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Addressing the impacts of climate variability and change on NAFO fisheries

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Keywords: Northwest Atlantic Ocean, climate change, fisheries, fisheries management, Northwest Atlantic Fisheries Organization, climate impacts, climate model.

Executive Summary

Objectives and Methods:

- *Objectives:* This study aims to increase knowledge and awareness of climate change impacts on fisheries and ecosystems within the Northwest Atlantic Fisheries Organization (NAFO) regulatory area and provide guidance on adaptation and mitigation for climate-resilient fisheries.
- *Methods:* A comprehensive literature review, supplemented by analyses of projected climate changes and their ecological impacts across the NAFO convention area.
- *Conclusions:* The study highlights the urgent need to integrate climate change considerations into fisheries management to ensure sustainable and resilient fisheries in the NAFO area. Addressing climate change's complex and multifaceted impacts on marine ecosystems and fisheries requires a coordinated and adaptive management approach informed by robust scientific data and predictive modelling. Immediate action and continuous adaptation are essential to mitigate the adverse effects of climate change and ensure the long-term sustainability of fisheries resources.

The northwest Atlantic Ocean is a climate change hotspot:

- *Observed climate trends:* Significant warming surface and bottom temperatures, deoxygenation, acidification, reduced sea ice, altered mixing, nutrient flux and primary production, and increased frequency and intensity of climate extremes.
- *Projected warming to 2100:* Surface temperatures are projected to rise by up to 4°C and bottom temperatures by up to 2-3°C by 2100.

- *Projected warming to 2050:* The average surface warming of ~1°C, with some areas experiencing warming up to 2.5°C under high emissions. The average bottom warming across both emission scenarios is 0.45°C, with some regions warming by as much as 2.1°C under high emissions. Some parts of the Grand Banks experience more significant warming on the sea bottom than at its surface.
- *Marine heatwaves:* Projected increases in the frequency and duration of marine heatwaves with significant ecological and socio-economic impacts.
- *Primary production:* Projected declines in primary production and changes in phytoplankton species composition and blooms.
- *Sea ice reduction:* Further declines in Arctic sea ice extent and thickness were projected.

Climate impacts on species, ecosystems, and fisheries are complex and multifaceted:

- *Productivity and Mortality:* Altered productivity rates and increased mortality in various species.
- *Phenology and Trophic Mismatch:* Changes in seasonal timing and mismatches in predator-prey relationships.
- *Trophic amplification:* Disproportionate climate impacts on high trophic species.
- *Distribution Shifts:* Species are moving poleward and into deeper waters in search of suitable habitat. Under high emissions, 23% of transboundary fish stocks are expected to shift by 2030, increasing to 45% by 2100.
- *Disease:* shifting distribution and prevalence of bacterial and viral pathogens, including vibrio, affecting marine life.
- *Size and maturity:* warming is associated with reduced body sizes and earlier ages at maturity.
- *Catch Potential:* Increased catch potential in higher latitudes and decreased potential in tropical regions due to poleward redistribution of fish stocks.
- *Disruption of Fisheries:* Significant disruption is expected, requiring fisheries to adapt to spatial redistribution or face reduced catches.
- *Biomass Decline:* Marine animal biomass is expected to decline across most of the southern NAFO area, with increases in the Arctic under high emissions scenarios.

Climate impacts on NAFO-managed species:

- *High-Risk Species:* Half of the NAFO-managed species, including Atlantic wolffish, capelin, northern shrimp, roughhead grenadier, splendid alphonsino, witch flounder, and yellowtail flounder, are likely to be adversely affected by climate changes.
- *Moderate-Risk Species:* Atlantic cod, Greenland halibut, redfish, and thorny skate are at moderate risk.
- *Low-Risk Species:* American plaice, white hake, and shortfin squid are at lower risk, although these assessments carry higher uncertainty due to limited studies.

Integrating climate into NAFO fisheries management:

- *Integrated data products:* Integrated and ready-to-use data products allow researchers to better incorporate climate variability and change into fisheries assessment and advice.
- *Remote sensing:* Greater use of remote sensing climate data products allows synoptic monitoring of marine climate conditions at high resolutions.
- *Climate modelling and forecasting:* High-resolution regional climate model for the northwest Atlantic Ocean to anticipate climate changes and their impacts on NAFO living resources.
- *Climate response database:* Consolidating the available scientific literature on climate changes and their impacts on NAFO species, including their environmental niches, into a centralized database to facilitate a more robust understanding of which climate impact pathways are most important for stocks, how they operate, and how to mitigate them.
- *Climate risk assessment:* Synoptic, spatially explicit climate vulnerability or risk estimates for NAFO-managed species and their ecosystems could support evidence-based decision-making under climate change, helping decision-makers to identify priorities for scientific and management efforts to implement proactive management measures, reduce impacts, increase resilience, and advance the adaptive capacity of fisheries.
- *Monitoring distribution shifts:* Joint dynamic species distribution models to evaluate species distribution in real-time or to predict where species will be months or years ahead, helping understand where survey or fishing efforts should be deployed, anticipating stock shifts across management boundaries, and proactively addressing transboundary conflicts.
- *Climate monitoring:* Climate-driven disease transmission, phenological shifts, climate vulnerability to early life stages, key climate variables, and fish stocks to better detect and respond to climate changes.
- *Climate-considered stock assessments:* Using approaches such as management strategy evaluations, climate-conditioned advice, or other methods.
- *International cooperation and data sharing:* to address climate impacts comprehensively.
- *Adaptive management:* to address climate impacts on fisheries.
- *Sustainability:* Promote sustainable fishing practices to mitigate adverse climate effects and support resilient fisheries.
- *Research:* Encourage further research on the impacts of climate change on marine ecosystems and fisheries.
- *Strengthen multidisciplinary collaborations:* Include climate scientists, oceanographers, ecologists, social scientists, fisheries managers, and policymakers in the fisheries assessment and management process to develop effective climate-resilient strategies.

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Abstract

Climate changes impact marine species, populations, ecosystems, and the fisheries and communities they support. While there is broad agreement that climate change must be considered when assessing the status of exploited stocks and making harvest decisions, there is little consensus on how to do so. This study aims to increase knowledge and awareness of climate change and its impacts on fisheries and ecosystems across the Northwest Atlantic Fisheries Organization regulatory area and to provide guidance on adaptation and mitigation in support of climate-resilient fisheries. A comprehensive literature review was undertaken, supplemented by analyses of projected climate changes and their ecological impacts across the NAFO convention area. Various climate changes are observed and projected, including surface and bottom warming, deoxygenation, acidification, reduced sea ice, and altered mixing and nutrient flux. In turn, these climate changes are associated with a multitude of ecological shifts, including altered productivity and mortality, geographic range shifts towards more northerly and deeper waters, early ages at maturity but reduced body sizes, shifted phenology and trophic mismatch, and disproportionate climate impacts on high trophic species. Notwithstanding the geographic and taxonomic variation in climate change and its impacts, half of NAFO-managed species were determined to have a high likelihood of being adversely affected by climate changes. Interpreting these findings through the NAFO management lens and in the context of its ecosystem approach to fisheries roadmap, several approaches to addressing the impacts of climate change on NAFO fisheries are discussed.

Introduction

The marine climate varies significantly at seasonal, decadal, and multidecadal scales, but for the past century, it has been systematically changing due to human activities. These long-term climate changes affect marine life through a complex web of pathways, posing an unprecedented risk to food and economic security for billions of people worldwide (*1*–*7*). Climate change is expected to have large effects on the distribution, yield, and productivity of marine fishing (*7*–*10*), yet studies also suggest that appropriate management can improve fisheries status (*11*, *12*) and offset adverse climate change effects **-** in some situations compensating for negative effects and amplifying positive effects (*13*).

Accordingly, there is a growing recognition of the need to consider both natural environmental variation and anthropogenic climate change when assessing and managing fish populations. Various data sources and approaches can now evaluate different harvest strategies for exploited species given past and projected future environmental and ecosystem conditions. However, the extent to which fisheries climate changes in their management strategies is variable but generally low and may contribute to the shortcomings of many fisheries management approaches worldwide (*14*–*17*) and associated fish population collapses (*14*, *18*–*21*). The risks to fisheries posed by climate change will also increase with each passing delay in the implementation of adaptation measures (*22*), and there is an urgency to understand how fisheries can be managed in a climate-considered manner (*5*, *23*–*27*).

This was recently articulated at the 35th meeting of the FAO Committee on Fisheries (COFI), where members adopted a resolution related to addressing the impact of climate change on NAFO fisheries (Appendix 1) and requested additional information and guidance to support climate-resilient fisheries management (Appendix 2). In response to this request and as part of the United Nations Food and Agriculture Organization (FAO) Global Sustainable Fisheries Management and Biodiversity Conservation in the Areas Beyond National Jurisdiction (ABNJ) program and the Northwest Atlantic Fisheries Organization (NAFO), the primary objectives of this report are to:

1) Summarize the literature and data available to address potential climate change impacts on NAFO-managed stocks, non-target species and associated ecosystems.
2) Describe the data available to determine climate change-related distributional shifts of the managed stocks across stock boundaries, including transboundary stocks.
3) Review the most recent ocean climate change predictions in the Northwest Atlantic for the following 10 years and 50 years and summarize how this may affect the ecosystem and the likely impacts on managed stocks and non-target species.
4) Identify any new data requirements needed to detect and monitor climate-related changes in key ocean variables, including fished stocks, bycatch species, and changes in catch and effort patterns and distributional shifts across stock boundaries. Comment on the existing and potential methods by which such data sets could be collected.
5) Identify how the long-term unidirectional changes and shorter-term extreme variability in environmental conditions characteristic of climate change could be incorporated into NAFO stock assessments.

Materials and Methods

Literature review

The study objectives were addressed through a systematic review of the scientific literature on climate change and fisheries – peer-reviewed publications, stock assessments, and gray reports - supplemented by interviews with NAFO stock assessment researchers. A database of peer-reviewed documents was compiled by querying scientific databases, including SCOPUS, the Web of Science, and Google Scholar. Documents were identified using key search terms and grouped thematically according to the previously described five primary objectives. Recent studies and those relevant to the NAFO convention area, hereafter referred to as the NAFO area, were prioritized. The database was supplemented by fisheries-centric studies from all NAFO Scientific Council Research (SCR) and Scientific Council Summary (SCS) documents published in the past five years (2019-2024). From a literature database containing over 800 documents, relevant information was systematically reviewed and extracted into an annotated bibliography and tabulated to facilitate interpretation, use, and synthesis (Appendices 3-9).

Projected climate changes in the northwest Atlantic Ocean

Monthly sea surface (SST) and bottom temperature (°C) projections (2015-2100) were obtained from two published Global Earth System Climate Models within the coupled model intercomparison project phase 6 CMIP6 archive to evaluate projected temperature trends across the NAFO area to 2050. These models included the Centre National de Recherches Météorologiques and Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique Climate and Earth System Model (CNRM-CM6-1) (*28*, *29*) and the MET Office Hadley Centre Climate model (HadGEM3-GC31-MM) (*30*). All projections were harmonized onto a regular 0.25° grid across the AOS. SST projections were made under two contrasting IPCC shared socioeconomic pathway (SSP) scenarios representing alternative socioeconomic developments. SSP5-8.5 (Fossil-fueled development; 'taking the highway') represents continued fossil fuel development, and SSP1-2.6 (Sustainability; 'taking the green road) represents an increase in sustainable development (*31*). Notwithstanding ongoing discussion on the likelihood of emission scenarios (*32*), the two extreme scenarios we evaluated bracket the range of possible outcomes.

Surface and bottom temperature changes were calculated as the difference between the average temperature in the current decade (2014-2024) and 2050 (2045-2055) within each 0.25 grid cell across the NAFO domain. Changes were calculated from each model projection individually before being averaged.

Timing and magnitude of projected climate changes and impacts on NAFO-managed species

The Climate Risk Index for Biodiversity (CRIB); (*33*, *34*) was used to estimate the climate exposure for each NAFO-managed species under contrasting emission scenarios, namely their projected timing of climate emergence and thermal habitat loss. The projected timing of climate emergence represents the timing of anticipated climate impacts or stress on a species. It is calculated at each location where a species is distributed as the year when the climate conditions are projected to exceed the upper temperature tolerance of the species. Alternatively, the projected thermal habitat loss denotes the magnitude of anticipated climate impact on a species and the potential for climate-driven shifts in its geographic range. It was calculated as the proportion of a species' present geographic range over which the projected climate will exceed its thermal limit.

The CMIP6 temperature projections described previously were combined with information about NAFO species' geographic distributions and thermal niches to calculate these metrics. For pelagic NAFO species that primarily inhabit the pelagic zone, projected sea surface temperatures were used, while for demersal species that primarily live in contact with the seafloor, projected bottom temperatures were used.

Present-day native geographic distributions for NAFO species were obtained from AquaMaps (*35*). AquaMaps predicts marine species' spatial distribution on a native 0.5° global grid using environmental niche models. The models predict the probability of occurrence for each species using bathymetry, upper ocean temperature, salinity, primary production, and the presence of, and proximity to, sea ice and coasts, and validated using independent survey observations(*36*) and evaluated against alternative methodologies and independent species distribution datasets(*37*). The native geographic distributions for each species were statistically rescaled to a 0.25° grid using nearest neighbour interpolation, described in Boyce et al. (*34*).

Each NAFO species' thermal tolerances and preferences were compiled from the literature database (Table 1).

Table 1. Thermal tolerances and preferences of marine species managed by NAFO. All values in °C.

Species	Min Temp. Tolerance	Max Temp. Tolerance	Min Temp. Preference	Max Temp. Preference	References
Acadian redfish (*Sebastes fasciatus*)	0.8	13	5.5	8.5	(*38*, *39*)
American plaice (*Hippoglossoides platessoides*)	-1.3	14	6	10	(*40*)
Atlantic cod (*Gadus morhua*)	-1.5	19	10	14.5	(*41*, *42*)
Atlantic wolffish (*Anarhichas lupus*)	-1.5	10	-0.4	6	(*43–45*)
Capelin (*Mallotus villosus*)	-1.5	14	-1	6	(*46*)
Greenland halibut (*Reinhardtius hippoglossoides*)	-1.9	15	0	7	(*47–52*)
Northern shortfin squid (*Illex illecebrosus*)	0.5	27.3	4	14	(*53–55*)
Northern shrimp (*Pandalus borealis*)	1	6	1	5	(*56–58*)
Roughhead grenadier (*Macrourus berglax*)	-0.5	5.4	1	4	(*59*, *60*)
Splendid alfonsino (*Beryx splendens*)	6.6	17			(*61*)
Thorny skate (*Amblyraja radiata*)	-0.5	12.5	-0.5	3	(*62*, *63*)
White hake (*Urophycis tenuis*)	0.6	21	5	11	(*64*, *65*)
Witch flounder (*Glyptocephalus cynoglossus*)	-1	11.4	2	8	(*66–68*)
Yellowtail flounder (*Limanda ferruginea*)	-1	18	-1	5.8	(*69–72*)

Results and Discussion

Climate changes and their effects on fisheries living resources: stressors, pathways and impacts

The literature review highlights that understanding the impacts of climate change on fisheries living resources – species, populations, and ecosystems - is exceedingly challenging (Figure 1). Climate impacts are mediated through multiple stressors (*e.g.,* temperature, oxygen, pH, or ocean circulation; Figure 1A) and operate through several direct and indirect pathways (*e.g.,* metabolic rates, altered prey availability, or predation) that can affect species synergistically or antagonistically and can vary depending on the species life stage and part of its geographic distribution (Figure 1C). Coincident impacts such as exploitation can further obscure the detection of climate effects.

In addition to the difficulty of resolving climate impact pathways, one must also consider the timescales over which they operate. The climate varies significantly at seasonal, decadal, and multidecadal scales, but for the past century, it has been systematically changing due to human activities. Seasonal and decadal-to-multidecadal climate variation and its effects on marine life can be immense but transient (*73*–*75*). In contrast, longer-term climate changes tend to be more modest year over year but can cause abrupt and unanticipated effects on marine life (*76*). Complicating matters, shorter-term climate variation and longer-term changes are increasingly interacting to create shifting patterns of seasonality and more frequent and extreme climate fluctuations (*77*–*79*). There is a pressing need to consider both the shorter-term variations and longer-term trends in the climate system in the assessment and management of marine fisheries to achieve sustainable outcomes now and in the future. This is particularly challenging for the Northwest Atlantic, one of the most dynamic regions of the global ocean that exhibits huge seasonal and decadal-to-multidecadal variation (*80*) and is a hotspot of climate change (*81*, *82*).

Temperature

Studies have reported warming globally and across the northwest Atlantic (*74*, *83*–*89*); (Appendix 3). Boyce et al. (*83*) reported that SST had warmed more rapidly (0.93°C; S.D. = 0.47°C) than the global average across the AOS. Rapid warming occurred in the NAFO area between 1985 and 2016, with 2012 and 2023 being anomalously warm years (*90*). Published studies have highlighted the rapid pace of warming in the Gulf of Maine, particularly between 2005 and 2015 (*15*), and that this warming will continue at extreme rates throughout the Northwest Atlantic over the next century (*91*). Ocean bottom temperatures have also increased across the AOS, albeit at more modest rates (*84*–*88*, *92*, *93*).

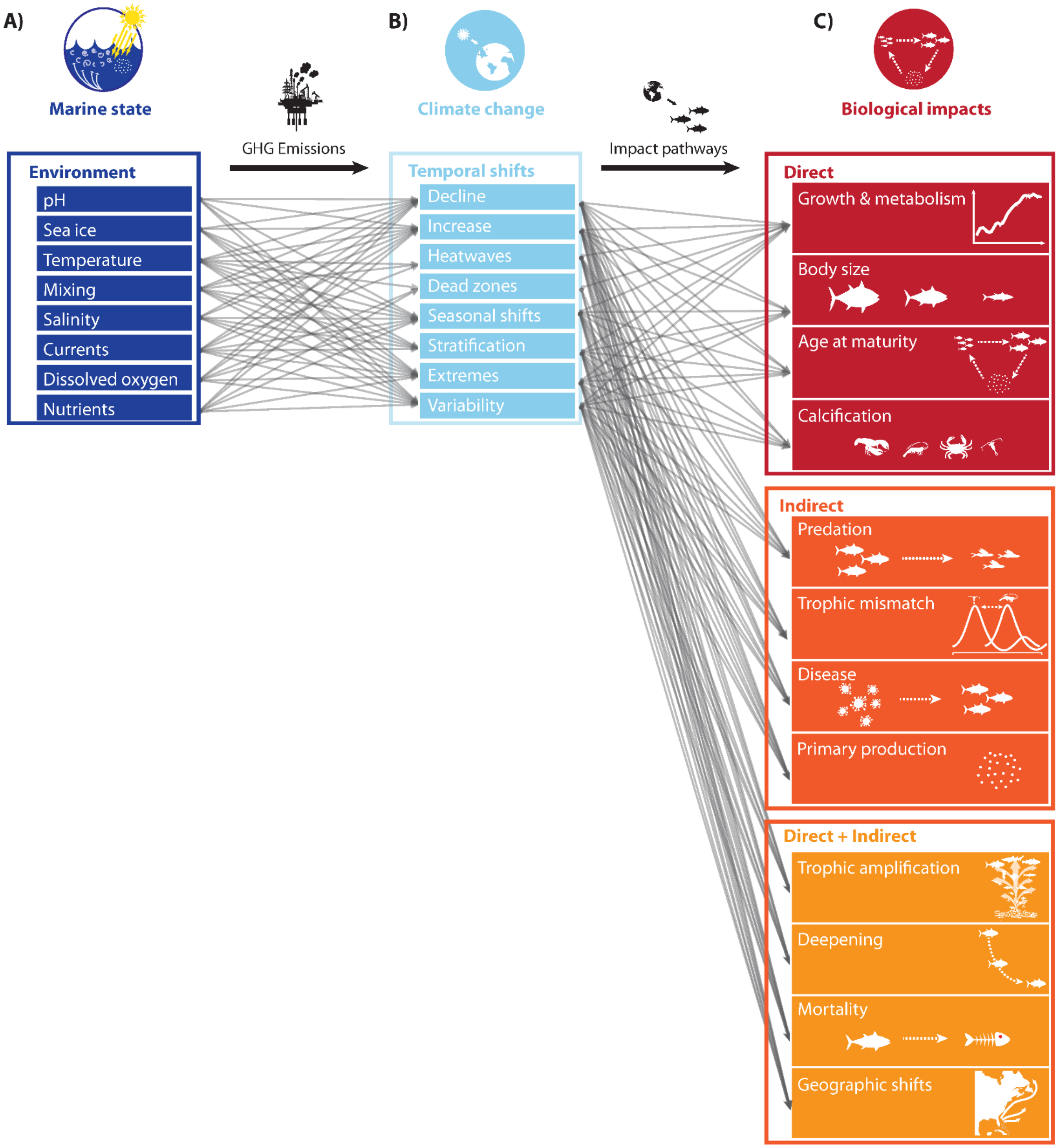

Figure 1. Complex multifaceted climate impact pathways on marine life. The marine environment is characterized by several marine state variables (A; dark blue) which, due to anthropogenic greenhouse gas emissions (GHG), are undergoing a range of diverse temporal shifts (B; light blue). The large number of climate change pathways (arrows at left) create a complex and multifaceted array pathways by which climate change can impact marine species, populations, ecosystems, and fisheries (C; red). Climate impacts on marine life can be manifest directly (red), indirectly (orange), or both directly and indirectly (yellow).

Warming is associated with changing growth rates and reduced size of plankton, fish and invertebrates (*94*–*98*). Shackell *et al.* (*94*) reported a 60% decline in the average body mass of predatory fish and invertebrate species between 1970 and 2008, coincident with increasing temperature, stratification and size-selective harvesting. Such changes in size, which are often exacerbated by size-selective fishing (*99*, *100*), have wide-ranging effects on the growth and energy use of these species as well as on trophic interactions and ecosystem structure.

Temperature affects predator-prey (trophic) interactions in marine food webs globally (*101*) and across the North Atlantic ocean (*102*–*104*). However, understanding how changing temperature influences trophic dynamics is notoriously tricky, as effects can operate through direct and indirect pathways and can be time-lagged. Shackell *et al*. (*94*) reported that while aggregate predator biomass remained constant over time, reductions in their average size eroded their predation efficiency and led to 300% increases in the biomass of their prey between 1990 and 2008. Warming can also decouple predators' and prey's metabolic demands, altering predation intensity. For example, Grady *et al.* (*105*) recently reported that the per capita prey encounter rates, capture efficiencies, and maximum capture rates of cold-blooded ectotherms (*e.g.* most fish and invertebrates) would change with warming. In contrast, those of warm-blooded endotherms (*e.g.* mammals, some tunas, sharks, and billfish) would remain constant. As an emergent consequence of this metabolic effect, ectotherms would benefit from consuming a larger share of the available prey than endotherms. Resolving the biological impact of warming on marine species is one of the critical uncertainties and limitations to projecting the effects of climate on marine species and ecosystems (*6*, *106*).

Dissolved oxygen

Global warming is a primary driver of deoxygenation globally and across the NAFO area (*84*–*89*, *92*, *107*, *108*). Warming reduces the solubility of oxygen in water and is estimated to account for approximately 50% of the oxygen loss in the upper 1,000 m of the ocean (*107*). Dissolved oxygen has declined in almost all regions of the North Atlantic between 1960 and 2009 (*108*). Lower oxygen, combined with warming and associated changes in metabolism, can cause reductions in fish size (*94*, *109*) and related reproductive output (*110*).

Warming and associated stratification and reduced nutrient supply in conjunction with increasing frequency and magnitude of phytoplankton blooms (*111*) have exacerbated reductions in dissolved oxygen and increasing hypoxia, a condition where oxygen (O_2) concentrations drop below 30% (*90*, *108*, *112*, *113*). Hypoxia has been associated with mass mortality events in marine species and is known to have adverse effects on the growth, reproduction, and distribution of species.

Acidification

Acidification in the Northwest Atlantic is reportedly increasing faster than in most other oceans (*83*–*85*, *88*, *92*), adversely affecting species such as plankton molluscs, crustaceans, and corals forming calcium carbonate skeletons. Studies also highlight the spatiotemporal variability in pH, highlighting areas and seasons with notably lower pH levels (*114*). More significant acidification has also been reported in coastal areas near large estuaries and cold-water currents compared to deeper offshore waters of warmer origin (*115*). Acidification is especially relevant at high latitudes because the solubility of CO_2 is greater in colder waters and to a shoaling of the aragonite saturation horizon as a function of depth (*116*), leading to the onset of under-saturation to occur earlier. Declines in pH and calcium carbonate have been reported in the Arctic and may be partly driven by increasing freshwater influx from melting ice caps (*117*). Acidification has been found to cause tissue damage in larval Atlantic cod, leading to increased susceptibility to infection (*118*). Notwithstanding this, the impacts of acidification on North Atlantic finfish are generally poorly understood (*115*).

Ocean circulation, mixing, and nutrient supply

Warming of the ocean surface has been associated with reduced mixing, enhanced vertical stratification and reduced nutrient availability in surface waters (*73*, *74*, *119*–*121*) and a decline in phytoplankton concentration across the Northwest Atlantic (−0.6% yr^{-1}; 1911–2010) and the Arctic (−0.4% yr^{-1}; 1899–2005) oceans over the past century (*74*, *119*) and in the NAFO area between 1999 and 2016 (*90*). Yet, while phytoplankton concentrations are declining overall, coastal blooms are becoming more frequent and intense (*111*). Warming, stratification, and reduced nutrient concentrations have been associated with increases in picophytoplankton (<0.2 um) across the North Atlantic (*95*) and shifts in major phytoplankton species groups, including diatoms, dinoflagellates, and coccolithophores (*122*–*124*) and rapid poleward and eastward shifts in many species in the North Atlantic Ocean (*124*).

Similar shifts have also been documented in zooplankton, with an increase in small warm-water zooplankton and a reduction in the large energy-rich copepod *Calanus finmarchicus* (*125*). *C. finmarchicus* has been declining across the NAFO area since 2009. Alternatively, smaller copepods such as *Pseudocalanus* spp. have increased, particularly on the Newfoundland Shelf (*90*). Such shifts can greatly affect energy flow through marine ecosystems, with consequences for fisheries. Due to size-based predation and trophic transfer efficiency, a smaller fraction of the energy in smaller plankton is transferred to upper trophic levels (*126*). This means that more production is cycled in the microbial loop that is transferred to upper trophic levels to support fisheries (*127*, *128*). Likewise, plankton communities' size, structure and composition strongly affect the amount of organic matter exported to support deep-sea ecosystems and fisheries.

While climate impacts on bacteria and viruses are less well understood, their effects on marine ecosystems and fisheries are likely to be profound (*129*). Hosts and parasites will likely track species as they shift poleward under climate change. Climate-driven increases in storm surges and sea level rise are projected to expand bacteria's geographic and seasonal ranges (*130*). A poleward range shift of outbreaks of *Vibrio* has already been reported in the North Atlantic, the North Sea, the Baltic Sea, and Alaska and is associated with shifting temperature and salinity (*130*, *131*).

Sea ice

Ocean winter warming across the NAFO area is associated with ice volume and duration reductions. Hutchings *et al.* (*85*) reported that Arctic sea ice cover in both summer and winter has been declining since 1979, with the September sea ice extent declining by 12% per decade and a projected ice-free Arctic in the fall of 2071. Sea ice thickness declined 48% between 1980 and 2008 (*132*). Linearly declining sea ice extent and thickness have also been reported between 1979 and 2011 for the Gulf of St. Lawrence (−3.9%) and Newfoundland and Labrador shelves (−3.1%), and sea ice extents reached their lowest historical levels in each of these two regions in 2010 and 2011, respectively. Sea ice volume and duration have declined in Newfoundland and Labrador since 1969, with the third-lowest value recorded in 2021 (*133*).

These changes in sea ice have essential consequences for mixing, nutrient availability, and oxygen levels. Ocean surface warming has been associated globally and within the NAFO area with enhanced vertical stratification and reduced nutrient availability in surface waters (*73*, *74*, *119*–*121*). Increased stratification has been reported on the Scotian Shelf between 1960 and 2008, with rapid increases in the 1990s (*134*).

Disease transmission

Climate change may also render some species more susceptible to infection. For example, ocean acidification caused tissue damage in Atlantic cod larvae, weakening their immune systems and making them more susceptible to bacterial invasion (*118*). Warming in the Arctic is projected to lead to increased disease transmission between species in the Eastern and Western Arctic ecosystems. Disease outbreaks can also lead to mass mortality of keystone species such as sea stars and urchins, leading to cascading ecosystem effects (*135*). Harmful algal blooms that can lead to fishery closures and reduced productivity are projected to increase in frequency and extent with climate change (*136*). Despite the potential for severe adverse effects, climate-driven changes in disease transmission and their impacts on marine life are poorly understood.

Distributional shifts

Several studies have documented distributional shifts in response to climate changes, with shifts being more rapid in marine systems than terrestrial ones due to greater connectivity. Species have generally shifted into either deeper or more northern waters, presumably in search of more thermally suitable habitat (*137*–*139*), although directional shifts can also be more complex (*138*). Regional-scale distributional shifts have been increasingly documented in the North Atlantic and Arctic oceans, including the northeastern US (*138*, *140*), North Sea (*141*), and Denmark Strait (*142*). For example, Nye *et al.* (*143*) reported poleward shifts in 17 of 36 commercial fish stocks between 1968 and 2007 in US waters associated with ocean warming. Climate change has also been associated with a northward expansion of bluefin tuna outside their usual range and into the subpolar waters near Greenland (*142*).

The general trend of warmer-adapted species moving into more northerly habitats has been termed ‘tropicalization’ in temperate systems and ‘borealization’ in the Arctic. DFO has recently noted an increasing number of exotic warm-water species reported in the summer research vessel survey, particularly in more southerly regions (*90*). Reduced sea ice duration in the Arctic has also led to more frequent occurrences of killer whales in the Eastern Arctic and associated changes in the behaviour of other whales as they seek to avoid them (*87*). It is unknown to what extent the introduction of new species and the emigration of others will restructure marine ecosystems in the NAFO area and what the consequences for fisheries will be.

Seasonal shifts and trophic mismatch

Changes in the cyclic seasonal development (phenology) of phytoplankton occurred within the NAFO area between 1999 and 2016, with large variability in the magnitude and timing of the spring bloom and a gradual decline in the bloom duration (*90*). The decline in spring bloom duration in the NAFO area is comparable to reports that the duration of the phytoplankton growing season has declined at temperate-polar latitudes (35–65°N) between 1998 and 2007, coincident with surface temperature changes (*144*). Despite strong interannual variability in phytoplankton bloom timing on the Newfoundland shelf, no long-term changes have been detected (*84*).

Delayed timing of seasonal plankton blooms can affect the survivorship of larval fish, with effects on adult productivity (*145*, *146*). Platt *et al.* (*147*) reported reduced survivorship of larval haddock on the Eastern Scotian Shelf, where the spring phytoplankton bloom was delayed. In a separate study, Koeller *et al.* (*148*) reported that shrimp (*Pandalus borealus*) egg-hatching times were significantly related to the seasonal spring timing of phytoplankton and bottom water temperature. Similar but community-wide shifts in seasonal spawning times have been reported for fish in the northwest Pacific Ocean between 1951 and 2008, associated with seasonal temperature changes (*149*).

Decadal to multidecadal climate variability

The North Atlantic Oscillation (NAO) is a dominant mode of climate variability across the North Atlantic, characterized by fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high, impacting climate sea surface temperatures, ice cover, salinity, ocean currents and biological productivity (*80*).

During positive NAO phases along the Eastern Seaboard of the U.S. and Canadian Atlantic, the Gulf Stream tends to strengthen and transport more warm water northward along the U.S. East Coast and into the Canadian Atlantic, resulting in SSTs that are warmer than average. Conversely, in the subpolar gyre region, a positive NAO typically leads to enhanced westerly winds that can push cold polar water southward, resulting in cooler SSTs in areas like the Labrador Sea and around Greenland. The degree of temperature change in SSTs during different phases of the NAO can vary considerably depending on the specific location and local conditions, but it can be several degrees warmer (*e.g.,* over 3°C) in some areas.

Due to the large magnitude and rapid onset of climate changes, the NAO can profoundly affect marine species and ecosystems. The NAO has effects on the abundance (*74*) and composition (*150*) of marine phytoplankton, as well as the timing of the spring bloom (*150*, *151*). Zooplankton abundance also correlates to the NAO (*152*). Thus, the NAO can impact higher trophic species directly via changes in environmental conditions or indirectly via changes in the productivity and composition of the plankton (*153*, *154*). The ecological responses to the NAO include changes in population dynamics, abundance, mortality, geographic distribution, the timing of spawning, and altered trophic relationships (*155*).

Climate extremes

Climate change is associated with increased frequency and intensity of climate extremes (*156*–*159*). Oliver *et al.* (*159*) reported that the average frequency and duration of marine heatwaves have significantly increased by 34% and 17%, respectively, since 1925, with socio-economic and ecological consequences. Notable marine heatwaves have also occurred in several locations, including the Northwest Atlantic in 2012 (*160*). These warming extremes have been associated with widespread ecological and socio-economic effects, including habitat loss (*161*, *162*), reduced primary production and harmful algal blooms (*163*, *164*), mass mortality events (*165*), range shifts (*161*), altered community structure, and fisheries disruption (*165*–*167*). However, a recent study found that the ecological impacts of marine heatwaves on demersal fish were minimal and could not be distinguished from natural variability (*168*)

Climate change has also been associated with improbable ‘black swans’ events in animal populations (*169*). Anderson *et al.* (*169*) examined 609 animal populations and reported that black swan events occurred in ~4% of populations and were associated with climate effects, severe winters, predators, parasites, or synergistic drivers. These extreme events primarily occur as population crashes (86%) rather than increases.

Emergent patterns

Notwithstanding the variety and complexity of climate impacts, some general patterns have emerged (Table 2). These include warming-driven increases in growth rates and associated reductions in body sizes and earlier ages at maturity (*94*–*98*), “trophic amplification,” whereby high trophic species experience disproportionate climate impacts relative to low trophic species (*10*, *170*, *171*), metabolic decoupling leading to increased grazing rates on phytoplankton (*120*, *172*), competitive advantages of ectothermic species over endothermic in a warmer ocean (*105*), and geographic shifts in species distributions to more northern and deeper ocean waters (*138*, *140*, *142*, *173*–*175*).

Table 2. Observed climate trends and their effects on marine life within the AOS.

Phenomenon	Observed pattern	References
Range expansion or contraction	- By 2060, 55% of species are projected to lose thermal habitat, 21% gain, and 24% remain constant.	(*138*, *140*, *143*, *176*, *177*)
Latitudinal range shifts	- Northward range shifts - 'Borealization' of Arctic, 'tropicalization' of temperate ecosystems - A shift in the spatial distribution of larvae for 43% of taxa in the northeastern US; mostly northward	(*138*, *140*, *142*, *173–175*)
Depth distribution	- A shift towards inhabiting deeper, colder waters	(*138*, *173*, *174*)
Species invasions	- New arrivals from US waters on the Scotian Shelf associated with latitudinal range shifts - New arrivals in the Arctic from the south, with effects on low diversity ecosystems there	(*90*, *142*)
Seasonal	- A shift in seasonal timing of larval occurrence for 49% of taxa in the northeastern US shelf - Earlier melting of sea ice in the year - Trophic mismatch between phytoplankton spring bloom and larval haddock and shrimp.	(*87*, *147*, *148*, *175*, *178*)
Trophic amplification	- Increased zooplankton grazing - Increased predation of ectotherms relative to endotherms - A shift towards resource control of marine ecosystems - Stronger adverse climate impacts on high trophic species relative to low	(*10*, *101–105*, *170*, *171*)
Size structure	- Reduction in size of primary and secondary producers	(*94–98*)
Temperature	- Warming almost everywhere - Rapid warming in the Gulf of Maine, Gulf of St. Lawrence, Scotian Shelf - Increasing frequency and severity of marine heatwaves	(*85*, *91*, *159*, *179–183*)
Freshwater flux	- Increased at high latitudes from hydrological cycle intensification	(*184*, *185*)
Sea ice	- Melting Arctic ice and Greenland ice sheet, leading to a freshening of the Arctic - Spatially variable changes in sea ice type (old versus seasonal), thickness, and extent in the Arctic	(*85*, *87*, *90*, *186*, *187*)
Stratification	- Increased, especially at low latitudes - Associated with nutrient limitations at low to mid-latitudes	(*73*, *121*)
Acidification	- Increasing, especially in the Gulf and Arctic - Negative effects on calcifying species	(*87*, *90*, *115*, *117*, *188*, *189*)
Deoxygenation	- It follows the global deoxygenation trends but with widespread spatial variability driven by natural oscillations. - Deoxygenation is driven by the retreat of the Labrador Current and a slowdown of the Atlantic Meridional Overturning Circulation.	(*87*, *90*, *108*, *112*, *190–193*)
Primary production	- Spatially variable but generally declining, especially at lower latitudes - Complex responses in the Arctic, including changes from ice algae to phytoplankton, moderate declines in some areas but increases in others - Phytoplankton blooms are becoming more frequent, intense, and widespread.	(*73*, *74*, *87*, *111*, *119*, *194*)
Disease transmission	- Increased, especially at high latitudes.	(*118*, *130*, *131*, *195*)
Growth and demography	- Faster growth - Earlier age at maturity	(*196–198*)

The future of the northwest Atlantic Ocean

Projected climate changes

With continued high emissions, the global oceans are projected to become warmer and have lower rates of primary production (reviewed in *128*), supporting reduced marine animal biomass (*6*, *7*, *92*, *128*, *199*); (Appendix 4). The ocean is projected to warm by 2.6°C by 2100 relative to the 1995–2005 average, with more rapid warming at higher latitudes (*85*). Studies also project near-permanent marine heatwave conditions in many parts of the sea by 2100 (*182*). Marine animal biomass (excluding zooplankton) is projected to decline by 17% (±11% S.D.) with an average 5% decline per 1°C warming (*6*).

Larger magnitude changes are anticipated across the northwest Atlantic Ocean (*15*, *34*, *91*, *200*). Boyce et al. 2021 reported that under a high emission scenario (RCP8.5), significant surface warming and associated reductions in NPP, zooplankton biomass, and animal biomass are expected across the AOS, with spatial variability in the direction, magnitude, and certainty of changes (Figure 5.2 in Boyce et al. 2021. Models suggest an increase in bottom temperatures, accelerated acidification, reductions in dissolved oxygen, shifts in phytoplankton composition and blooms, and reductions in sea ice across the NAFO area (*200*–*207*), with increasing marine heatwaves (*208*), but with considerable spatial variability. Some studies project surface warming up to 4°C and bottom warming of up to 2-3°C by 2100 (*203*, *204*, *209*–*211*). Along with this warming trend, the average annual Arctic sea ice extent has been projected to decline by about 15% per degree of global warming (*212*).

Using a regional climate model, Brickman & Shackell (*213*) reported a climate-projected shift in thermal phenology across the northwest Atlantic Ocean to the year 2050. The study suggested the SST-defined spring would arrive earlier by up to 8 or even 10 weeks by 2050 across the northwest Atlantic, with some of the largest changes taking place on the nose of the Grand Banks. This study also suggests a lengthening of the growing season and a longer duration of seasonal thermal stress, again with some of the largest projected changes on the Grand Banks.

Shorter-term projections also indicate warming of the sea surface and bottom over the next 25 years across the AOS, with geographic variation in the magnitude of change (Figure 2). Surface waters are projected to warm over almost the entirety of the AOS, particularly under high emissions and along the continental shelves (Figure 2A). The average surface warming across both emission scenarios in the NAFO area was 1°C, with some regions experiencing larger magnitude warming under high emissions (2.5°C) and others slightly cooling under low emissions (-0.8°C). Most of the warming of the bottom water occurs within the 500 m isobath, with slight cooling in some offshore waters (Figure 2B). The average bottom warming across both emission scenarios in the NAFO area was 0.45°C, with some regions warming by as much as 2.1°C under high emissions or cooling by as much as -0.37°C under low emissions. Contrary to expectation, some parts of the Grand Banks experience more significant warming on the sea bottom than at its surface.

Projection reliability remains a challenge for climate models. While the reliability of CMIP6 projections is improved relative to those in CMIP 5 and statistical approaches to account for uncertainty exist (*7*), significant differences can exist between modelled and observed fields (*203*). In this analysis, projected surface temperature changes from the two models agreed in their direction of change in 94% to 96% of the grid cells examined. In comparison, bottom temperature changes from the two models agreed in 77% to 82% of grid cells.

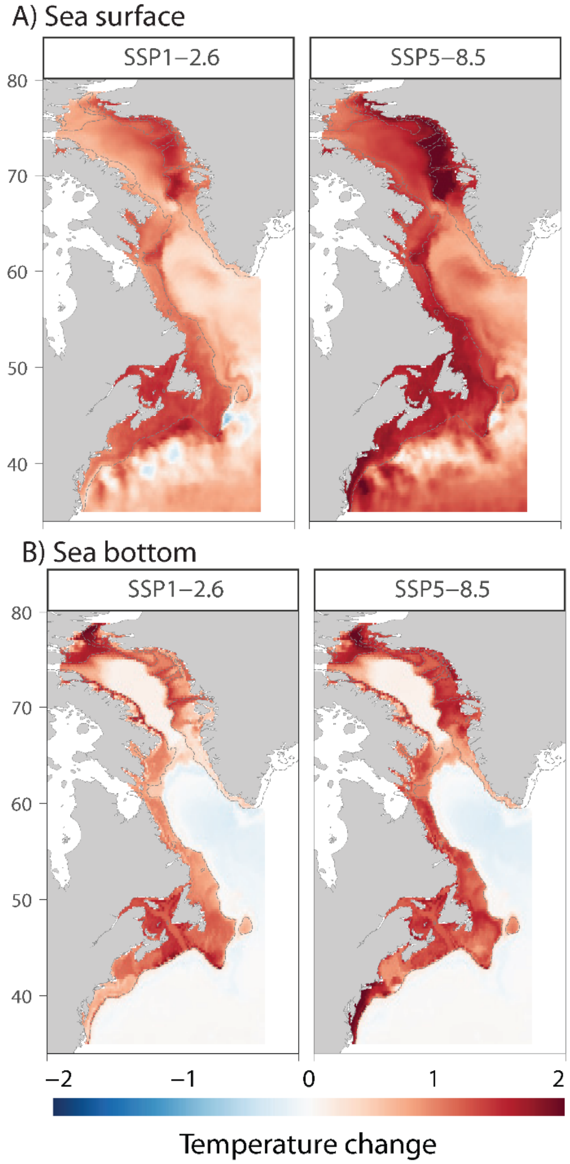

Figure 2. Climate projections to 2050 across the NAFO area from two climate models in the CMIP6 inventory. Projected future change in average temperature at the sea surface (a), and bottom (b), between 2014-2024 and 2045-2055 under low (left columns) and high (right columns) emissions scenarios. Red depicts warming and blue cooling.

Projected climate impacts on fisheries living resources

Projected climate changes are expected to increase fisheries catch potential in higher latitudes and to decrease in tropical regions due to the poleward redistribution of fish stocks in the northern hemisphere (*6*, *7*, *214*, *215*); (Appendix 6). However, there is still significant uncertainty in projecting climate effects on fisheries (*216*) and fisheries performance (*217*), particularly in the Arctic (*6*, *7*, *87*, *215*) and nearshore waters of the northwest Atlantic, with uncertainty varying by emission scenario (*202*).

Boyce et al. (2021) reported that marine animal biomass is projected to decline across most of the southern NAFO area (<~60°N), with increases in the Arctic under high emissions (Figure 5.2 in Boyce et al. 2021). These projections broadly agree with reports that under high emissions, marine animal biomass will decline from 1971 to 2099 by an average of 7.7% within the entire Canadian EEZ, but with substantial spatial variability (±29.5%); (*215*).

Across the AOS, waters supporting the highest fishery landings (2000–2018) were projected to lose the greatest biomass of marine animals due to climate change regardless of the emission scenario (Figure 5.5 in Boyce et al. 2021). This suggests that ongoing climate change will disrupt fisheries across the NAFO area and that fisheries will either need to track the spatial redistribution of fisheries biomass or experience reduced catch. Either way, a significant disruption of the fishing industry is likely, particularly with high emissions. This report further reported that areas projected to experience the largest climate-driven losses in marine animal biomass are subjected to many additional stressors, such as pollution, fishing pressure, shipping traffic, and acidification, indicating that there may well be unanticipated synergies between the impacts of climate change on fisheries and the effects of other human activities.

Projected species and ecosystem redistributions

Climate change is driving widespread shifts in species distributions (*138*, *142*, *143*), a trend that is projected to continue. Under high emissions, 23% of transboundary fish stocks are expected to shift by 2030, with 45% shifting by 2100 (*218*). Such projected shifts in species distributions are particularly apparent across the northwest Atlantic. Shackell *et al.* (*176*) predicted changes in the thermal habitat of 46 marine species in the Northwest Atlantic (~35°N to ~48°N), reporting that by 2060, most species (55%) would lose thermal habitat, with 21% gaining and 24% remaining constant; in the US, 65% of species lost thermal habitat, with 20% gaining and 15% remaining constant. As a group, planktivores such as herring, sand lance, and capelin were predicted to lose significant habitat in both Canada and the US. This is troubling, as these forage species are critically important keystone species in many marine food webs and support a range of valuable higher trophic level fisheries.

In addition to species shifts, biodiversity patterns and whole ecosystems are projected to shift under climate change. Reygondeau et al. (*219*) projected shifts in the geographic distribution of 56 biogeochemical provinces (*e.g.* "Longhurst provinces") between 1950 and 2100 under high and low emission scenarios. The study reported poleward shifts in the distribution of biogeographic provinces by an average of 18.4 km per decade and the emergence of novel biogeochemical provinces that emerge by 2040 and will encompass 1.2% of the global ocean by 2100.

Predictive climate modelling for NAFO fisheries: approaches and considerations

Climate projections and forecasts are used to inform decision-makers of projected climate changes and their impacts on biodiversity, ecosystem dynamics, and food production (*92*, *107*, *220*) and are increasingly beginning to be used to assess and provide advice to fisheries management under climate change (*107*, *179*, *221*–*223*). However, the potential usefulness of climate models to fisheries depends on their availability, reliability, geographic and temporal resolution, and other factors.

The resolution of global models can be ~25 km^2 but are more commonly ~100 km^2, which is relatively coarse in a fisheries context and insufficient to resolve some critical processes. The skill of these global models is often poor in nearshore waters and inland waterways when assessed against observed data (*203*, *224*, *225*). A review of six ESMs by Loder *et al.* (*224*) reported that the models could reproduce large-scale patterns in surface temperature and salinity across the North Atlantic well but did not capture detailed features such as the position of the Gulf Stream. Instead, regional ocean models can more reliably represent dynamic nearshore features and are often available at the higher spatial resolutions required by fisheries (*91*, *224*, *226*). For instance, Laurent *et al.* (*203*) reported that a regional model for the northwest North Atlantic shelf ocean reproduced temperature, chlorophyll, and nitrate observations significantly better than 29 coarse-resolution global ESMs.

The drawbacks of regional and local models are the specialized knowledge required to develop them, the computational requirements to run them, and the large volume of projected output. While there is a general consensus that 10 km^2 is the minimum geographic resolution needed to resolve fine-scale oceanographic processes, refining coarse 100 km^2 models to this scale would incur a more than 100-fold increase in computational cost (*227*). While the use of such models is less common, some that exist within the NAFO area include:

1) The Bedford Institute of Oceanography North Atlantic Model (BNAM) is a climate model at 1/12° resolution across the North Atlantic between ~7°N and 75°N (*228*, *229*). This model provides projections of physical ocean variables for 2055 and 2075 under representative concentration pathway (RCP) scenarios 4.5 and 8.5.

2) The NOAA Geophysical Fluid Dynamics Laboratory Climate Model 2.6 (CM2.6) has also been used to project changes in physical variables such as temperature across the North Atlantic (*91*, *179*).

3) The Atlantic Canada Model (*230*, *231*) is a 9.5 km^2 resolution regional implementation of the Regional Ocean Modeling System (ROMS, version 3.5); (*232*) for the northwest Atlantic, nested

within an ocean-ice model (*233*). The model has 30 vertical layers and evaluates ten variables, including temperature, nutrients, and plankton.

It is important to distinguish climate projections and forecasts. The global, regional, and local models discussed thus far produce climate *projections* – future outcomes under given assumptions of future human-related activities such as socioeconomic and technical developments that generate emissions – yet the scenarios bracket a wide range of possibilities. There is debate and uncertainty over which is most plausible. Alternatively, *forecasts,* also sometimes referred to as *predictions*, represent the expected future outcomes based on realistic assumptions and expectations (*234*, *235*). In consequence, forecasts are often restricted to shorter time intervals (*e.g.* weeks, months, few years) and spatial domains (*e.g.* local, regional) than are projections (*235*) but can be more appropriate for fisheries' assessment and management.

Forecasts can help set real-time tactical decisions of when and where to fish (*236*) and seasonal projections over weeks to months (*237*) and are currently used in the management of southern bluefin tuna (SBT; *Thunnus maccoyii*) in southeastern Australia (Eastern Tuna and Billfish Fishery). Since 2003, a temperature-based habitat model (*238*) has been used to estimate current SBT distribution (nowcast), allowing managers to decide where to place management boundaries. During the fishing season, real-time reports of the predicted location of SBT habitat are made, allowing managers to dynamically set management boundaries to reduce unwanted catches (*239*). Since 2011, POAMA temperature forecasts have also been used to generate SBT forecasts 3–4 months ahead of time (*240*), which are used to prepare for the upcoming season proactively. The temperature forecasts are combined with a habitat model to forecast the spatial distribution of larval SBT up to four months in advance and used by fishers to improve the efficiency of fishing operations (*223*). The forecasts are used to manage aquaculture operations such as tiger and banana prawns in Queensland and Atlantic salmon (*Salmo salar*) in Tasmania. Aquaculture farmers use the forecasts to plan when to stock and harvest their ponds, determine optimal feed mixes, implement disease management strategies, modify labour needs, and manage market expectations (*223*).

Forecast models are also an integral part of the National Ocean and Atmospheric Administration (NOAA) Climate, Ecosystem, and Fisheries Initiative (CEFI) – an operational ocean modelling and decision support system to reduce impacts, increase resilience, and adapt to climate change. A nationwide ocean modelling component is an essential foundation for early warnings, socio-ecological projections, risk assessments and climate-informed advice. Likewise, the J-SCOPE system uses the model of Siedlecki *et al.* (*241*) to forecast across the US northwest coast and applies them to the assessment of sardines and hake distributions (*242*).

Despite the use of climate forecasts in fisheries in the US, Australia, and elsewhere, there is a notable lack of ocean forecasts available in the northwest Atlantic Ocean. The Canadian Seasonal to Interannual Prediction System version 2 (CanSIPSv2); (*243*) uses the CanCM4i and GEM-NEMO global coupled models to produce global multimodel ensemble forecasts of temperature and other physical fields for the ocean and atmosphere up to one year from the start of each forecast cycle (*243*). However, the spatial resolution is 100-

150 km², which is unsuitable for fisheries. Developing a high-resolution forecasting model for the Northwest Atlantic would support fisheries' assessment and decision-making regarding climate change.

Climate impacts on NAFO-managed species

The climate risk for 14 NAFO-managed species across the northwest Atlantic Ocean was systematically assessed by 1) reviewing the literature database to evaluate the available science basis (Table 3 and Appendix 7) and 2) using the CRIB framework to quantitatively estimate the magnitude of projected climate impacts on each species across the NAFO area and the timing of their onset (*33*). Together, these information sources provided a foundation for understanding and assessing the overall climate risk for each species across the NAFO area at low, moderate, or high risk of being impacted by climate variability or change (Figure 3) and to evaluate the confidence (certainty) and the overall level of scientific understanding of climate impacts on each species, helping to pinpoint where further information may be required.

Table 3. Studies into the climate impacts on NAFO-managed species.

Species	Studies considered	Climate risk
Atlantic wolffish (*Anarhichas lupus*)	(*244–262*)	High
Capelin (*Mallotus villosus*)	(*46, 263–272*)	High
Greenland halibut (*Reinhardtius hippoglossoides*)	(*47–49, 273–285*)	Moderate
Northern shrimp (*Pandalus borealis*)	(*56–58, 146, 148, 278, 286–304*)	High
Roughhead grenadier (*Macrourus berglax*)	NA	High
Splendid alphonsino (*Beryx splendens*)	NA	High
Witch flounder (*Glyptocephalus cynoglossus*)	(*66, 67, 305*)	High
Yellowtail flounder (*Limanda ferruginea*)	(*69–71, 306–320*)	High
Atlantic cod (*Gadus morhua*)	(*41, 49, 98, 118, 153, 154, 294, 321–357*)	Moderate
Redfish (*Sebastes fasciatus*)	(*39, 358–367*)	Moderate
Thorny skate (*Amblyraja radiata*)	(*62, 63, 368–371*)	Moderate
American plaice (*Hippoglossoides platessoides*)	(*40, 69, 258, 306, 307, 309, 318, 366, 372–384*)	Low
White hake (*Urophycis tenuis*)	(*140, 143, 297, 385–387*)	Low
Shortfin squid (*Illex illecebrosus*)	(*53, 54, 388–391*)	Low

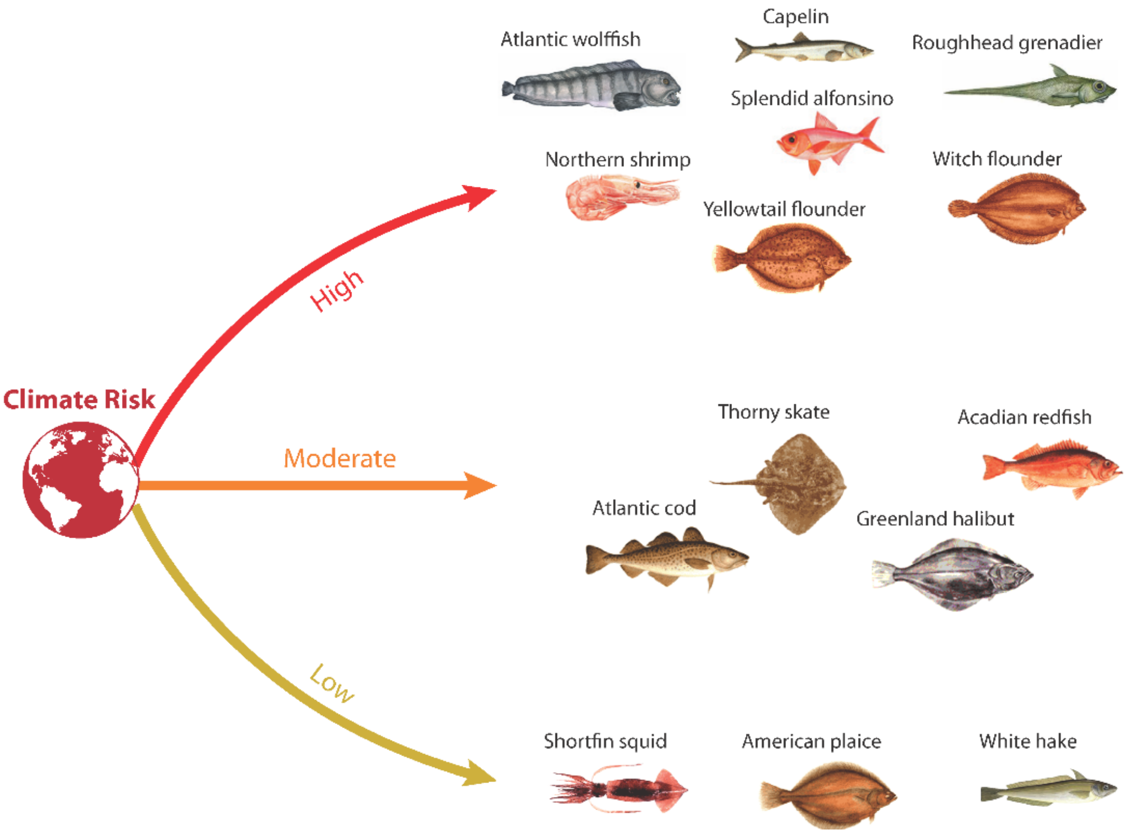

Figure 3. Assessed climate risk of NAFO-managed species.

High risk

Half of the fourteen species were assessed at high climate risk across the AOS, including Atlantic wolffish, Capelin, Northern shrimp, Roughhead grenadier, Splendid alphonsino, Witch flounder, and Yellowtail flounder. These species tended to have narrower thermal niches (Table 1) greater projected thermal habitat losses to 2050, and to experience thermal stress earlier across their geographic ranges. Many high-risk species are already experiencing thermal stress and habitat loss; roughhead grenadier, splendid alfonsino, and northern shrimp have already lost roughly 20% of their thermally suitable habitat, mainly around their southern range extents (Figure 4). High-risk species experience climate impacts through several pathways, including for instance, phenology effects and trophic mismatch on early life stages affecting recruitment (*e.g.* shrimp and capelin) (*148*, *270*), altered migration routes (*e.g.* halibut and capelin) (*46*, *263*, *265*, *280*), changing sea ice conditions (*e.g.,* capelin); (*392*). Climate effects on growth, recruitment, mortality, geographic distribution and trophic interactions were among these species' most commonly reported impact pathways.

Few climate impact studies were available for roughhead grenadier, splendid alfonsino and witch flounder, rendering their assessment status less certain.

1) **Atlantic wolffish (*Anarhichas lupus*):** Wolffish is significantly affected by warming and deoxygenation (*244*, *245*, *254*–*257*). The optimal temperature for adult growth is 6.6°C to 8°C for adults (*247*, *262*), and 11.5°C for juveniles (*261*), above which reduced growth and increased mortality are observed. Wolffish have been found to alter their distribution northward and into deeper waters in response to warming (*251*) and to shift their migration routes (*252*).

   Due to its relatively narrow thermal range (-1°C – 10°C); (*43*–*45*), wolffish is already experiencing ~6% loss of thermal habitat across its native geographic range in the NAFO area (Figure 4). This is projected to increase modestly until 2075 when it increases to ~20% by 2100 under high emissions and remains relatively constant at 10% under low. The year when halibut is projected to become thermally stressed varied markedly across its geographic range, being much earlier at its southern range extent. On the Grand Banks and Flemish Cap and the east coast of Greenland, the climate has already exceeded wolffish's thermal limit.

   These results suggest that wolffish is sensitive to the direct effects of long-term temperature change and that it will likely experience indirect effects via, for instance, altered prey availability.

2) **Capelin (*Mallotus villosus*):** Capelin has a moderately wide thermal range (-1.5°C - 14°C) with a preference for waters between -1°C and 6°C (*46*). However, due to projected surface warming, the species may already be experiencing thermal habitat loss of over 10% across its native range within the NAFO area (Figure 3). Under both emission scenarios, capelin is expected to lose thermally suitable habitat - almost 20% by 2050 and over 20% by 2100. The year when capelin is projected to become thermally stressed varies across its geographic range but was much earlier at its southern range extent with a leading edge around 50°N. These projections agree with analyses of historical distribution patterns indicating that temperature is an overarching driver of capelin distribution and migration, with warmer conditions associated with northward capelin shifts (*46*, *263*, *265*).

   In the late 1980s and early 1990s, cooling led to an extension of capelin distribution into the southern Gulf of St. Lawrence and eastern SS (*46*, *266*). Rose (2005) reported that temperature changes as small as 1 °C were associated with changes in distribution over scales of hundreds of kilometers. Considerable temperature changes may result in much larger displacements, including the establishment of new spawning sites. Orlova et al. (*267*) reported several indirect effects of climate on capelin distribution and energy reserves involving the abundance and species of copepod prey. Warming also impacts vertical migration (*268*) and behaviour (*269*) of capelin and has been linked to changes in spawning timing (*270*). Climate-driven sea ice reductions also affect capelin, affecting primary production and prey availability (*392*).

There is limited information about the impacts of climate on capelin, especially of changing oxygen and pH. Yet, the available information suggests that capelin is sensitive to the direct and indirect effects of temperature variability and change. Continued warming will likely affect capelin directly and indirectly by altering migration routes, spawning dynamics, seasonal development, sea ice formation, and prey availability, as well as experiencing significant thermal habitat loss. These changes will likely have knock-on effects on capelin predators.

3) **Northern shrimp (*Pandalus borealis*):** One study conducted over a century ago in the northwest Atlantic reported an upper thermal limit for shrimp of 12°C (*301*). Still, this result appears anomalous, and the majority of studies suggest that northern shrimp has a narrow thermal range (1°C - 6°C) with a preferred range of 1 – 4°C (*56*–*58*, *302*). The optimum temperature for larvae is reported to be 9°C, with respiratory stress occurring above this (*303*).

Warming in the northeast Atlantic adversely affects shrimp recruitment (*286*, *304*). Koeller et al. (*298*) reported that the warming decreased growth rates, possibly due to increased metabolic demands, which led to reduced body size. Several studies reported that warming will significantly affect shrimp hatching and recruitment, including altered timing of hatching (*148*, *287*–*289*). In particular, Koeller et al. (*148*) reported a coherence between shrimp hatching times and that of phytoplankton seasonal blooms across the North Atlantic driven by bottom temperature, suggesting that climate change could lead to a phenological mismatch (*146*) and poor recruitment (but see (*290*) for an alternative hypothesis). Studies suggest that shrimp are relatively tolerant to hypoxia, with males being more tolerant on average than females (*291*).

Shrimp has a narrow thermal range, and projected bottom warming rates suggest it is already experiencing thermal habitat loss of ~20% across its native range within the NAFO area (Figure 4). Shrimp are expected to lose thermally suitable habitat - ~25% by 2050 and over 40% by 2100 under a high emission scenario. Results suggest that shrimp are already experiencing thermal stress across much of their geographic range, particularly on the Grand Banks, eastern Greenland, and its southern range extent. These projections are supported by Le Corre et al. (*292*), who reported that bottom temperature warming of more than 4°C by 2090 would lead to significant changes in suitable habitat and geographic range of shrimp on the Newfoundland and Labrador shelves. The early emergence times at the southern range extend are also supported by Richards et al. (*293*), who reported a complete collapse of northern shrimp in the Gulf of Maine driven by a marine heatwave in 2012.

These results suggest that shrimp are highly sensitive to the direct effects of temperature variation and change, particularly during their early life stages, which affect their prey availability. Additional effects such as altered predation are largely unexplored but are likely; for instance, Worm et al. (*294*) reported that temperature-driven increases in cod populations were associated with reduced shrimp via top-down trophic control across the North Atlantic. The impacts of changing oxygen and pH on shrimp are poorly studied.

4) **Roughhead grenadier (*Macrourus berglax*):** Roughhead grenadier has a narrow thermal range (-0.5°C – 5.4°C), and projected bottom warming rates suggest it is already experiencing significant thermal habitat loss of ~21% across its native range within the NAFO area (Figure 4). Under both emission scenarios, grenadier are expected to continue losing thermally suitable habitat - ~30% by 2050, and ~60% by 2100 under a high emission scenario and ~30 under low. Results suggest that grenadiers are already experiencing thermal stress across much of their geographic range and most areas south of 50°N, particularly on the Grand Banks, eastern Greenland and across its southern range extent.

   Overall, these results suggest that Roughhead grenadier is extremely sensitive to the direct effects of long-term temperature change in addition to experiencing likely indirect effects via altered prey availability, predation, or others.

5) **Splendid alphonsino (*Beryx splendens*):** Splendid alfonsino has a moderate thermal range (-2°C – 17°C). However, due to its small geographic range within the AOS, projected bottom warming rates suggest it is already experiencing significant thermal habitat loss of ~21% (Figure 4). Under both emission scenarios, alfonsino is expected to continue losing thermally suitable habitat, reading over 50% by 2100 under a high emission scenario. Results suggest that alfonsino are already experiencing thermal stress across the extreme southern extent of their geographic range.

   These results suggest that splendid alfonsino is extremely sensitive to the direct effects of long-term temperature change in addition to experiencing indirect effects via, for instance, altered prey availability and predation.

6) **Witch flounder (*Glyptocephalus cynoglossus*):** Witch flounder has a moderately wide thermal range (-1°C – 11.4°C), with 15°C reported as optimal for larval growth (*66*). Witch Flounder is already experiencing ~6% loss of thermal habitat across its native geographic range in the NAFO area (Figure 4). This is projected to increase to ~10% by 2075 and then increase to ~20% by 2100 under high emissions and remain relatively constant at ~10% under low. The year when witch flounder is projected to become thermally stressed varied across its geographic range, being much earlier in the Gulf of Maine and Eastern Scotian Shelf. Witch flounder is projected to become thermally stressed by ~2060 on the Grand Banks under high emissions and by ~2080 under low emissions.

   There are limited studies into the effects of witch flounder to ongoing climate change. However, the available information suggests that witch flounder is sensitive to the direct impacts of long-term temperature change and that it will also likely experience indirect effects, such as altered prey availability and predation.

7) **Yellowtail flounder (*Limanda ferruginea*):** Yellowtail flounder has a wide thermal range (-1°C – 18°C), yet oxygen consumption has been found to decline at temperatures above 14°C (*69*). The preferred temperature range is -1 to 5.8 C (*70*), while optimal feeding is between 6.8°C and 7.1°C (*314*). Species distribution modelling suggests that yellowtail flounder will shift northward from the Gulf of Maine in response to warming (*315*). Temperature variation has been found to affect growth and development (*316*) as well as distribution (*317*) and movement (*314*). Warming has been found to negatively affect recruitment variability (*318*). However, using data from the 1960s, Brodie et al. (*319*) reported positive effects of warming on yellowtail flounder on the Grand Bank, with cooling associated with stock declines and warming with recovery. Walsh et al. (*71*) also reported that flounder distributions were relatively insensitive to temperature fluctuations.

Due to its wide thermal range, yellowtail flounder is not projected to experience a significant loss of thermal habitat until after 2070 and only reach ~10% under a high emission scenario (Figure 4). The climate is projected to have emerged from the yellowtail flounder's thermal niche at the extreme south of its range and in the Gulf of St. Lawrence under high emissions.

These results suggest that yellowtail flounder is sensitive to climate variation and change with observed effects on distribution, growth and recruitment. However, projections indicate that outside of the extreme south of its range, the species will not lose a significant amount of thermal habitat but may instead become thermally stressed, leading to reduced productivity.

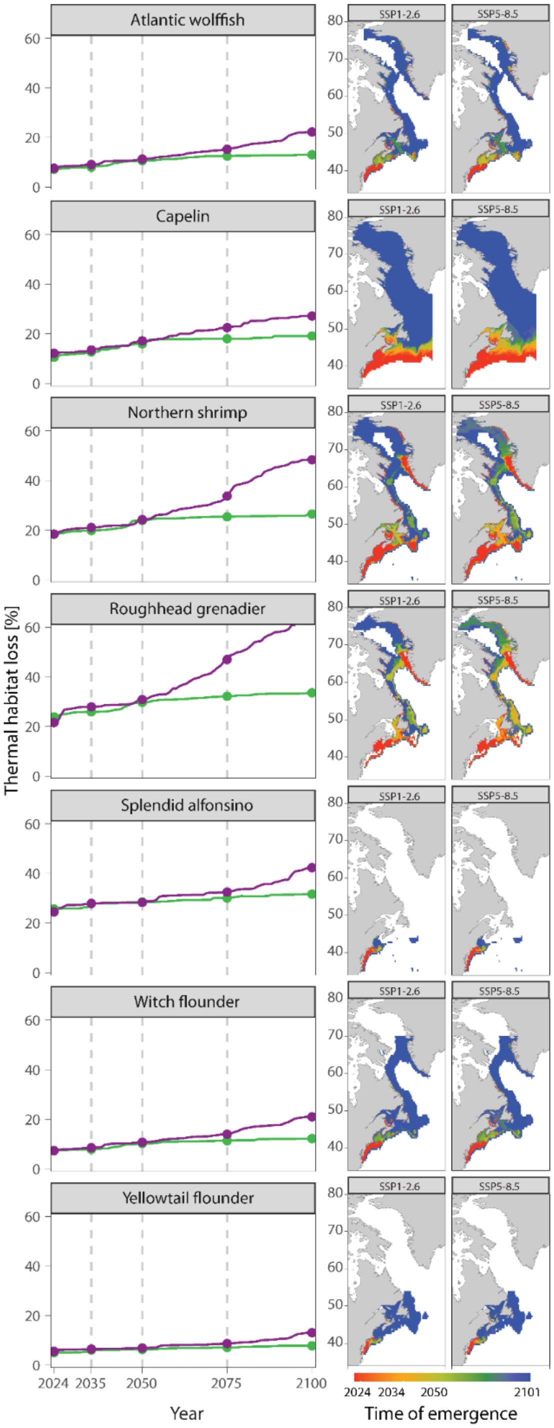

Figure 4. Projected magnitude and timing of climate impacts on NAFO species classified as at high climate risk.

(Left) The projected proportion of thermally suitable habitat lost across the NAFO area under high (purple) and low (green) emissions. Vertical lines denote years 2035, 2050, and 2075, respectively. (Right) The year when the temperature is projected to exceed the species' upper thermal limit across the AOS. Red depicts earlier, and blue late emergence.

Moderate risk

Four of the 14 species were assessed at moderate climate risk, including Atlantic cod, Greenland halibut, redfish, and thorny skate. These species tended to have broader thermal niches (Table 1) but were also experiencing thermal stress across a portion of their geographic ranges, but this was more modest and primarily restricted to the southernmost extent of the NAFO area or in the Gulf of St. Lawrence (Figure 5). Cod is among the most studied species, yet far fewer climate impact studies are available for redfish and thorny skate (Table 3). While most studies of cod and halibut suggested adverse effects of climate change and a notable response to climate variability, some indicated positive responses (*52*), highlighting the uncertainty around resolving climate impacts and that they can often be nonlinear, context-specific, and vary by life stage, location, and species.

1) **Atlantic cod (*Gadus morhua*):** Atlantic cod has a wide thermal range (-1.5°C - 19°C), yet studies have reported an optimal metabolic scope between 10 and 14.5°C (*41*). Optimal growth is higher (15.1°C) for smaller younger individuals (*355*), and smaller cod have been experimentally found to prefer warmer temperatures (*356*). Experiments indicate that even at 17°C, cod experience heightened immune activity indicative of stress (*357*), while at 18°C, they experience energetic limitations (*321*). At 9°C, cod have been found to experience erratic spawning frequencies (*322*). Studies suggest that temperature significantly affects the geographic distribution of cod (*323*). During warmer regimes, cod have been found to inhabit deeper, cooler waters, particularly larger older individuals, while cold regimes led to reduced activity and vertical movement (*324*, *325*). Evaluating historical data in the North Sea, Winter et al. (*326*, *327*) reported that warming exacerbated Allee effects, increasing the risk of population collapse and requiring a larger population size of recovery. Experiments suggest that cod experience severe tissue damage at higher CO2 levels and that continuing increased ocean acidification could affect the survivorship and recruitment of cod (*328*). Controlled warming of 2°C and 4°C showed that warming might accelerate development and increase mortality in larval cod (*329*).

   On the other hand, Holt and Jorgensen (*330*) predicted that 2°C warming would lead to increased cod growth rates and larger asymptotic sizes, while others have reported increased cod growth and biomass in response to warming (*331*–*333*). These results may be partly explained by the context dependency of temperature effects; for instance, Mantzouni *et al.* (*334*) reported that warming effects were positive on cod recruitment at temperatures below 5°C but negative above it, while Lindmark et al. also reported a temperature threshold effect on cod condition (*335*).

   Experiments have shown that cod can be sensitive to acidification, with elevated CO2 levels altering gene expression, suggesting stress at the molecular level (*336*). Bioeconomic modelling results agree, indicating the harmful effects of acidification on recruitment (*337*). Acidification has also been found to cause tissue damage in larval Atlantic cod, leading to increased susceptibility to infection (*118*). Alternatively, Shackell et al. (*49*) reported that cod in the Canadian northwest Atlantic were impervious to pH changes within the range of values projected to 2100; this conclusion, however, was largely based on experiments involving Baltic rather than Atlantic cod (*338*). Deoxygenation is associated with deteriorating health in cod (*335*, *339*).

Studies have also demonstrated that cod recruitment is influenced by the North Atlantic Oscillation (NAO), with effects varying geographically and temporally. For example, Brander (*153*) found that recruitment in European waters south of 62°N is particularly sensitive to climatic changes driven by the NAO when the spawning stock biomass (SSB) is low. This suggests a non-linear relationship where the effect of NAO on recruitment is modulated by the existing population size of the stock. Solow (*154*) reported that the correlation between NAO and recruitment success was evident in some time periods but not others. For Arctic cod, a clear relationship between NAO and recruitment was identified between 1973 and 1996 but not in earlier years (1946-1972), indicating potential shifts in ecological sensitivities or other modifying factors over time.

Due to its wide thermal tolerance range, cod is not projected to experience a significant loss of thermal habitat until after 2070 and then only under a high emission scenario (Figure 5). The mean time when climate is projected to emerge from cod's thermal niche is 2099 under low emissions and 2098 under high.

While these results are somewhat mixed, there is significant evidence that cod are moderately sensitive to climate variability and change. Cod response to warming is expected to vary spatially; for instance, Drinkwater (*98*) suggested negative warming effects on cod recruitment for southern stocks but positive effects for more northern stocks. Excepting the extreme south of their range or in the Gulf of St. Lawrence, cod will likely not experience lethal temperatures until after 2050, yet temperatures will likely become sufficiently warm to induce stress, particularly at the early life stages. Climate variability and change will quite likely affect cod through secondary pathways, including altered prey availability, for instance, via climate impacts on capelin, shrimp or other key prey species (*294*).

2) **Greenland halibut (*Reinhardtius hippoglossoides*):** Greenland halibut has a moderately wide thermal range (-1.89°C – 15°C) but with preferred temperatures between 0 and 7°C (*47*–*52*). Halibut has an optimal temperature for aerobic scope of 2.4°C (*48*), and decreased survival and growth have been reported above 7.5°C (*279*). Temperature has been identified as a key factor affecting genomic variation, affecting growth and migration patterns (*280*). As with other species, warming has been associated with vertical distribution shifts to maintain preferred temperatures, with younger individuals showing the largest shifts (*281*). Alternatively, Sunksen et al. (*282*) reported that bottom temperature warming between 1993 and 2003 led to increased growth rates of juvenile Greenland halibut of 1.6cm$°C^{-1}$.

Experiments indicate that juvenile halibut are sensitive to even small reductions in dissolved oxygen, with severe hypoxia reducing the maximum metabolic rate by 55% (*283*). Juveniles appear more sensitive to hypoxia than adults (*283*). Distribution models predicted that further warming and deoxygenation in the Gulf of St. Lawrence would reduce the highest density halibut aggregations by 55% and that oxygen levels were already at the species limit (*284*).

Due to its moderately narrow thermal range, halibut is already experiencing a loss of thermal habitat of ~4% across its native geographic range in the NAFO area (Figure 4). This is projected to remain relatively constant by 2075, increasing to ~10% by 2100 under high emissions. The year when halibut is projected to become thermally stressed varied markedly across its geographic range, being much earlier at its southern range extent, on the Grand Banks and Flemish Cap and the east coast of Labrador.

Several studies suggest halibut are vulnerable to warming (*48*), yet others indicate increased halibut catches and projections of positive effects of warming and expansion of thermally suitable habitats (*52*).

These results suggest that halibut is moderately sensitive to the direct effects of warming and deoxygenation, particularly in smaller, younger individuals. Adverse effects in areas such as the Grand Banks and Flemish Cap are likely as these areas are already approaching halibut's upper limits. Studies of indirect effects are limited, yet there is a high likelihood of climate-driven impacts on halibut prey availability.

3) **Redfish (*Sebastes fasciatus*):** Redfish has a moderate thermal range (-0.8°C - 13°C) with a reported core thermal habitat between 5.5°C and 8.5°C (*39*). Pedchenko (*358*) reported that increasing temperatures were a major factor driving the spatial redistribution of redfish in the Irminger Sea. Warming has also been linked to earlier spawning, altered prey, and trophic mismatch on the Flemish Cap (*360*) and to reduced size at maturity in the Gulf of St. Lawrence (*361*). Increasing acidification adversely affects survival and behaviour during early life stages. Alternatively, Carrion et al. (*362*) reported higher redfish fecundity under warming on the Flemish Cap between 1996 and 2020.

Due to its moderately wide thermal range, redfish is not projected to lose thermal habitat before 2050 (Figure 5); afterward, the species will lose a maximum of ~12% thermal habitat by 2100 under high emissions but almost none under low emissions. The year when redfish is projected to become thermally stressed varied across its geographic range but was much earlier at its extreme southern range extent and was around 2050 on the Grand Banks under high emissions.

These results suggest that redfish have moderate sensitivity to the direct effects of long-term temperature change. Several studies have observed indirect effects of warming on prey availability, trophic mismatch, and spawning behaviour and success, and there is a high likelihood of indirect climate effects.

4) **Thorny skate (*Amblyraja radiata*):** Thorny skate has a moderately broad thermal range (-0.5°C – 12.5°C) (*62*, *63*), with a preference for temperatures between -0.5°C and 3°C (*63*). Swain et al. (*368*)

reported skates shifting their vertical distribution in response to temperature variation, suggesting that temperature drives their distribution. Warming was associated with increased metabolic demands in skates in the Gulf of Maine and a reduced tolerance for hypoxia (*369*).

Thorny Skate has a moderate thermal range, and projected bottom warming rates suggest it is already experiencing thermal habitat loss of ~5% across its native range within the NAFO area (Figure 5). Under a high emission scenario, skates are expected to slowly lose thermally suitable habitat to a maximum of ~10% by 2100, while it remains constant at 5% under low emissions. However, results suggest that Skates are already experiencing thermal stress across quite a bit of their range south of 50°N, particularly in the Gulf of St. Lawrence and the Eastern Scotian Shelf offshore banks. Skate is projected to lose habitat on the Grand Banks sometime around 2075.

Overall, these results suggest that Thorny Skate is moderately sensitive to the direct effects of long-term temperature change in addition to experiencing indirect effects via altered prey availability, predation, or others. Pennino et al. (*63*) reported a positive relationship between thorny skate and snow crab distribution, suggesting that temperature-driven shifts in crab could impact skate abundance and distribution.

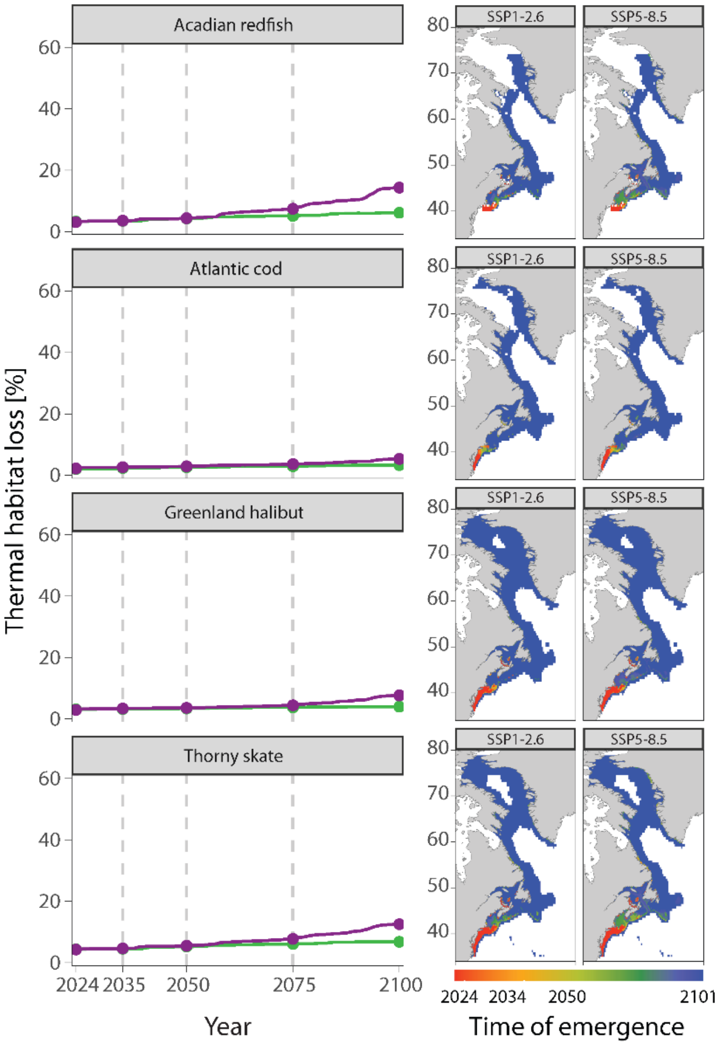

Figure 5. Projected magnitude and timing of climate impacts on NAFO species classified as at moderate climate risk.

(Left) The projected proportion of thermally suitable habitat lost across the NAFO area under high (purple) and low (green) emissions. Vertical lines denote years 2035, 2050, and 2075, respectively. (Right) The year when the temperature is projected to exceed the species' upper thermal limit across the AOS. Red depicts earlier, and blue late emergence.

Low risk

Three species were assessed at low climate risk. American plaice, White hake, and Shortfin squid tended to have broader thermal limits (Table 1), leading to later emergence times, reduced thermal habitat loss (Figure 2), and lower climate risk. However, these assessments come with a high degree of uncertainty, as there are very few studies into the effects of climate on these species (Table 3).

1) **American plaice (*Hippoglossoides platessoides*):** While plaice can tolerate a relatively wide range of temperatures (-1.3°C - 14°C), experimental studies suggest the optimal temperature range for growth and development is between 6 and 10°C (*40*), while surveys suggest plaice are most common

between -1°C and 5°C (*49*). Morgan (*374*) reported that temperature preference for plaice varied with their ration level, suggesting that the productivity regime and prey availability could affect their climate sensitivity. Several studies have reported temperature effects on plaice recruitment and survival rates either directly or by affecting prey availability, with effects being both positive and negative (*379*, *380*, *382*). Temperature has also been found to affect plaice swimming endurance, suggesting that temperature could affect their catchability (*381*). Little is known of the effects of hypoxia or pH on plaice.

Due to its relatively wide thermal range, plaice is not projected to experience a significant loss of thermal habitat until after 2070 and only under a high emission scenario (Figure 6). The mean time when the climate is projected to emerge from Plaice's thermal niche is after 2100 under low emissions and 2099 under high. These results suggest that American plaice has a low sensitivity to the direct effects of long-term temperature change but that it will likely experience indirect effects, such as altered prey availability or predation.

2) **White hake (*Urophycis tenuis*):** Due to its wide thermal tolerance range (-0.6°C - 21°C), hake is not projected to experience loss of thermal habitat until after 2100, and even then, the loss is modest under a high emission scenario (Figure 5). The time when the climate is projected to emerge from hake's thermal niche is generally late across its geographic range within the NAFO area but is already occurring at the extreme south of its distribution. These results conflict with reports of temperature-driven northward shifts in white hake distribution across the northeast US continental shelf between 1968 and 2008, influenced by the position of the Gulf Stream and the Atlantic Multidecadal Oscillation (*297*).

   There is a lack of information about the nature and magnitude of climate effects on white hake. Studies suggest climate-driven range shifts at the south of their range, yet projections indicate that hake will not become thermally stressed until later this century. Due to its wide thermal range and late emergence times, white hake appears to have a low sensitivity, although further research is needed.

3) **Shortfin squid (*Illex illecebrosus*):** Shortfin squid has a wide thermal range (0.5°C – 27.3°C) with a preference between 4°C and 14°C (*53*, *54*) and spawning associated with temperatures between 16°C and 18°C (*388*). Chang et al. (*389*) and Ying et al. (*390*) reported a squid preference for cooler water temperatures with adverse effects under warming.

   Due to its wide thermal range, shortfin squid is not projected to experience a significant loss of thermal habitat until after 2070 and only reach ~9% under a high emission scenario (Figure 6). The climate is projected to have emerged from the shortfin squid's thermal niche at the extreme south of its range. While there is limited literature on the effects of climate variation and change on shortfin squid, the available information suggests that squid have a low sensitivity to the direct effects of long-term temperature change but that warming could lead to adverse effects, particularly at their southern range extent. While indirect effects are poorly known, there is a high likelihood that altered prey availability and predation will impact squid.

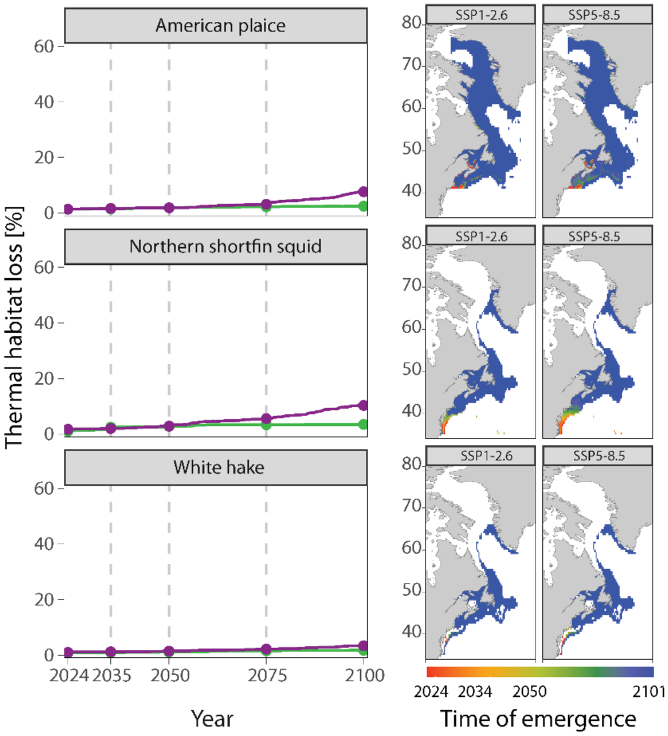

Figure 6. Projected magnitude and timing of climate impacts on NAFO species classified as at low climate risk.

(Left) The projected proportion of thermally suitable habitat lost across the NAFO area under high (purple) and low (green) emissions. Vertical lines denote years 2035, 2050, and 2075, respectively. (Right) The year when the temperature is projected to exceed the species' upper thermal limit across the AOS. Red depicts earlier, and blue late emergence.

Discussion and recommendations

This study suggests that the climate system across the northwest Atlantic Ocean is dynamic, with substantial seasonal, decadal, and multidecadal variability overlaying long-term climate changes (Appendices 3-4). Overall, the ocean is becoming warmer, more acidic, and deoxygenated, and these trends are expected to continue into the foreseeable future with the magnitude of changes depending on emission trajectories.

Marine species managed under NAFO are already experiencing a range of direct and indirect climate impacts, which will likely continue or accelerate over the coming years (Appendices 5-7). Direct effects of temperature are most prevalent, particularly for well-studied species such as Atlantic cod, while indirect climate effects, such as altered predation, prey availability, shifting phenology, and disease transmission, are less commonly studied but likely. Indirect climate impacts can be exceedingly challenging to pinpoint, as they often cooccur with other drivers such as fishing, competition, or anthropogenic stressors. Across species, early life stages appear to consistently be more sensitive to climate impacts, and juveniles and smaller individuals commonly have narrower thermal limits than adults, highlighting the importance of considering life history in climate impact evaluations (*393*). Notwithstanding these challenges, there are several avenues for incorporating climate variability and change into fisheries management to strengthen their resilience and productivity (Appendix 9).

Bringing the available evidence to bear and considering it through the lens of NAFO management, several recommendations are presented as avenues for integrating climate change effects into NAFO assessments and advice. These ideas are summarized below under data requirements, monitoring approaches, and climate integration into stock assessments.

Climate data

1) **Integrated data products:** The Marine Environmental Data Section (MEDS) of Fisheries and Oceans Canada provides a range of environmental data to the NAFO subcommittee for the environment (STACFEN). These environmental data include vertical profiles, gliders, drifting buoys, ship-based sampling, animal tracking, and others (*394*) that can be challenging to use. The observations are collected differently – some from standardized surveys, others opportunistically – and have different levels of measurement biases, sampling intensities and frequencies, and completeness. Consequently, significant effort is often required to prepare these data for use in fisheries assessment, which can hinder their use. Integrating environmental data layers would allow researchers to better incorporate climate variability and change into fisheries assessment and advice. The Newfoundland climate index combines 10 climate subindices into an annually updated time-series (1951-2024) representing the climate state of the Newfoundland and Labrador shelf (*395*). Additional climate products exist (*396*, *397*) or are in development, including the Canadian Atlantic Bottom Temperature and Salinity (CABOTS) database that integrates *in situ* observations to provide seasonal values across the northwest Atlantic and eastern Arctic shelf regions from 1980 to 2023 (*398*, *399*). Providing similarly integrated spatial-temporal data layers for key climate variables pH, dissolved oxygen, sea ice, primary production, and vertical mixing, as well as indicators of spatial and phenological shifts and climate projections and forecasts (see below), would aid the inclusion of climate considerations into fisheries.

2) **Remote sensing:** Remote sensing measurements of the surface ocean conditions have been collected since the 1970s and allow for spatially resolved evaluations of surface temperature, wind, chlorophyll, and other fields at high sampling frequencies (*e.g.,* daily or monthly) in near real-time. For instance, Copernicus, the Earth observation component of the European Union's Space program, merges observations from multiple sensors to provide daily measurements of the sea surface

globally[1]. Remote sensing observations are widely used in climate impact studies but are an underutilized resource for fisheries assessment and management in the northwest Atlantic. Remote sensing observations would be a valuable resource for synoptically monitoring the environment in real-time, assessing species geographic range shifts (read below), and monitoring for seasonal shifts and trophic mismatches (read below).

3. **Climate models:** Climate projections and forecasts are increasingly used in fisheries assessment and management. Since 2003, climate projections and forecasts have been used to manage fisheries and aquaculture operations in southeastern Australia (Eastern Tuna and Billfish Fishery), and they have become an integral part of the National Ocean and Atmospheric Administration (NOAA) Climate, Ecosystem, and Fisheries Initiative (CEFI) – an operational ocean modelling and decision support system to reduce impacts, increase resilience, and adapt to climate change. Despite the use of climate forecasts in fisheries in the US, Australia, and elsewhere, they are not yet used within NAFO. Developing or supporting the creation of a high-resolution regional climate model for the northwest Atlantic Ocean would be incredibly valuable for anticipating climate changes and their impacts on NAFO living resources. Ideally, the model would forecast, rather than project, climate changes at a high resolution (~1-10 km^2) across the NAFO convention area five to 10 years ahead. Such a model would have numerous potential uses; it could be coupled to stock assessment operating modelling within a management strategy evaluation (MSE) to help determine harvest quotas under climate change; and combined within a dynamic species distribution model (see below) to predict likely geographic range shifts (*400*); input into a seasonal model to anticipate potential phenological shifts and trophic mismatches; or used in climate risk assessments for species (*33*) and/or fisheries (*401*, *402*) to understand climate impacts on fisheries living resources.

4) C**limate response database:** The successful development of climate-considered fisheries will critically depend on understanding climate change, its impact on managed stocks and ecosystems, and the many complex pathways by which climate impacts operate. Consolidating and summarizing the available scientific literature on climate changes and their impacts on NAFO species, including their environmental niches, into a centralized database would facilitate a more robust understanding of which climate impact pathways are most important for stocks, how they operate, and how to mitigate them. Such a database could also help identify information gaps where additional investigations are needed. This report and the literature summarized in Appendices 2-9 are a start but should be enhanced and updated as new information becomes available.

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[1] satellite-ocean-colour | Copernicus

Monitoring and assessing climate change and its impacts

1) **Climate risk:** Climate vulnerability and risk assessments have gained wide traction to understand climate impacts on marine life and incorporate them into conservation and management. Such assessments have been an area of priority focus for intergovernmental organizations (*4*, *403*) and are included in the US NMFS Fisheries Climate Science Strategy (*25*, *404*, *405*) and in development at Fisheries and Oceans Canada for its Atlantic fisheries (*402*).

   Hundreds of climate vulnerability assessments have been published (*406*), yet there is no consensus on how to quantify vulnerability in a standardized and objective manner, and assessments are often undertaken *ad hoc* (*407*). The Climate Risk Index for Biodiversity (CRIB) was developed to fill this gap, providing standardized, spatially explicit climate vulnerability and risk estimates for species in a flexible manner that could be useful to marine conservation and management (*408*), including fisheries (*34*, *402*).

   The CRIB captures climate change impacts that are generalized across species with varying life histories which are grounded in ecological theory, widely accepted, and validated through peer review; it integrates historical, present-day, and projected future information about species' climate vulnerability and calculated or obtained in their native units. The CRIB assesses the likelihood of adverse consequences(*409*) at individual locations within species' native geographic distributions to inform conservation and management efforts where they operate. Of particular relevance to NAFO's goal of an ecosystem approach to fisheries (*410*), the CRIB evaluates climate risk at both the species and ecosystem levels (*33*).

   Synoptic, spatially explicit climate vulnerability or risk estimates from the CRIB or an alternative climate risk assessment framework for NAFO-managed species and their ecosystems could support evidence-based decision-making under climate change, helping decision-makers to identify priorities for scientific and management efforts to implement proactive management measures, reduce impacts, increase resilience, and advance the adaptive capacity of fisheries.

2) **Distribution shifts:** Most studies suggest that species will shift into more northern and deeper waters (*138*, *140*, *173–175*), yet unexpected range shifts have also been observed (*138*), highlighting the species-specific nature of climate responses and the need for ongoing monitoring. Geographic range shifts pose several challenges for fisheries assessment and management, including transboundary disputes, added effort and cost for fishermen to track the fish, and creating potential biases in stock assessments. For instance, many of the NAFO assessments rely on surveys that are often fixed in time and space; the fixed nature of the surveys means that they could miss shifting species distributions, leading to biased estimates of abundance on which fishing quotas rely.

Several avenues exist for monitoring shifting species distributions, yet species distribution models (SDMs) offer a flexible and proactive approach. SDMs predict the relative probability of species occurrence and habitat suitability as functions of the environment. Many SDMs, including the widely used AquaMaps (*411*), are static, ignoring temporal variation and predicting occurrence from species occurrence records and the average environmental conditions at those locations. However, to be useful to fisheries, SDMs must instead be dynamic, considering the spatial and temporal variation between species occurrence and their environment. Dynamic SDMs are often more reliable and allow for species distribution shifts to be tracked at a higher frequency over time (*400*). Dynamic SDMs could conceivably be developed for NAFO species using observations of species occurrence, for instance, from existing surveys, geolocated catch records, or animal tracking, and coincident temperature and other environmental observations, either sampled directly or inferred from independent data sources such as remote sensing or integrated data products. This process could be simplified using freely available statistical software packages (*412*). Ideally, and in consideration of NAFO's goal of an ecosystem approach to fisheries (*410*), such models could eventually be developed as joint dynamics SDMs, incorporating the correlated distributions of multiple species over time (*413*).

With such models, remote sensing observations could be used to evaluate species distribution in real-time, or forecasted climate conditions could be used to predict where species will be months or years ahead. This information could be valuable for understanding where survey or fishing efforts should be deployed, anticipating stock shifts across management boundaries, and proactively addressing transboundary conflicts.

3) **Pathogens and Disease:** Disease is rarely studied or considered in marine fisheries outside of aquaculture, yet climate changes are projected to expand bacteria's geographic and seasonal ranges (*130*). Climate-driven warming and salinity changes have already been associated with a poleward range shift of outbreaks of *Vibrio*, a bacteria that can have devastating effects on fish (*414*), in the North Atlantic, the North Sea, the Baltic Sea, and Alaska (*130*, *131*). There is a high likelihood that climate variability and change will affect the distribution and prevalence of disease (bacteria and viruses) in northwest Atlantic marine ecosystems. Given the potentially severe consequences for fisheries productivity, monitoring for changes in disease transmission is vital to managing fisheries under climate change. While monitoring the fisheries' catch for signs of disease is one avenue, environmental DNA (eDNA) is another new data stream that would be useful for monitoring species occurrence, including invasive species, and shifts in harmful bacteria and viruses (*415*–*417*). eDNA is helpful in monitoring disease and pathogen prevalence in aquaculture (*418*, *419*) and could be a relatively low-cost means of monitoring for invasive species and disease outbreaks in the northwest Atlantic.

4) **Phenology and trophic mismatch:** The literature review suggests that seasonal variation in the environment across the northwest Atlantic is projected to continue until at least 2050 (*213*). These seasonal shifts can substantially affect population productivity and fisheries, particularly by influencing recruitment and the success of early life stages (*87*, *147*, *148*, *175*, *178*). Further, seasonal shifts in the timing of species movements and key events can lead to biased stock biomass estimates when developed from surveys fixed in time and space. Developing indicators of seasonal environmental shifts, such as the timing and magnitude of the spring phytoplankton bloom, would help monitor climate-driven phenology changes and their impacts on NAFO stocks. For instance, Brickman & Shackell (*213*) developed a series of phenology indicators and explored their application for predicting ecological responses, for instance, in the timing of inshore lobster migration, spawning times for cod, egg development times for shrimp, thermal stress in herring, and habitat condition for halibut and snow crab. Such indicators can be incredibly valuable for evaluating climate-fisheries interactions and could be developed from daily or weekly remote sensing observations of chlorophyll concentrations or surface temperature.

5) **Climate vulnerability of early life stages:** A notable but vital information gap in understanding the impacts of climate change on fisheries' living resources is the effects on early life stages, which are critical to fisheries productivity and sustainability. While climate change is expected to amplify the variability, frequency, and intensity of fluctuations in critical fish life cycle events (*420*, *421*), impacts on spawning aggregations or larval and juvenile life stages are poorly understood. The literature review suggests that early life stages of marine life (*e.g.,* juveniles, larvae) can often have narrower environmental tolerances than adults, rendering them more sensitive to climate variability and change (*393*). At the same time, they are often less well-monitored or studied than adults. Due to the general deepening that occurs with increasing size or age in demersal fishes (*e.g.* Heincke's law); (*422*), understanding climate impacts on fish populations involves understanding climate changes and their effects on bottom-dwelling adults, as well as individuals occupying the pelagic zone (*423*). Despite these challenges, early-life-stage individuals could serve as sentinels of climate impacts and monitoring them could provide early warnings of impending climate impacts on adult biomass and productivity.

Climate-informed stock assessments

1) **Climate-integrated stock assessment models:** Several approaches can incorporate climate impacts directly within fisheries assessment models (Appendix 9), often allowing for climate effects to be explicitly addressed when providing science advice on quota. Management strategy evaluation (MSE)

is a flexible modelling approach for establishing management procedures that can be shown through simulation to be robust to a range of uncertainties associated with data limitations, species, ecosystem, model architecture, climate impacts, or other factors (*424*). A hallmark of MSE is quantifying uncertainty and ensuring that harvest decisions are robust to it. The approach relies on operating models, which are analogous to stock assessment models (*425*, *e.g. 426*). However, rather than relying on a single assessment model, MSE considers an ensemble of plausible models, enabling consideration of some critical biological uncertainties (*e.g.* nature of the stock-recruitment relationships, level of natural mortality), as well as those related to the likelihood and consequences of climate change and other factors (*427*).

To achieve ecosystem and multispecies objectives, MSE can be implemented using multispecies models that incorporate species interactions and the effects of environmental variability and change on them (*427–431*). Similarly, uncertainties related to past (*388*) or future (*432*) climate changes can be evaluated within MSE using observed or forecasted climate time series under different emission scenarios (*428*). MSEs are flexible, ranging from fully coupled biophysical models of regional ecosystem responses to climate change to climate-informed single- or multispecies projection models. Fully coupled ecosystem models estimate species interactions in space and time using ecological principles of bioenergetics, size-based dynamics, predation, and the probability of prey encounters. Climate-informed single- or multispecies models use time series of physics, prey availability, predation, and bioenergetics to inform functional responses, model parameterizations, covariates, and model structure to make future projections. For example, A'mar *et al.* (*432*) included climate change factors dynamically in an MSE of walleye pollock (*Gadus chalcogrammus*) in the Gulf of Alaska. This approach allows important climate change impacts to be quantitatively included in the estimation of population dynamics and subsequent management strategy optimization. MSE studies have been used to determine how the stock-recruitment relationship for Pacific sardine (*Sardinops sagax*) changes with SST; based on this, the average SST over the most recent three years is used to establish the sardine quota for the next year (*433*).

For these reasons, MSE is often touted as a solution to meeting current objectives in fisheries management, such as incorporating climate change, ecosystem-based considerations, and the precautionary principle (*424*). MSE use is growing (*424*, *425*) and they have been used to manage fisheries in South Africa for over 20 years (*425*) and are used to set quotas for several species, including anchovy (*Engraulis encrasicolus*), sardine (*Sardinops sagax*), Cape hake (*Merluccius paradoxus*), rock lobster (*Jasus lalandii*), and horse mackerel (*Trachurus trachurus capensis*); (*425*). MSE has also been used to manage a range of species, including, for instance, southern bluefin tuna (*434*), sockeye salmon (*Oncorhynchus nerka*); (*435*), and rock lobster (*436*), and to evaluate a bycatch management rule for seabirds (*437*). In the northeast Atlantic, MSEs have been used to manage Greenland halibut (*438*) and pollock (*Pollachius virens*); (*439*).

Duplisea *et al.* (*440*) introduced a risk-based approach to incorporating climate change considerations into fisheries management in Canada through what the authors refer to as "climate change conditioning of science advice" (CCSA). CCSA requires information on how the environment affects the productivity dynamics of a resource and takes climate change into account when estimating the probability of a management objective being met. The CCSA approach is based on risk equivalency, the concept of making management decisions of equal risk despite differences in, for instance, data availability, resource dynamics, knowledge, assessment methods, and advisory contexts. The equivalency operates by factoring in 'buffers' to the advice such that the recommended activity level decreases with increasing risk. Environmental variable(s), together with a baseline environmental reference(s), are used to track environmental trends and thus condition the risk of resource use on the deviation of the environment from its baseline. Yet, such baselines are notoriously difficult to estimate and interpret due to natural environmental variability and cycles, a lack of long-term observations, and non-stationary dynamics (*441–444*). Estimating such baselines would require a long time series that is notably lacking in many climate and/or fisheries variables in Canada and elsewhere. The authors suggest that information regarding baseline conditions can be derived from experiments of independent studies, yet it is not immediately apparent how this would work. The risk posed by climate change is ultimately represented by a risk profile—often visualized as the human activity to be managed (*e.g.* fishing) versus the probability of meeting a management objective (*e.g.* B/BMSY). The risk profile and associated climate conditioning factor are either estimated or approximated by comparing different model scenarios with varying assumptions about resource dynamics' dependence on the baseline climate conditions. Should the climate conditioning factor be >1, maintaining risk equivalency would require reducing the level of human activity accordingly and vice versa.

Risk-equivalency approaches have been applied in the management of Australian fisheries and in the US (*445*). Still, they are less common than MSE, and their efficacy has yet to be rigorously tested. With good knowledge about the effects of climate change on the dynamics of stock and good long-term data, implementing CCSA appears to be a feasible approach. Yet, such situations are far from the norm, and how CCSA would proceed is unclear. Many fisheries are data-limited, and obtaining reliable long-term time series to derive baseline conditions would be highly challenging, particularly in overfished systems and where synoptic observations were required. Like MSE, CCCA evaluates climate change in terms of risk, but it is unclear what advantages CCCA offers over the more widely used and flexible MSE.

2) **Climate-considered advice:** Two-thirds (66%) of NAFO-managed stocks lack assessment models. In these situations, bringing climate variation and change into the assessment and decision-making process is less well-defined (Appendix 9). Understanding the nature and magnitude of climate

impacts on a fishery and when and where they will arise is of fundamental importance to setting quotas that ensure sustainability. Synthesizing the available climate impact literature for managed species and their environmental niche limits (see above recommendation) would provide vital baseline knowledge that would help understand species' responses to observed and anticipated environmental changes. As suggested by the literature review, species often respond to the environment nonlinearly, and understanding species' environmental limits and optimal values would be valuable in resolving the variable responses of species to environmental variability and change and adjusting management decisions accordingly (*e.g.,* Table 1). Including climate risk assessments (see previous recommendation) as a standard component of NAFO ecosystem, multispecies, and stock assessments would allow for contextualizing advice based on climate impacts. The California sardine, Peruvian anchovy, and Bering Sea snow crab fisheries described under climate variability (below) provide real-world examples of how fisheries harvest control rules can be adjusted to account for changing climate conditions.

3) **Climate variability:** The NAO is a dominant signature of climate variability across the northwest Atlantic, with the lower frequency Atlantic Multidecadal Oscillation (AMO) being of secondary importance (*74*, *75*, *80*, *81*, *446*). The NAO causes abrupt changes in temperature, wind, and other climate fields that have a wide range of impacts throughout marine ecosystems, affecting fisheries. The NAO has low predictability and is poorly represented in climate models, meaning its impacts on fish stocks are difficult to anticipate. Instead, a more dynamic approach to fisheries assessment and management may be needed to incorporate the effects of the NAO and its interaction with climate change on stock productivity. This could involve monitoring the marine environment in real-time to determine the NAO's onset and adjusting the fishing quota on the fly, as dictated by the magnitude and duration of the climate changes and their expected impacts on stocks. This approach is used in other fisheries subjected to similar decadal-to-multidecadal climate variability, such as the Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO). For instance, due to the devastating effects of ENSO and associated warming on anchovy populations in the Humbolt current, Peru closes its fishery during ENSO events to additional fishing mortality (*447*). Marine species in the eastern Bering Sea experience alternating regime shifts driven by the PDO (*448*), and reference points for the snow crab (*Chionoecetes opilio*) fishery are estimated only after a climate shift has occurred (*449*). Likewise, because California sardines (*Sardinops sagax*) are more productive when ocean temperatures are near 17.5°C (*450*), ocean temperature has been incorporated into the harvest rule for sardines such that a larger fraction of the available stock is allowed to be harvested in warmer rather than colder years, though never more than 15% or less than 5% (*24*). Adopting a similar approach in the northwest Atlantic would require a working understanding of the effects of

NAO on particular stocks, real-time monitoring for the NAO onset, and agreed-upon guidelines for adjusting quota during NAO events.

Conclusions: Placing climate in the NAFO context

A climate roadmap

To be successful, these climate considerations must be integrated and harmonized within NAFO management frameworks, cycles, and governance structures, namely the NAFO Roadmap. The Roadmap is designed to guide the transition to an Ecosystem Approach to Fisheries to ensure long-term ecosystem sustainability by incorporating ecological, social, and economic perspectives into fisheries management (*410*). It emphasizes the long-term health and stability of the ecosystem and is objective-driven, requiring clear management goals to achieve it. The Roadmap's key components include identifying ecosystem-based management units for tailored approaches, a hierarchical approach, establishing exploitation rates at ecosystem, multispecies, and stock levels, ensuring sustainability across these scales, and considering the effects on non-target species and benthic communities (Figure 7). The NAFO governance structure includes a Scientific Council (SC) that provides scientific advice and a Commission (COM) that makes management decisions. The roadmap evolves through stages, with the SC providing science support to COM by undertaking ecosystem state assessments (Tier 1), multispecies assessments (Tier 2) and fisheries stock assessments (Tier 3). The following explores how the various recommendations outlined above could integrate within the Roadmap.

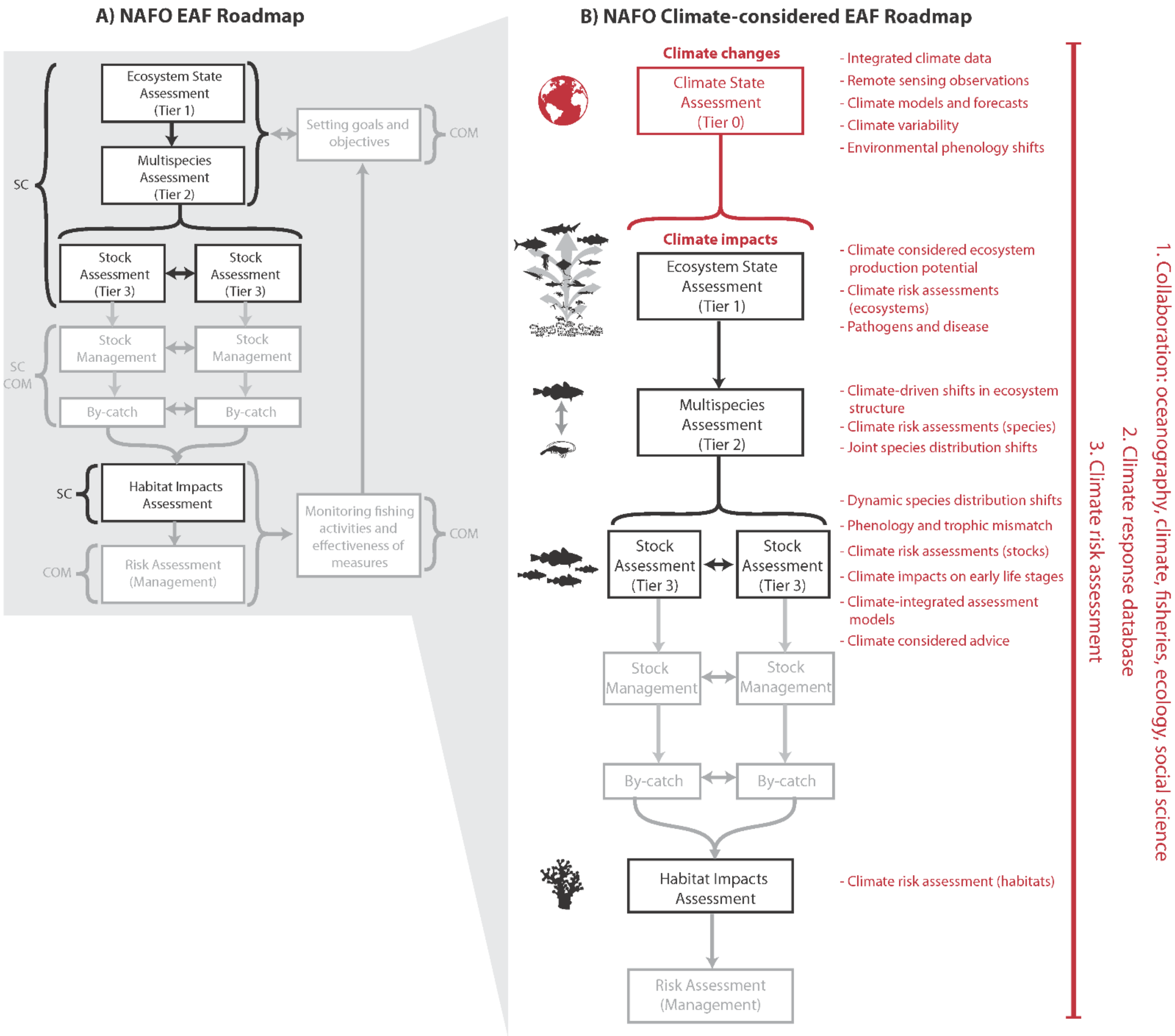

Figure 7. NAFO climate considered EAF roadmap. Current working template of the NAFO Roadmap (A) and steps to enhance its climate readiness (B; red text). SC: Scientific Council; COM: Commission.

Climate state assessments

Adding a Climate State Assessment as an overarching Tier (Tier 0) to the Roadmap would provide foundational climate information and data supporting the integration of climate variability and change into the ecosystem and fishery assessment and management processes at Tiers 1-3. Such an assessment would incorporate suggestions related to climate data products, including developing integrated data products of key oceanographic variables (*e.g.,* surface and bottom temperatures, dissolved oxygen, chlorophyll) to evaluate climate trends, evaluating indices of changing phenology, assessing the onset and magnitude of climate variability (*e.g.,* the NAO and AMO), and forecasting or projecting how climate conditions will evolve over time. While the report would describe the past, current and future climate state across the NAFO area, a vital contribution would be the generation of integrated, quality-checked, and ready-to-use climate data products that could be deployed in other SC Roadmap assessments (*e.g.,* Tiers1-3).

The International Council for the Exploration of the Seas (ICES) produces an annual report on ocean climate conditions across the North Atlantic (*451*), providing an example of how such an assessment could be developed within the NAFO Roadmap. The ICES reports on ocean climate (IROCs) combine historical ocean observations to describe ocean conditions, trends and variability across the North Atlantic Ocean and summarize and distribute the climate data in an interactive, easy-to-use, publicly available web platform[2]. While the IROCs focus on historical data and trends, a NAFO analogue ideally includes forecasted or projected trends.

Climate impacts on NAFO ecosystems and stocks

Within the ecosystem assessment (Tier 1), climate data from the climate state assessment should be used to understand how ecosystems respond to climate variation and change and how forecasted or projected climate changes may affect ecosystem productivity and catch limits for the ecosystem unit. Studies suggest that ocean biogeochemical provinces that shape biodiversity and constrain ecosystem structure and fisheries productivity will shift under ongoing climate change (*219*), meaning that the ecosystem production units used within the Roadmap should also be monitored to detect climate-driven productivity shifts and adjust fisheries quota accordingly. Geographic patterns of ecosystem climate risk could be assessed and monitored using approaches such as the Climate Risk Index for Biodiversity (CRIB), which also allows for future climate scenarios and their ecological impacts to be evaluated (*33*, *34*). Catch limits for the ecosystem unit could be adjusted depending on climate-driven productivity shifts, following the approach of other fisheries (*24*, *447*, *449*). Climate-driven shifts in disease and pathogens could also be monitored and assessed, for instance, using eDNA, within the ecosystem assessment (*452*, *453*).

Within the Roadmap, multispecies assessments (Tier 2) are a means of understanding species interactions and trends, the role of anthropogenic and environmental drivers on ecosystem structure and dynamics, and defining multispecies reference points (*410*). Climate data from the climate state assessment provides a means of exploring climate variability and change on multispecies dynamics and adjusting reference points accordingly. Dynamic joint SDMs could be used to examine climate-driven shifts in species distribution time (*413*), while climate risk assessment could evaluate spatial patterns in climate risks at the species level with an aim to mitigating them (*e.g., 33*). The impacts of shifting environmental phenology on species interactions (*e.g.* trophic mismatch); (*146*, *454*) could likewise be explored at this level. Fisheries and ecosystem models are becoming increasingly detailed and reliable and could be explored as a way of resolving the effects of projected or forecasted climate changes on the biomass of exploited species and ecological interactions (*455*–*457*).

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[2] ICES Oceanography - IROC

In the Roadmap, single species assessments (Tier 3) form the basis for stock-specific catch levels based on Tiers 1-2. Stock assessments represent the most detailed examination of trends and drivers in fish populations, and several recommendations discussed previously fall under their purview, including evaluating past and anticipated distribution shifts *(e.g.* dynamic SDMs), phenology, trophic mismatch and its effects on recruitment, climate impacts on early life stages, climate risk analyses at the level of individual stocks, and developing climate-integrated assessment models. In particular, evaluating climate impacts on each stock as a standard assessment practice would be a meaningful way to support climate-informed assessment and advice, particularly for the 66% of NAFO stocks that lack assessment models. Such an impact assessment would interpret population dynamics in the context of climate trends reported in the climate state assessment (Tier 0), integrate the available knowledge from the suggested climate impact database, and include a standardized climate risk assessment carried out for each stock, such as has been undertaken using the CRIB framework (*34*, *402*). Such vulnerability and risk analyses have been widely promoted as a means of developing climate-informed fisheries advice and are included as a priority in the Fisheries Climate Science Strategy of the US NMFS as a tool to inform research and management activities related to understanding and adapting marine fisheries management to climate change (*25*).

Overarching considerations

While fisheries scientists have traditionally been solely responsible for assessing stock status and providing advice, the Roadmap's objectives around EAF and integrating climate considerations within it are multidisciplinary, requiring expertise from climate scientists, oceanographers, ecologists, fisheries experts, and eventually social scientists. Climate considerations pervade the Roadmap, and thus, including oceanographers and climate scientists at each level (Tiers 0-3) would help support its integration into the assessment and management process.

Integrating climate considerations into the Roadmap will require a solid evidence base - a high-level understanding of the pathways by which climate operates on species, populations, and ecosystems. A climate impacts database synthesizing the current state of knowledge regarding climate changes and their impacts on NAFO species and stocks and regular climate risk assessment at the species and ecosystem scales would help support this process across all Tiers. Climate vulnerability and risk assessments can supplement this knowledge, providing objective evaluations of how the likelihood of climate impacts varies taxonomically and geographically and if and how it could be managed.

While including ecosystem considerations in the Roadmap requires broadening the taxonomic scale of consideration, including climate considerations will require enhanced consideration in the time domain of the assessments. Further, climate change can interact with seasonal and basin-scale climate variability to create large, abrupt climate changes. NAFO assessment cycles must respond dynamically to meet these challenges and thus be carried out annually.

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