent the total pH limit condition (7.54). The white lines are the boundaries of the units of assessment.

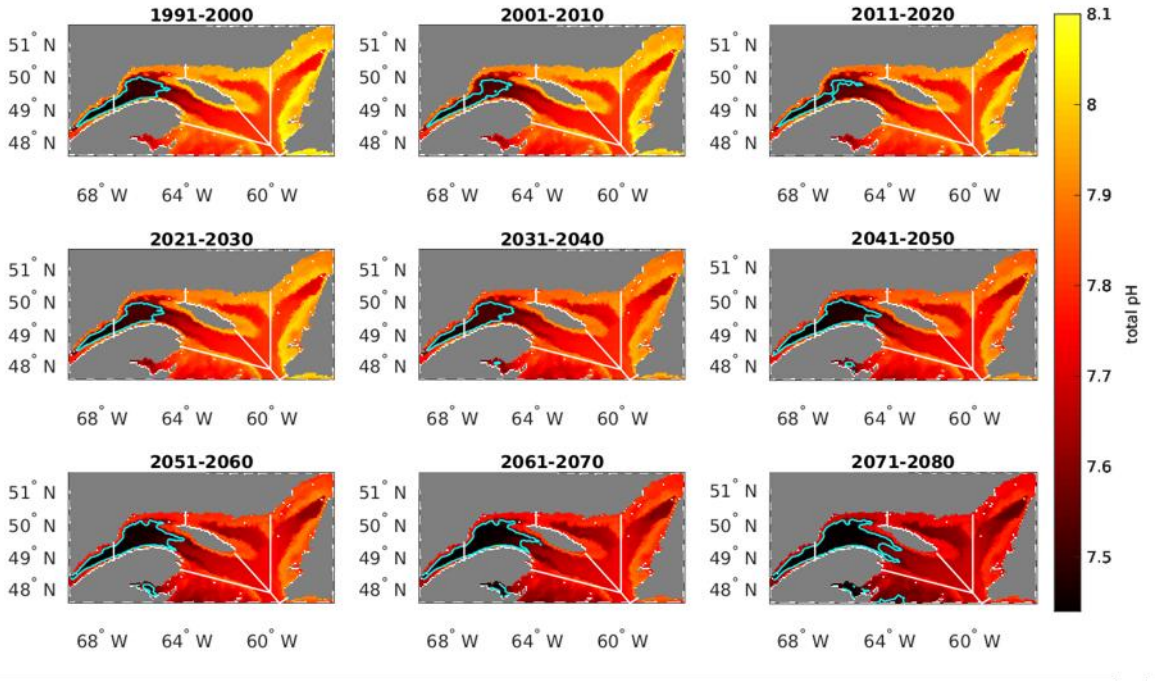


Figure 26. Past and future ten-year means of the total pH on the bottom for the month of August obtained with simulation PROJ1A. The cyan blue lines represent the total pH limit condition (7.54). The white lines are the boundaries of the units of assessment.

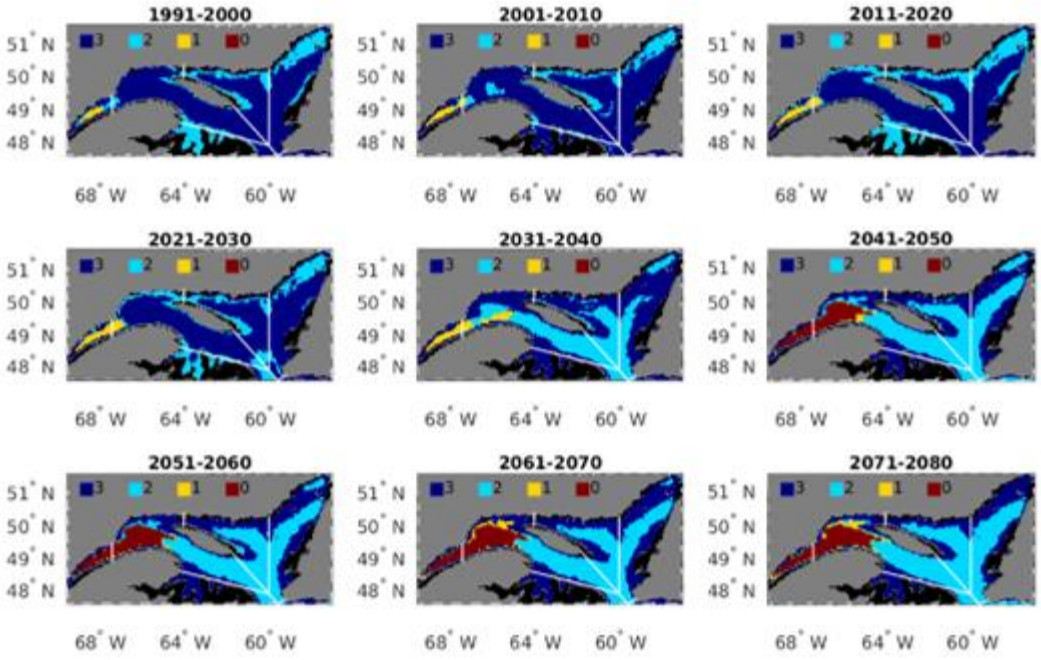


Figure 17. Number of variables (temperature, dissolved oxygen and pH_T) whose values at the bottom correspond to conditions suitable to the northern shrimp in the Gulf of St. Lawrence (see Table 1). The white lines indicate the boundaries of the units of assessment. Mean conditions per decade were calculated from simulation PROJ1 for temperature, PROJ2A for dissolved oxygen, and PROJ1A for pH_T.