# Challenges to transboundary fisheries management in North America under climate change

[THIRD DRAFT]

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## Abstract

Climate change is shifting the distribution of fish stocks that straddle between Exclusive Economic Zones (EEZ), challenging transboundary fisheries management. In this paper, we examine the projected sharing of jointly managed transboundary fish stocks between the EEZs of Canada and the United States. We hypothesize that ocean warming will alter the sharing of fish stocks between the two countries, and that such changes will intensify under a high carbon emission scenario impacting the stock-share ratio of different stocks. Firstly, we projected changes in potential catch of 33 transboundary stocks of North America in the 21$^{st}$ century based on multiple Earth system models' simulations and species distribution models, under two climate change scenarios. We then look at the specific cases of the International Pacific Halibut Commission that manages pacific halibut (*Hippoglossus stenolepis*) and a resource sharing agreement in the Gulf of Maine for cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and yellowtail flounder (*Limanda ferruginea*). Results show that, even under a low emission scenario, most transboundary fish stocks sharing ratios, i.e., the proportion of the total catch of a fish stock taken by a given country, will change by 2050 relative to present in the direction as expected from the effects of ocean warming. The overall reduction in catch potential, in addition to the changes in stock-share will further exacerbate trade-offs between changes in species catch potential. Such trade-offs in the Atlantic and Pacific regions will be amplified if a high emission scenario is followed, relative to a low carbon emission scenario. Our paper highlights the challenges that transboundary fisheries management will face as species shift their current distribution under a changing climate.[1]

Keywords: *Transboundary fisheries management; climate change; joint fisheries management; species distribution shift*

# INTRODUCTION

Transboundary fisheries are defined as fish stocks that move freely between (*i*) Countries economic exclusive zones (EEZs) and (*ii*) between EEZs and the high seas (also called straddling stocks) (Song et al. 2017a). The management of transboundary stocks can be analized using game theory, as often, success depends on effective cooperation between parties (Miller and Munro 2002, Sumaila 2013). Therefore, in 1985, the United Nations incentivized actions to cooperate on the management of transboundary fisheries through the Law of the Seas (UNCLOS) (United Nations 1986). Today, an estimated 347 (Teh and Sumaila 2015) to 1500 (Caddy 1997) fish stocks cross national borders, some of them jointly managed by two or more countries. These stocks are responsible for almost 50% of these countries total fish catches (Teh and Sumaila 2015). Transboundary stocks such as salmon (*Oncorhynchus spp.*), Pacific halibut (*Hippoglossus stenolepis*), and Atlantic cod (*Gadus morhua*) are of utmost importance for Canada and the United States (US). Management of these stocks is extremely hard due to the participation of several fishing "players", different countries and sometimes jurisdictions within a country, the migration patterns of the stock, and their abundance fluctuation within space and time (Miller and Munro 2002).

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The ocean is getting warmer (Rheim et al. 2013), less oxygenated (Schmidtko et al. 2017), and increasing in acidity (Ross et al. 2011). To cope with these changes in ocean biophysic properties, marine species, including transboundary fish stocks, have been shifting their distribution towards the poles and/or deeper waters (Poloczanska et al. 2016). As climate change reshapes the ocean's environment worldwide (Gattuso et al. 2015), transboundary fisheries' delicate governance is threatened as new migration patterns may arise (Miller et al. 2013, Pinsky et al. 2018), historic distribution and abundances might shift (Cheung et al. 2010), and species basic natural traits may modify (Pauly and Cheung 2018). Catches of shared stocks like tropical tunas, have significantly increased in subtropical regions of the Atlantic and western Pacific Oceans (Monllor-Hurtado et al. 2017). Multiple transboundary species in North America have been observed to shift in distribution following changes in optimal conditions such as sockeye salmon (*Oncorhynchus nerka*) (McDaniels et al. 2010), Atlantic cod (Pershing et al. 2015), and flounders (Pinsky and Fogarty 2012). Moreover, these shifts are projected to continue towards the end of the 21$^{st}$ century (Cheung 2018) at a rate of tens to hundreds of km and/or tens of meters per decade towards the poles and/or deeper waters, respectively, although there will be regional variations (Morley et al. 2018). As a result, some countries or management jurisdictions may see more transboundary stocks and their catches shifting into their waters while others will stand to lose (Miller et al. 2013, Pinsky et al. 2018). Nevertheless, management rules for shared stocks (e.g. quota or spatial delimitation) are often determined based on current and historic knowledge of the stock's distribution and do not consider future shifts in distributions (Fredston-Hermann et al. 2018). In addition, many international treaties do not directly consider climate change in their management scheme, despite evidence of target species shifting their distribution.

The shifts in distribution of transboundary fish stocks would impact the economics of their fisheries (Sumaila et al. 2011, @Sumaila:2019gh, Pinsky and Fogarty 2012, Lam et al. 2016), and create international disputes in the sharing of fish stocks between nation's EEZs (Miller and Munro 2002, Spijkers and Boonstra 2017). As climate change alters the sharing of fish stocks between countries to an extent that is beyond historical changes, existing policies and governance structures may not be able to cope with these changes. Consequently, countries may not be satisfied with the sharing or allocation of access to resources, leading to international disputes (Pinsky et al. 2018). Disputes over Pacific salmon between Canada and the US arose in the 1990s because of climate-related changes in stock abundance and migratory behavior (Miller and Munro 2002, Miller et al. 2013, Song et al. 2017b). Currently, Europe is involved in an unsolved dispute over *Scomber scombrus* known as the "mackerel wars". The conflict erupted in 2007 when the stock shifted their distribution from the Norwegian Sea towards northern and western regions of the Nordic Seas, consequently spreading into Iceland's national waters (Spijkers and Boonstra 2017).

Transboundary fisheries between Canada and the US offer a unique lens to understand the extent to which climate-induced distributional shifts will challenge the future sustainability of these fisheries. Canada and the US have a long history of fisheries cooperation (Song et al. 2017b). They participate in diverse, jointly managed, commercial transboundary stocks through various fisheries management organizations (Merten 2015). Cooperation schemes vary by fisheries stocks, regulatory areas, legal terms of agreement, and management measures, among others (Fig. 1). In the Atlantic coast, Canada and the US are part of the Northwest Atlantic Fisheries Organization (NAFO) that oversees the management of 19 stocks of 11 transboundary species (although around 41 taxa are fished within Canadian and US waters) from southern Gulf of Maine to Greenland[2]. Within NAFO's region 5Z, Canada and the US have a "Resource Sharing Understanding" (hereafter referred to "GoM agreement") to set catch-limits of Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and, yellowtail flounder (*Limanda ferruginea*) (Soboil and Sutinen 2006, CIA 2017). In the Pacific coast, Pacific halibut (*Hippoglossus stenolepis*) is managed under the International Pacific Halibut Commission (IPHC) (IPHC Secretariat and Gustafson 2017). All five salmon species (chinook, *Oncorhynchus tshawytscha*; chum, *O. keta*; coho, *O. kisutch*; pink, *O. gorbuscha*; and sockeye *O. nerka*), are managed by the Pacific Salmon Commission (PSC 2017). Finally, under the Pacific Whiting Treaty, Canada and the United states jointly manage the coastal stock of this Pacific hake species (*Merluccius productus*) (Merten 2015).

It is expected that climate induced shifts in stock distribution affect the rules in place that keeps these treaties alive. Therefore, the main objective of this paper is to assess the level of exposure of international

[2]Northwest Atlantic Fisheries Organization, Available at https://www.nafo.int/Science/Species

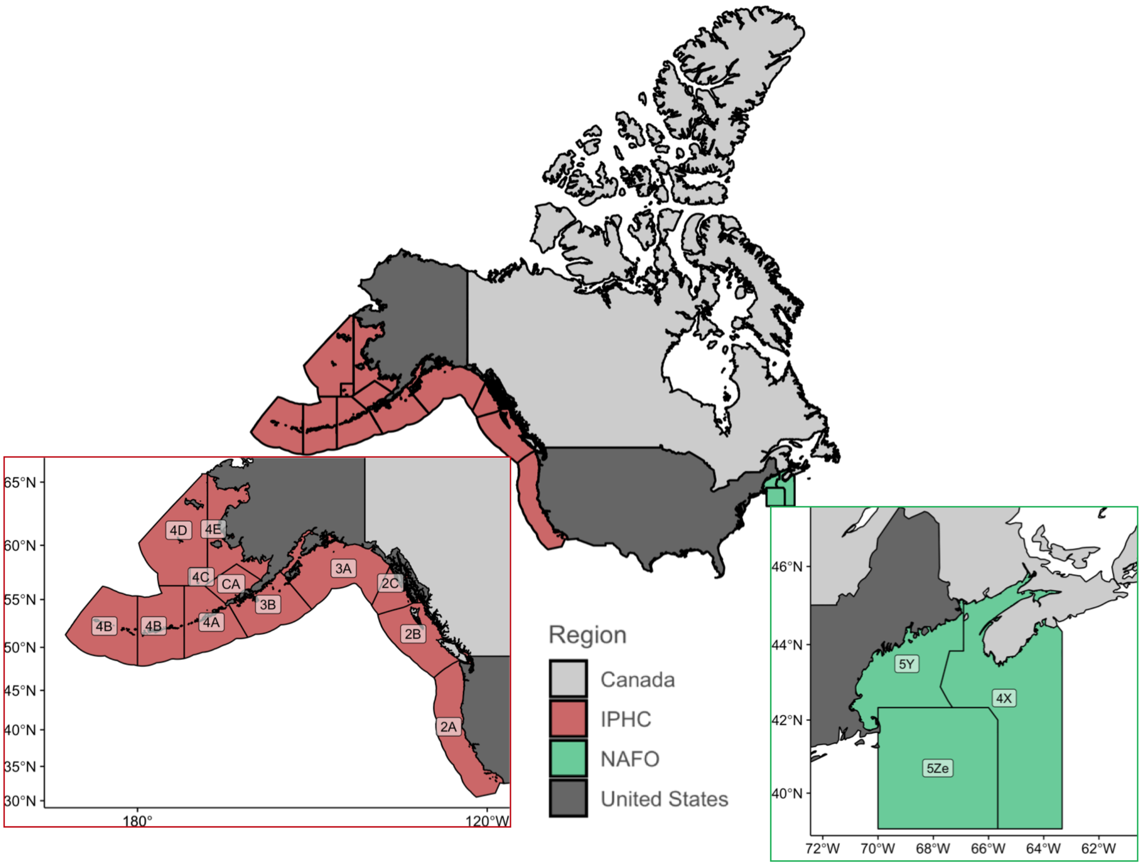


Figure 1: Map of North America with the regulatory areas of the IPHC and the NAFO sub-region related to the Gulf of Main agreement

Table 1: Treaties and number of species included in the current analysis.

| Treaty | Species | Coast |
|---|---|---|
| International Pacific Halibut Coomission (IPHC) | 1 | Pacific |
| Pacific Salmon Coomission (PSC) | 5 | Pacific |
| Pacific Whiting Treaty (PWT) | 1 | Pacific |
| Northwest Atlantic Fisheries Organization (NAFO) | 26 | Atlantic |
| Gulf of Main's Agreement (GoM Agreement) | 3* | Atlantic |

[a] *These species are also part of NAFO

fisheries management treaties between Canada and the US to climate change impacts through shifts in stock distributions. Specifically, we rely on a species distribution model and scenario planning to project the changes in the distribution of 33 fish stocks jointly managed by Canada and the US. Moreover, we use two specific treaties as case studies (IPHC and the GoM agreement) to explore the potential impacts that climate change will have on selected transboundary fisheries management. Finally, we explore similar situations around the world and identify opportunities to improve the adaptability of transboundary fisheries management to climate change in North America. Despite an overall expectation of species following a poleward shift, important geographic features (e.g. Gulf of Alaska representing a latitudinal block), geo-political (e.g. the localization of Alaska in reference to Canada and the contiguous states), and management rules (e.g. quota allocations, spatial management rules) may play an important role in the redistribution of benefits. Understanding these stocks shifts will shed a light on future conditions and inform decision makers on the paths to follow under a changing climate.

# METHODS

### Study Area and Fisheries

The current study focuses on transboundary fisheries jointly managed by Canada and the US for both the Atlantic and the Pacific coasts. The analysis was carried out within the 200 nautical miles of both nation's EEZ from the Gulf of Mexico to The Labrador Sea in the Atlantic, and from California to Chukchi Sea, in the Pacific coast (Fig. 1). Subsets of the total area were carried for both the IPHC and the Gulf of Maine agreement. For the IPHC, we used the most updated spatial regulatory data provided by the Commission (IPHC Secretariat and Gustafson 2017). For this specific case, we considered Alaska as a separate entity, the US contiguous states as a second one (Washington, Oregon and California), and lastly British Columbia (Canada). For the GoM agreement we used NAFO's divisions 5Y, 5Ze, and 4X within latitudes 46.2°N and 41.5°S, and longitudes -72°W and -64°E (Fig. 1).

The species analyzed (**Table A2.1**) were selected based on five treaties in both the Atlantic and Pacific coast of North America (Table 1). All species under the IPHC, PSC, WT, and the GoM agreement were analyzed as these treaties are management agreements between Canada and the US. However, in the case of NAFO, their management covers over 41 taxa and its governance extends to international waters and the EEZ of Greenland. Therefore, a subset of 26 species reported was made based on those fished in NAFO regions that fall within the EEZs of Canada and the US (NAFO subareas 2's, 3's with the exception of 3M and 3N and limited to the EEZ, 4's,5's and 6 A,B, and C.) (Northeast Atlantic Fisheries Commission n.d.). Data related to fisheries was gathered from the *Sea Around Us* from 1951 to 2014 (Zeller et al. 2016).

### Projecting Future Species Distribution

We used a Dynamic Bioclimatic Envelope Model (DBEM) to project the distribution of species from 2015 to 2100, under two scenarios of climate change (Cheung, Jones, Lam, et al. 2016, Cheung, Jones, Reygondeau, et al. 2016). The DBEM algorithm integrated ecophysiology, habitat suitability with spatial population dynamics of exploited fishes and invertebrates to project shifts in abundance, and potential fisheries catches under climate change. The algorithm predicted species distribution based on depth range, latitudinal range, habitat preferences and an index of species association with major habitat types to estimate changes in abundance distribution over a 0.5' x 0.5' grid of the world oceans. For each grid cell and time step, the model then calculated species carrying capacity according to sea surface temperature, salinity, oxygen content, sea ice extent (for polar species) and bathymetry, as well as the species preferences to these conditions. It then incorporated the intrinsic population growth, settled larvae, and net migration of adults from surrounding cells using an advection-diffusion-reaction equation. Finally, the model also simulated the effects of changes in temperature and oxygen content on growth of individuals (Cheung et al. 2013). Ultimately, the model simulates spatial and temporal population dynamics, and estimates a proxy of maximum sustainable yield (MSY) by applying fishing at MSY level for each grid cell, hereafter referred as maximum catch potential (MCP).

The DBEM was projected using three earth system models (ESM), the Geophysical Fluid Dynamics Laboratory Earth System Models 2M (GFDL)[3], the Institute Pierre Simon Laplace Climate Model 5 (IPSL-CM5)[4], and the Max Planck Institute for Meteorology Earth System Model (MPI)[5]. Each model was downscaled to match the DBEM 0.5' x 0.5' grid using the nearest neighbor method, and in some cases, bilinear interpolation (Cheung, Jones, Lam, et al. 2016). Finally, we used the model outputs for two scenarios of the Intergovernmental Panel on Climate Change (IPPC)-Representative Concentration Pathways (RCP); 2.6 (RCP 2.6) and 8.5 (RCP 8.5) representing a low greenhouse gas emission (strong mitigation) and a high greenhouse gas emission (business-as-usual) scenario, respectively (IPCC 2014). To estimate model robustness and capture the structural uncertanty build within ESM models we averaged the DBEM results for all three models ($\mu \acute{s} \sigma$) and marked regions where at least one ESM disagree with the rest.

## Estimation of Maximum Catch Potential Change

For estimating the percentage change of MCP at the regional scale, we frst aggregated the yearly mean MCP of all species per region ($X_{ry}$) and period:

$$X_{yr} = \sum_{s=1}^{n} M\hat{C}P_s$$

where $y$ is year, $r$ is region, $s$ is species, $n$ is total number of species, and $M\hat{C}P$ is the MCP averaged by the three ESMs. In the case of North America and the GoM agrement, region is defined as the 0.5' x 0.5' grid-cell within the EEZ and the specific NAFO regulatory areas, respectiveley. For the IPHC analysis, region is defined as the comission's regulatory areas (Fig. 1). We then average the values in three time periods ($t$) to reduce temporal model sensitivity. Thus, we computed the regional percentage change in MCP ($\Delta MCP_r$) as follows:

$$\Delta MCP_r = -(1 - \frac{X_t}{X_{t0}}) * 100$$

where $X_t$ is the future agregated MCP for two periods, $t_1$ = mid 21$^{st}$ century (2045-2055); and $t_3$ = end of 21$^{st}$ century (2090-2099), and $t_0$ is the present aggregated MCP ($\mu$ 2005-2014).

In addition, we borrowed the concept of "threat point" from game theory (see Sumaila et al., this Volume) and estimate the change in the $M\hat{C}P$ that each country would have for each species (hereafter referred as stock-share ratio), for both the IPHC and the GoM agreement. For this, we first modify equation 1, to estimate the aggregated yearly mean MCP of each species per region. We then average the results by the same previouslly metioned periods (present, mid and end of the 21$^{st}$ century). Next, for each species we estimated the stock-share ratio ($\alpha$) that each region had during each time period:

[3] More information related to the Geophysical Fluid Dynamics Laboratory Earth System Models 2M can be found at www.gfdl.noaa.gov

[4] More information related to the Institute Pierre Simon Laplace Climate Model 5 can be found at www.icmc.ipsl.fr/

[5] More information related to the Max Planck Institute for Meteorology Earth System Model can be found at www.mpimet.mpg.de/en/science/models/

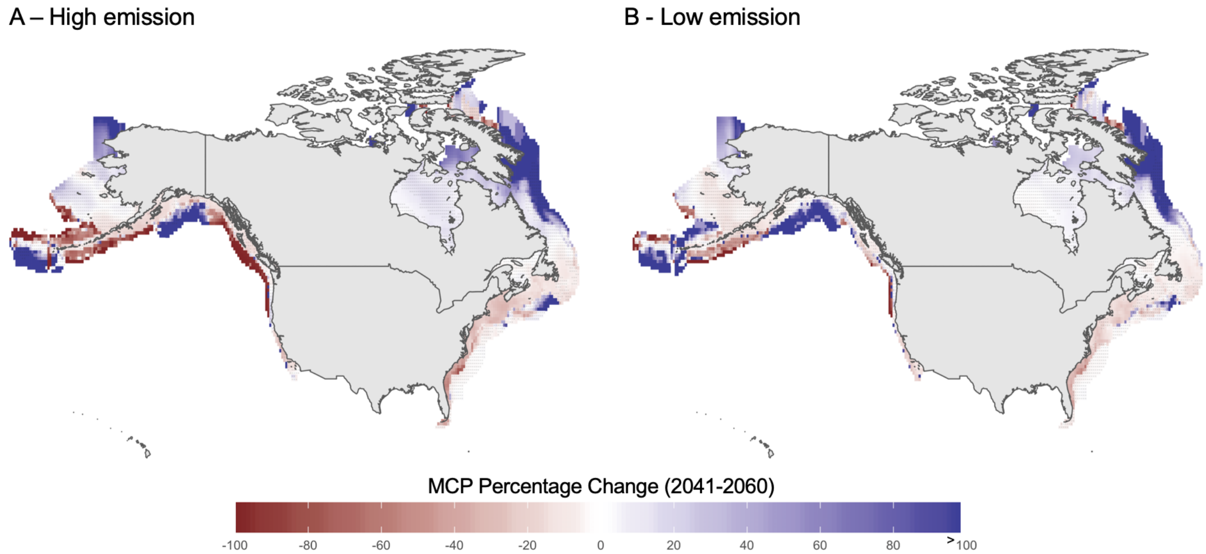


Figure 2: Percentage change of MCP of transboundary fisheries of North America for mid century (2046-2055) referent to 2005-2014 under a A) low emission scenario and; B) high emission scenario.

$$\alpha_{ts} = \frac{\theta_{rt}}{\delta_{ts}}$$

where $\theta_r$ is the aggregated $M\hat{C}P$ of each region, and $t$ is period. Finally, we estimated the percentage change in stock-share ratio substituting $X_f$ and $X_p$ by $\alpha_{fs}$ and $\alpha_{ps}$, respectively in equation 2.

# RESULTS

### North American transboundary fisheries are shifting poleward

Shifts in the distribution of 33 jointly managed transboundary stocks of North America show that by 2050 maximum catch potential (MCP) of transboundary stocks will increase in Atlantic-Canadian and Alaskan waters and decrease in Pacific-Canadian and the US contiguous states (Fig. 2). Despite the overall trend, such changes will be less intense under the low emission scenario (Fig. 2-A). Under the high emission scenario, MCP will be reduced in a larger area and with greater intensity (Fig. 2-B). Such changes are expected to intensify towards the end of the 21st century, although with greater uncertainty (**Fig A1.1**).

In consequence, country's share-ratio of different species would change in the direction as expected from the effects of ocean warming, regardless of the RCP scenario. Overall, shifts will be amplified under the high emission scenario relative to the low greenhouse emission scenario pathway (Table 2). While in 2050, the average shift of species will be higher for East Canada and lower for East US under the high emission scenario, the stock-share ratio of some species is expected to increase more than 50% as in the case of Atlantic menhaden (*Brevoortia tyrannus*) in Eastern Canada, and decrease by more than 50% for species such as Cusk (*Brosme brosme*) in the Eastern US under a low emission scenario. By the end of the 21$^{st}$ century, losses will intensify with the eastern US potentially losing on average 15.2% or 46% of stock-share, depending on the scenario.

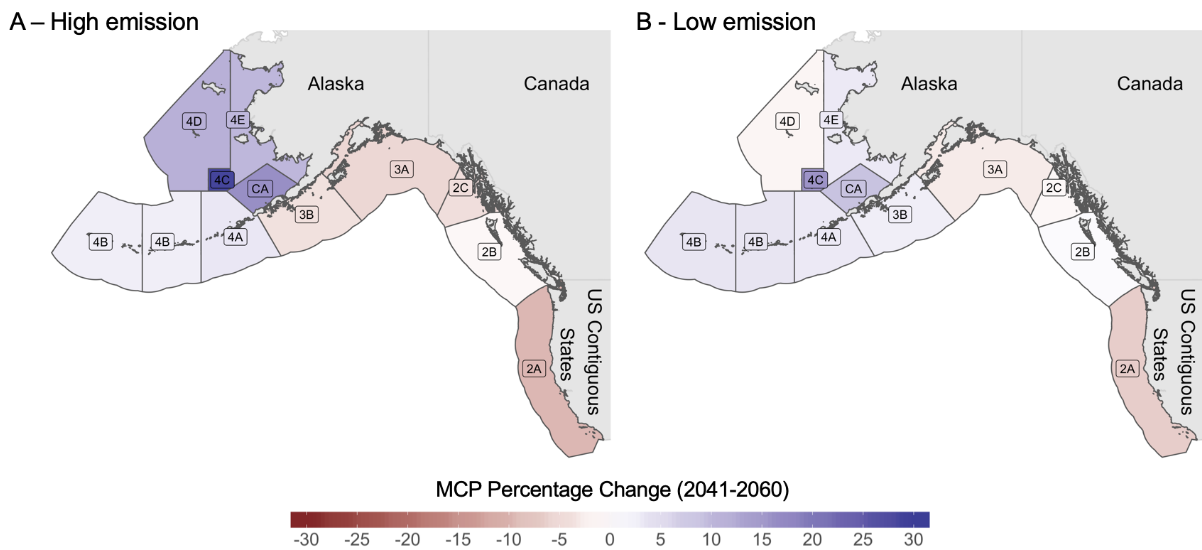


Figure 3: Percentage Change of MCP for Species managed by the IPHC. A, RCP 2.6 represents a low emission scenario (high mitigation). B, RCP 8.5 represents a high emission scenario (status quo)

**Projected change to species managed by the IPHC**

Even under a low emission scenario, most transboundary fish stocks sharing ratios will change by 2050 in the direction as expected from the effects of ocean warming. However, such changes will vary depending on the species, resulting in management consequences related to the rules placed by the different treaties. In the case of the IPHC, at least three of the 12 regulatory areas will see a reduction in MCP of Pacific halibut by 2050 in reference to current MCP of each area, regardless of the climate change scenario (Fig. 3). Poleward shifts might be constrained by the geopolitical position of countries, as well as geographic design of the coastline. It is likely that the stock shift from the US contiguous states towards Canada will offset the shift of the former towards northern regions, resulting in undetectable changes in areas 2B and 2C. Similarly, to the potential increase in MCP of regulatory areas 3B and 4ABCE along the Aleutian Islands and Bering Sea.

The same poleward trend is expected in the change of Pacific halibut stock-share ratio with the average proportion increasing up to 25% in some northern regions and decreasing by 10% in southern regions, in relation to the present proportion (Fig. 4). Maintaining emissions to lower levels by 2050 would potentially leave unchanged the stock-share ratio of three regulatory areas (3AC, and 4D) and negatively change regulatory area 2A. On the other hand, failing to achieve such target will decrease the stock-share ratio almost half of the regulatory areas (2AC, 3AB).

**Projected change to species managed under the GoM agreement**

While some regulatory areas of the IPHC will see increments in species' MCP, the results for the Gulf of Maine (NAFO area 5Z) show an overall decrease in MCP by 2050, depending on the climate change scenario. MCP of cod and haddock will decrease within the whole Gulf with no apparent win for any country in reference to 2014 (Fig. 5). For yellowtail flounder, some discrete areas are expected to increase with no particular pattern. Despite the overall reduction in MCP in comparison to current values, there is a benefit of achieving a low emission scenario, as reductions intensify under the high emission scenario.

Despite the expected decrease in MCP for the region, changes in the stock-share ratio of MCP for the Gulf of Maine show different outcomes depending on the species in question. Following the high emission path will

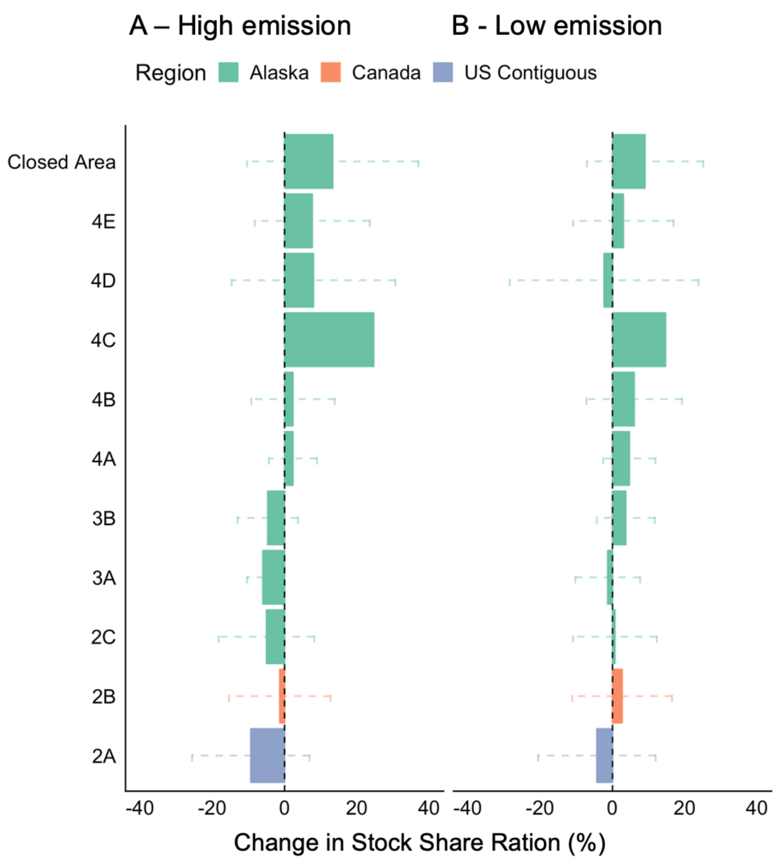


Figure 4: Percentage change of stock-share ratio for IPHC under A) low emission scenario and B) high emission scenario for mid century (2046-2055) referent to 2005-2014.

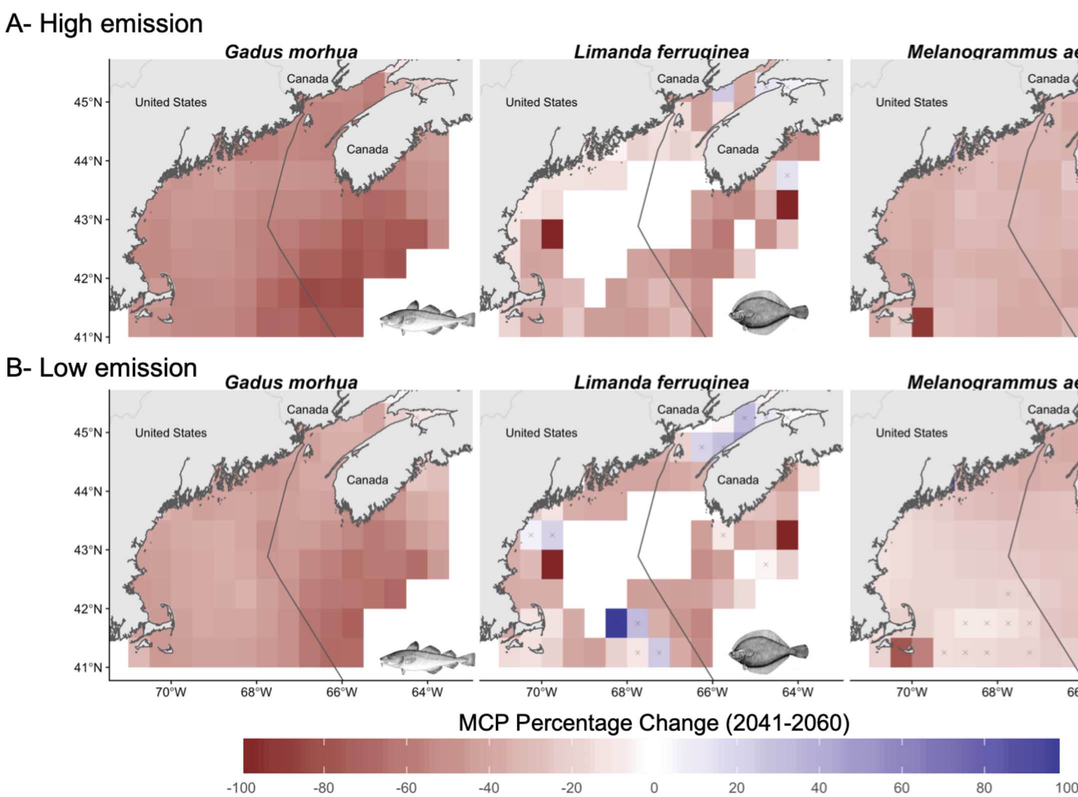


Figure 5: Percentage change of MCP in the Gulf of Main under, A) low emission scenario; and B) high emission for mid century (2041-2060) referent to present (2005-2014)

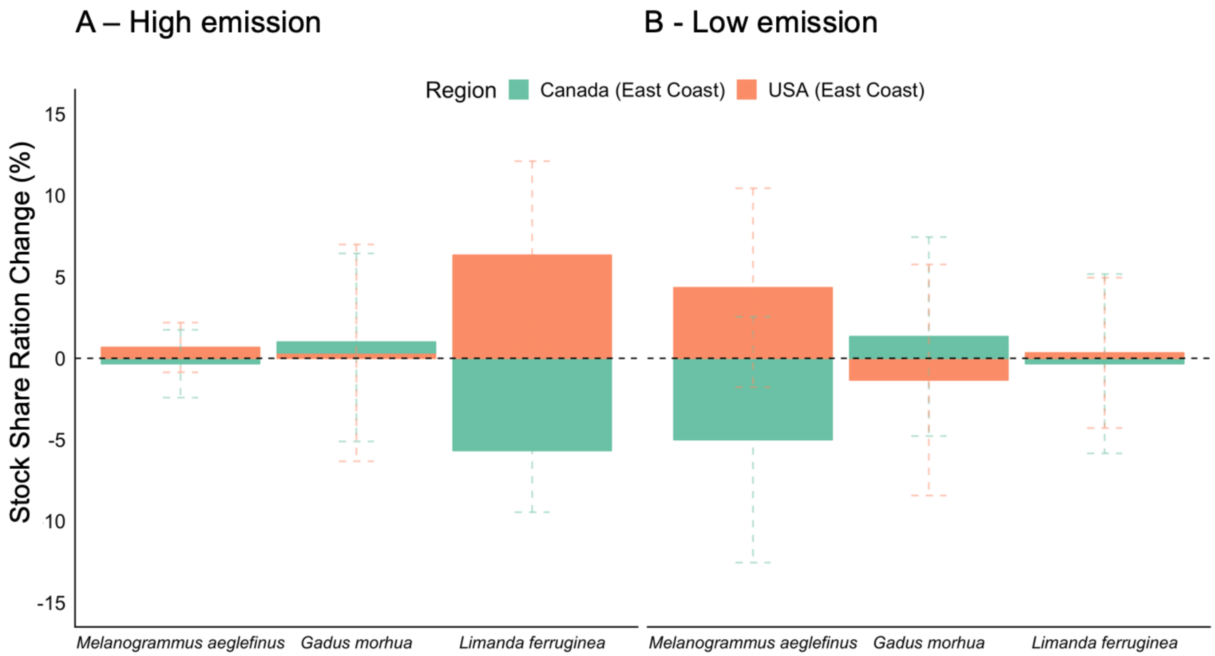


Figure 6: Changes in MCP stock-share ratio for Gulf of Main under (A) low emission scenario; and (B) high emission for mid century (2041-2060) referent to 2005-2014

affect mostly Canada's share of Y. flounder and in less degree Haddock, with an increase of Cod share. For the low emission scenario, patterns somehow invert with Canada losing a larger share of Haddock versus Y. flounder, while increasing Cod's share (Fig 6).

# DISCUSSION

The results of the present study suggest that, by 2050, climate change will alter the MCP of 33 transboundary fish stocks in North America consequently altering Canada's and the US's species' stock-share ratio. For some species, such changes will intensify under the high emission carbon scenario while for others, the change will be scenario depending. These results are aligned with global (Cheung et al. 2010) and regional (Morley et al. 2018) projections suggesting that climate change will push marine species towards the poles and deeper water (Pinsky et al. 2013) in search of their ecological niche (Poloczanska et al. 2016). Moreover, poleward shifts in Eastern Atlantic off the coast of the US have been previously recorded for American lobster (*Homarus americanus*), summer (*Paralichthys dentatus*) and yellow flounders, and red hake (*Urophycis chuss*) from North Carolina to Main (Pinsky and Fogarty 2012). Our models suggest that shifts will continue towards the end of the 21$^{st}$ century resulting in changes in the proportion of the catch of important shared stocks between Canada and the US. As the effects of climate change endure, even with high mitigation, joint plans should prepare to face changes in the stock-share ratio of transboundary stocks along the coast of North America.

Geographic barriers (Cheung et al. 2015), local temperature gradients (Pinsky et al. 2013), species interactions and human activities like fishing (Serpetti et al. 2017) might change the rate and direction of species shifts. Species such as haddock in the Atlantic (Morley et al. 2018), and big skate (*Raja binoculata*) in the pacific coast (Pinsky et al. 2013) have been projected to shift away from the poles. In this manner, the stock-share gain of yellow flounder and haddock by the US in the GoM (Fig. 5) and the westward increase of stock-share in IPHC regions (Fig. 4) could be a response to a temperature gradient shift, combined with geographic barriers, rather than latitudinal shifts. In recent years, Maine has seen its landings of Y. flounder increased at the expenses of southern states like New York (Pinsky and Fogarty 2012). Moreover, previous studies have found that under the low emission scenario, haddock is expected to stay at lower latitudes, contrary to what would happen under a high emission scenario (Morley et al. 2018). Finally, the Gulf of Main is deeper at southern latitudes, hence, some fish are predicted to move south (Kleisner et al. 2016, Pinsky and Selden 2017). These particular cases could explain the US gain in MCP in the GoM in relation to Canada as species shift their distribution from lower latitudes naturally reaching the US (lower) region first, and towards colder and deeper waters located at southern latitudes of the Gulf. At the same time, in the North West Pacific region, species can only migrate northward into the Arctic Ocean through the Bering Sea and Bering Strait (Cheung et al. 2015), potentially pushing pacific halibut west of region 3A. This westward displacement could represent a potential loss for both nations as the Gulf of Alaska is historically the most productive region of the fishery (IPHC Secretariat and Gustafson 2017), and potential international conflict as the stock migrates to the high seas or even reach other westerly countries' EEZ.

The shifts in the distribution of transboundary species can jeopardize management objectives such as, conservation measures, gear operation, and quota allocations. Hypothetically, fish moving out of fishing grounds and into protected areas could result in a pressure increase to open such area to fishing. Shifting stocks could also interfere in gear-limitation management rules. Bycatch of halibut by other fisheries happen mostly on areas 3A and 4B (NOAA 2013, IPHC Secretariat 2017). Moreover, in past years, the Alaskan trawl fisheries have been closed before reaching annual quota due to the attainment of halibut bycatch quota limits (Karim et al. 2010). Although not assessed in the present study, some trawling target species like Pacific cod (*Gadus macrocephalus*) are expected to move in similar direction than P. halibut (Pinsky et al. 2013). Conflicts between fleets already exists and could be extrapolated if the situation is not foreseen (Van Der Voo 2016). The overlap of target species could be addressed by applying ecosystem-based management and dynamic management tools (Hazen et al. 2018) to manage these fisheries and reduce potential lost of sustainable harvest for both the halibut and the trawl fisheries.

Quota allocation ruled by historic distributions will most likeley be outdated. Changes in the proportion of the quota have created tension between countries (Spijkers and Boonstra 2017) including Canada and the US in the case of the Pacific salmon (Miller and Munro 2002, Miller et al. 2013, Song et al. 2017b). Poleward shifts along the coast of Oregon, Washington and British Columbia (Canada) were first addressed by the IPHC in 1985 (McCaughran and Hoag (1992)). Changes in the distribution of the stock resulted in an adjustment in the quota allocation method, from a fixed quota allocation to a dynamic one. As climate change continues, these shifts are not expected to stop, and treaties should be flexible enough to cope with the pace and magnitude of change in order to achieve sustainable harvest under a changing climate.

Side payments have been previously used to address changes in species distribution due to environmental forcings. In game theory, a side payment is received by a player as a compensation from the other player, with the idea that keeping cooperation is still better than playing solo (Bjørndal and Munro 2012, Sumaila 2013). Side payments do not have to be in monetary form and are widely used in transboundary fisheries around the world. For example, Norway and Russia have implemented a quota swap strategy for jointly managed stocks of cod, haddock and capelin in the Barents Sea.[6] The adaptation of a similar agreement could help the management of fisheries in the Gulf of Main. Another example is the Nauru Agreement (PNA), responsible for managing the world's largest sustainable skipjack tuna (*Katsuwonus pelamis*) purse seine fishery.[7] The PNA has a system of internationally tradable fisheries access that allows members to adapt to the effects of the El Niño Southern Oscillation (Aqorau et al. 2018). While this is a good way to address climate variation within members of a treaty, it might fall short to address the newcomer issue, a situation that can threaten the sustainability of the stock (Pinsky et al. 2018). A combination of the methods employed by PNA with the proper modification to incorporate new fishing nations could help mitigate future conflicts in fisheries like the Pacific halibut. Finally, It has been suggested that agreements that make cooperation the preferred strategy for all players are stronger. However, the level of government at which negotiations are held can directly impact management outcomes, as low-level agreements might lack proper penalties for

[6] Joint Fish, joint Russian-Norwegian Fisheries Comission available at http://www.jointfish.com/eng/THE-FISHERIES-COMMISSION/HISTORY.html

[7] The Parties to the Nauru Agreement (PNA), available at http://www.pnatuna.com/

non-cooperative behavior (Miller et al. 2013). Officializing treaties like the case of the Gulf of Maine could provide better ground for the management rules and increase treaty resilience.

In the current paper we follow a modeling approach to explore the potential impacts that climate change will have in the management of transboundary fisheries in North America. Models are attempts to represent reality (in our case a future reality) based on observational data, previously established theory, and future scenarios, and are thus, subjected to different degrees of uncertainty (Payne et al. 2016). First, our study incorporates multiple earth system models to project the future distribution of transboundary stocks while accounting the structural uncertainty built within each ESM (Bopp et al. 2013). In terms of the structural uncertainty build within the DBEM, previous analysis shown that the trends of changes in MCP are not affected by its structural uncertainty (Cheung, Jones, Reygondeau, et al. 2016). Secondly, scenario planning has been widely used in climate change studies as a method to account for the uncertainty build in future decision making (Vuuren et al. 2011). In this aspect we considered two extreme RCPs that comprises the vast spectrum of possibilities proposed by the IPCC (IPCC 2014). A lower-than-2.6 RCP (1.5º warming) was discussed at the recent Paris Agreement sessions celebrated in Paris France. While we did not include this scenario in our analysis, previous research suggest that stronger mitigation efforts would bring large benefits to fisheries (Cheung, Reygondeau, et al. 2016). Finally, future changes to species distributions could be influenced by interactions between species (Pecl et al. 2017), adaptation of species to environmental changes, and anthropogenic factors (Serpetti et al. 2017). However, these factors are expected to increase the rate of range-shifting of the species making our results conservative (Cheung et al. 2010, Serpetti et al. 2017).

# CONCLUSIONS

Shifts in species distribution due to climate change have the potential of creating local extinction of economically important species while enhancing fisheries in areas where they were not present before. In this paper, we have explored the potential impacts of climate change in the joint management of 33 transboundary stocks managed by Canada and the US. We found that, transboundary species are likely to shift north in the upcoming years changing the proportion of the catch of jointly managed fisheries of Canada and the US. Lessons from other countries can provide solutions to such challenges. More specific, side payments, dynamic management, and interchangeable quotas were identified as potential solutions for North American region. While not directly addressed in this study, socio-economic impacts of shifting transboundary stocks could add an extra layer of complexity to the problem. Addressing shifts in species distribution sooner rather than latter could avert the so called "fish wars", improve sustainability of jointly managed stocks, and secure the livelihood of thousand of families that depend on stocks that move freely between national jurisdictions.

# ACKNOWLEDGEMENTS

# LITERATURE CITED

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#### Old North America Estimation ####

for(r in 1:2){

  if(r == 1){
    RCP = c("GFDL26F1","IPSL26F1","MPI26F1") #Low RCP
  }else{
    RCP = c("GFDL85F1","IPSL85F1","MPI285F1") #High RCP
  }

  # OLD VERSION ________________________________________
```

```
# Mean for each cel from 2005-2014
Mean_Data <- DBEM_Corrected %>%
  filter(Model %in% RCP) %>%
  group_by(INDEX,
           Model) %>%
  summarise_at(vars(Beg_In:End_End), sum,na.rm=T) %>% # Sum the MCP of all species in each index by m
  select(INDEX,Beg_In:Beg_End) %>%
  group_by(INDEX) %>%
  summarise_at(vars(Beg_In:Beg_End), mean,na.rm=T) %>% # Yearly average of three models (Structural u
  mutate(Mean = rowMeans(.[,2:11])) %>% # Decal average (2005-2014) of results (Uncertanty related to
  select(INDEX,Mean) %>%
  arrange(INDEX)

#The future
Future <- DBEM_Corrected %>%
  filter(Model %in% RCP) %>%
  group_by(INDEX,
           Model) %>%
  summarise_at(vars(Beg_In:End_End), sum,na.rm=T) %>% # Sum the MCP of all species in each index by m
  group_by(INDEX) %>%
  summarise_at(vars(`2015`:End_End), mean,na.rm=T) %>% # Yearly average of three models
  arrange(INDEX)

#SD future
# for this we have to first average the temporal variabillity for each model and then average the mod

SD_Future <- DBEM_Corrected %>%
  # filter( INDEX == 67071) %>%
  filter(Model %in% RCP) %>%
  group_by(INDEX,
           Model) %>%
  summarise_at(vars(`2005`:`2099`), sum,na.rm=T) %>% # Sum the MCP of all species in each index by mo
  tidyr::gather("Year","Change",3:97) %>%
  filter(Year >= 2045 & Year <= 2054) %>% # Select mid century
  group_by(INDEX,Model) %>%
  summarise(
    Mean_Temp = mean(Change, na.rm = T), # Temporal Mean and SD
    SD_Temp = sd(Change, na.rm = T)
  ) %>%
  group_by(INDEX) %>%
  summarise(
    Mean_M = mean(Mean_Temp, na.rm = T), # Model mean
    SD_M = sd(Mean_Temp, na.rm = T) # Model SD
  ) %>%
  filter(!is.na(SD_M)) %>%
  mutate(SD_Plus = ifelse((SD_M*2) > Mean_M,"No agreement","Agree")) %>% # If 2xSD is bigger than the
  # filter(SD_Plus > 0) %>%
  left_join(DBEM_Coor,
            by="INDEX")

#### Overall agreement. Number of cells where models don't match

# SD_Future %>%
```

```r
#   group_by(SD_Plus) %>%
#   summarise(n())

# RCp 2.6 30% of grids don't agree
# Agree 3825
# Don't agree 1140

# RCp 8.5 32% of grids don't agree
# Agree          3564
# No agreement   1151

# #Devide one by the other

#### _______________________________________________ #

# Devide future projections by "today's"" projections

Cell_Index <- sweep(Future[2:86],#Future catch p.
                    1, #1 goes by row and 2 goes by colum
                    Mean_Data$Mean, #the means
                    "/") %>%
  mutate(INDEX = Future$INDEX) %>%
  select(INDEX,everything())


Mid_Century <- Cell_Index %>%
  select(INDEX,
         Mid_In:Mid_End) %>%
  mutate(Mean = rowMeans(.[,2:11])) %>% # Temporal average
  # left_join(NorthA_Coor_df,
            # by ="INDEX") %>%
  mutate(Percentage = round(-(1-Mean)*100)) %>% # Convert to percentage change
  mutate("Percentage Change" = ifelse(Percentage > 100, 100,Percentage)) %>%  # set everything over 1
  filter(!is.na(`Percentage Change`)) %>%
  left_join(DBEM_Coor,
            by="INDEX")

  #### North America Transboundary Plot ####

Seq <- seq(-100,100,by=20) #Axis

ggplot() +
  geom_tile(data = Mid_Century, # Percentage change data
            aes(
              x = longitude,
              y = latitude,
              colour = `Percentage Change`,
              fill = `Percentage Change`
            )
  ) +
  geom_point(data = subset(SD_Future, SD_Plus == "No agreement"), # ESM model uncertanty
             aes(
               x = longitude,
```

```
                 y = latitude
               ),
               size = 0.05,
               alpha = 0.5,
               shape = 6,
               colour = "grey20") +
  geom_sf(data = North_America_Land, fill = "grey90") + # Base map
  coord_sf(xlim = c(-190,-50)) +
  scale_colour_gradient2(
    limits=c(-100,
             100),
    breaks = Seq) +
  scale_fill_gradient2(
    limits=c(-100,
             100),
    breaks = Seq) +
  ggtheme_map()

 if(r == 1){
  Name = paste("North_America_Change_26_2050.png")
}else{
  Name = paste("North_America_Change_85_2050.png")
}

ggsave(Name,
       plot = last_plot(),
       width = 12,
       height = 10,
       units = "in",
       path = Path)


### now we average the results from the models for END century ###

End_Century <- Cell_Index %>%
  select(INDEX,
         `2090`:`2099`) %>%
  mutate(Mean = rowMeans(.[,2:11])) %>%
  mutate(Percentage = round(-(1-Mean)*100)) %>% # Convert to percentage
  mutate("Percentage Change" = ifelse(Percentage > 100, 100,Percentage)) %>%  # set everything over 1
  filter(!is.na(`Percentage Change`)) %>%
  left_join(DBEM_Coor,
            by="INDEX")

SD_End <- DBEM_Corrected %>%
  # filter( INDEX == 67071) %>%
  filter(Model %in% RCP) %>%
  group_by(INDEX,
           Model) %>%
  summarise_at(vars(`2005`:`2099`), sum,na.rm=T) %>%
  tidyr::gather("Year","Change",3:97) %>%
  filter(Year >= 2090 & Year <= 2099) %>%
  group_by(INDEX,Model) %>%
```

```r
  summarise(
    Mean_Temp = mean(Change, na.rm = T), # Mean temporal
    SD_Temp = sd(Change, na.rm = T) #Sd of 10 years average
  ) %>%
  group_by(INDEX) %>%
  summarise(
    Mean_M = mean(Mean_Temp, na.rm = T), # Models mean
    SD_M = sd(Mean_Temp, na.rm = T) #Models Sd
  ) %>%
  filter(!is.na(SD_M)) %>%
  mutate(SD_Plus = ifelse((SD_M*2) > Mean_M,"No agreement","Agree")) %>%
  # filter(SD_Plus > 0) %>%
  left_join(DBEM_Coor,
            by="INDEX")

ggplot() +
  geom_tile(data = End_Century,
            aes(
              x = longitude,
              y = latitude,
              colour = `Percentage Change`,
              fill = `Percentage Change`
            )
  ) +
  geom_point(data = subset(SD_End, SD_Plus == "No agreement"),
             aes(
               x = longitude,
               y = latitude
             ),
             size = 0.05,
             alpha = 0.5,
             shape = 6,
             colour = "grey20") +
  geom_sf(data = North_America_Land, fill = "grey90") +
  coord_sf(xlim = c(-190,-50)) +
  scale_colour_gradient2(
    limits=c(-100,
             100),
    breaks = Seq) +
  scale_fill_gradient2(
    limits=c(-100,
             100),
    breaks = Seq) +
  ggtheme_map()

if(r == 1){
  Name_End = paste("North_America_Change_26_2100.png")
}else{
  Name_End = paste("North_America_Change_85_2100.png")
}

ggsave(Name_End,
       plot = last_plot(),
```

```r
        width = 12,
        height = 10,
        units = "in",
        path = Path)

}

#### Old IPHC estimation ####

# Future change in MCP of IPHC per region
IPHC_MCP_Change <- DBEM_Corrected %>%
  mutate(RCP = ifelse(Model %in% c("GFDL26F1","IPSL26F1","MPI26F1"),"RCP 2.6","RCP 8.5")) %>% # Set the
  filter(Species %in% Selected_Species#,
         # INDEX %in% IPHC_Reg_DBEM_df$INDEX
         ) %>% # Filter species to halibut and the region for the IPHC regulatory area
  # group_by(INDEX,Model,RCP,Species) %>% # Add values per species
  # summarise_at(vars(`2005`:`2099`), sum,na.rm=T) %>%
  left_join(IPHC_Reg_DBEM_df,
            by = "INDEX") %>% # Include the regulatory areas info
  group_by(RegArea,RCP,Model) %>% #Sum grid-cells by regulatory area, RCP and Model
  summarise_at(vars(`2005`:`2099`), sum,na.rm=T) %>%
  tidyr::gather("Year","Change",`2005`:`2099`) %>%
  mutate(# Indicate the three period times
    Period = ifelse(Year >= 2005 & Year <= 2014,"Today",
                    ifelse(Year >= 2046 & Year <= 2055,"Mid Century",
                           ifelse(Year >= 2090 & Year <= 2099,"End Century",
                                  "Other_Years"))
    )
  ) %>%
  filter(Period != "Other_Years") %>% # Remove unwanted years
  group_by(RegArea,Model,RCP,Period) %>%
  summarise(
    Mean_Temp = mean(Change, na.rm = T), # Temporal mean
    SD_Temp = sd(Change, na.rm = T) #Temporal sd
  ) %>%
  group_by(RegArea,RCP,Period) %>% # Models (GFDL,IPSL,MPIs) mean and SD
  summarise(
    Mean_M = mean(Mean_Temp, na.rm = T),
    SD_M = sd(Mean_Temp, na.rm = T)
  ) %>%
  filter(!is.na(SD_M)) %>%
  mutate(Robust = ifelse((SD_M*2) > Mean_M,"No agreement","Agree"))  %>% # Flags robustness in data
  # filter(Robust > 0) %>%
  select(RegArea,RCP,Period,Mean_M) %>% # They all agree except for 4D mid century
  spread(Period,Mean_M) %>%
  mutate( # Estimate the percentage change
    Change_Mid = `Mid Century`/Today,
    Change_End = `End Century`/Today,
    Percentage_Mid = round(-(1-Change_Mid)*100),
    Percentage_End = round(-(1-Change_End)*100)
  ) %>%
  select(RegArea, RCP, Percentage_Mid,Percentage_End)
```

```r
#### Species Table for SS proportion change ####

#### OLD VERSION

# Average (GFDL, MPI, IPSL) MCP of each species from 2005-2099 for both RCP's
Overall <- DBEM_Corrected %>%
  left_join(EEZ_CellID,
            by = "INDEX") %>%
  # head() %>%
  filter(EEZID %in% Selected_Areas$EEZID) %>%
  mutate( # determine what nation is wach region, what result is fr each RCP and Basin
    Nation = ifelse(EEZID >= 958, "Alaska",
                    ifelse(EEZID == 925,"Can W",
                           ifelse(EEZID == 851, "USA E",
                                  ifelse( EEZID== 848, "USA W",
                                          "Can E"))
                    )),
    RCP = ifelse(Model %in% RCP,"Low_Emission","High_Emission"), # determine which model is ehat RCP
    Basin = ifelse(Nation %in% c("USA E","Can E"),"Atlantic","Pacific"),
  ) %>%
  group_by(Species,Nation,Basin,RCP,Model) %>% # Adds each species' MCP of all INDEX-cells within each
  summarise_if(is.numeric,sum,na.rm=T) %>% # sum of values
  group_by(Species,Nation,Basin,RCP) %>%
  summarise_at(vars(`2005`:`2099`),mean,na.rm=T) %>% # Average the MCP results from the three ESMs
  gather("Year","MCP",`2005`:`2099`) %>%
  mutate(  # Indicate the three period times
    Period = ifelse(Year >= 2004 & Year <= 2014,"Today",
                    ifelse(Year >= 2046 & Year <= 2055,"Mid_Century",
                           ifelse(Year >= 2090 & Year <= 2099,"End_Century",
                                  "Other_Years"))
    )
  ) %>% # Set the three time periods
  filter(Period != "Other_Years") %>% # Remove whatever is in the middle
  group_by(Species,Nation,Basin,RCP,Period) %>%
  summarise(Period_MCP = mean(MCP)) #Temporal average of results

#### Percentage Change in MCP for each species period, and RCP ####

MCP_Spp_Change <- Overall %>%
  spread(Period,Period_MCP) %>%
  mutate( # Devides the different timeframes by the present and estimates percentage change
    Change_End = `End_Century`/Today,
    Change_Mid = `Mid_Century`/Today,
    Mid_Century = -(1-Change_Mid)*100,
    The_End_Century = -(1-Change_End)*100
  ) %>%
  gather("Period","Percentage_Change",Mid_Century:The_End_Century) %>%
  ungroup() %>%
  select(-5)

# group_by(Nation,Period,RCP) %>% # Average the results per species
#   summarise(
#     Mean_All = mean(Percentage_Change, na.rm = T),
```

```r
#     sd_All = sd(Percentage_Change, na.rm = T)
#   ) %>%
#   View() # Average proportion change of all species


  #### Compare versions

  # Comparring <- MCP_Species_Data %>%
  #   select(1:5) %>%
  #   left_join(MCP_Spp_Change) %>%
  #   mutate(Diff = Mean_ESM_MCP_Chng - Percentage_Change)
  #
  #
  #

#### Percentage Change in stock-share ratio for each species period, and RCP ####

SS_Change <- Overall %>%
  group_by(RCP,Basin,Species,Period) %>%
  summarise(Total_MCP = sum(Period_MCP)) %>% #Estimate todays's total (both EEZs added) MCP for each sp
  left_join(Overall) %>% # Inlude each nation's MCP
  mutate(
    Proportion = (Period_MCP/Total_MCP)*100 # estimates each Country's catch proportion per period
  ) %>%
  select(Species,Nation,Basin,RCP,Period,Proportion) %>%
  spread(Period,Proportion) %>% # Spread for easier mutation
  mutate( # Estimate the percentage change
    SSR_Change_Mid = `Mid Century`/Today,
    SSR_Change_End = `End Century`/Today,
    SSR_Percentage_Mid = round(-(1-SSR_Change_Mid)*100),
    SSR_Percentage_End = round(-(1-SSR_Change_End)*100)
  ) %>%
  # View() # Average change in MCP proportion per Nation (comment it to have a mean +-sd of all areas)
  group_by(RCP,Nation) %>%
    summarise(mean = mean(SSR_Percentage_End),
              sd = sd(SSR_Percentage_End)
              )

#### IPHC proportion change

#### Old version

IPHC_Absolutes <- DBEM_Corrected %>%
  mutate(RCP = ifelse(Model %in% c("GFDL26F1","IPSL26F1","MPI26F1"),"RCP 2.6","RCP 8.5")) %>%  # Assign
  filter(Species %in% IPHC_Species,
         INDEX %in% IPHC_Reg_DBEM_df$INDEX) %>%  #Selects only IPHC species within regulatory areas
  left_join(IPHC_Reg_DBEM_df,
            by = "INDEX") %>% # Include Regulatory areas
  gather("Year","MCP",`2005`:`2099`) %>%
  group_by(RCP,RegArea,Year,Model) %>%
  summarise(Total_MCP = sum(MCP, na.rm = T)) %>% # Sums INDEX MCP per RegArea
  group_by(RCP,RegArea,Year) %>%
  summarise(Mean_MCP = mean(Total_MCP, na.rm = T), #Yearly mean per ESM model
```

```r
            SD_MCP = sd(Total_MCP, na.rm = )
  ) %>%
  mutate(Year = as.numeric(Year))

# Changes in the proportion in comparrison of the mean (2004-2014) proportion ####

# Estimate total MCP of each RCP per year
Proportion_Total <- IPHC_Absolutes %>%
  group_by(RCP,Year) %>%
  summarise(
    Total = sum(Mean_MCP),
    Total_SD = sum(SD_MCP)
  )

# head(Proportion_Total)

# Estimates the proportion of each RegArea catch pero RCP and Year
Proportion_Change <- IPHC_Absolutes %>%
  left_join(Proportion_Total,
            by = c("RCP","Year")) %>%
  mutate(Proportion = (Mean_MCP/Total)*100)

# Todays proportion
Early_Proportion <- Proportion_Change %>%
  filter(Year <= Beg_End) %>%
  group_by(RCP,
           RegArea) %>%
  summarise(Mean_Prop = mean(Proportion))

# Proportion change in the future (NOTE: not plotting by timeframe because of boxplot)
Proportion_Change <- IPHC_Absolutes %>%
  left_join(Proportion_Total,
            by = c("RCP","Year")) %>% # Join with total MCP
  mutate(Proportion = (Mean_MCP/Total)*100) %>% # Get proportions
  left_join(Early_Proportion,
            by= c("RCP","RegArea")) %>% # Include baseline proportion
  mutate(Change = Proportion/Mean_Prop) %>%  # devide future changes by baseline
  mutate(Percentage = round(-(1-Change)*100,2),
         Year = as.numeric(Year)) %>%
  arrange(RCP) %>%
   mutate(Time_Step = ifelse(Year >= Mid_In & Year <= Mid_End,"Mid Century",
                             ifelse(Year >= End_In,"End Century","NA")),
          Nation = ifelse(RegArea == "2A","US Contiguous",
                          ifelse(RegArea == "2B","Canada","Alaska")
                          )
          ) %>%
  filter(Time_Step != "NA",
         RegArea != "NA",
         Time_Step == "End Century")

Proportion_Change$RegArea <- gsub("2B","2B",Proportion_Change$RegArea)
```

```r
#### Option all in one####
PL <- ggplot(subset(Proportion_Change, RCP == "RCP 2.6"),
         aes(
           x = reorder(RegArea,Percentage, FUN = median), # from forcasts` package
           # x = Nation, # from forcasts` package
             y = Percentage,
             # fill = Nation,
           colour = Nation
         )
  ) +
  geom_boxplot() +
  ylab("") +
  xlab ("") +
  geom_hline(yintercept = 0, linetype = "dashed") +
  ggtheme_plot() +
  # scale_fill_brewer("Region",palette = "Set2") +
  scale_colour_brewer("Region",palette = "Set2") +
  theme(legend.position = c(0.2, 0.98),
       legend.direction = "horizontal") #+
  # geom_label(data=Proportion_Change, aes(label = "RCP 2.6", x = "2A" , y = 18, fill = NA), #RCP label
  #             colour = "blue",
  #             show.legend = FALSE,
  #             size = 5
  # )



PH <- ggplot(subset(Proportion_Change, RCP == "RCP 8.5"),
         aes(
           x = reorder(RegArea,Percentage, FUN = median), # from forcasts` package
           # x = Nation, # from forcasts` package
             y = Percentage,
             # fill = Nation,
           colour = Nation
         )
  ) +
  geom_boxplot() +
  ggtheme_plot() +
  ylab("") +
  xlab ("IPHC Regulatory Area") +
  geom_hline(yintercept = 0, linetype = "dashed") +
  ggtheme_plot() +
  # scale_fill_brewer("Region",palette = "Set2",guide=FALSE) +
  scale_colour_brewer("Region",palette = "Set2",guide=FALSE) #+
  # geom_label(data=Proportion_Change, aes(label = "RCP 8.5", x = "3B" , y = 18, fill = NA), #RCP label
  #             colour = "red",
  #             show.legend = FALSE,
  #             size = 5
  # )

ggdraw() +
  draw_plot(PL, x = 0, y = 0.5, width = 1, height = 0.5) +
  draw_plot(PH, x = 0, y = 0, width = 1, height = 0.5) +
```

```r
  draw_plot_label(label = c("A", "B"), size = 15,
                  x = c(0, 0),
                  y = c(1, 0.5)) +
  draw_plot_label(label = "Stock-Share Percentage Change", size = 12, angle = 90, fontface = "plain",
                  x = 0.02,
                  y =0.11999)

### OLD VERION GOM

#### Old analysis ##3
Mean_Data_GoM <- Atlantic_DBEM %>%
  mutate(RCP = ifelse(Model %in% c("GFDL26F1","IPSL26F1","MPI26F1"),"RCP 2.6","RCP 8.5")) %>%
  tidyr::gather("Year","Change",`2005`:`2099`) %>%
  mutate(# Indicate the three period times
    Period = ifelse(Year >= 2005 & Year <= 2014,"Today",
                    ifelse(Year >= 2046 & Year <= 2055,"Mid Century",
                           ifelse(Year >= 2090 & Year <= 2099,"End Century",
                                  "Other_Years"))
    )
  ) %>%
  filter(Period != "Other_Years") %>% # Remove unwanted years
  group_by(INDEX,Model,RCP,Period,Species) %>%
  summarise(
    Mean_Temp = mean(Change, na.rm = T), # Temporal mean
    SD_Temp = sd(Change, na.rm = T) #Temporal sd
  ) %>%
  group_by(INDEX,RCP,Period,Species) %>% # Models (GFDL,IPSL,MPIs) mean and SD
  summarise(
    Mean_M = mean(Mean_Temp, na.rm = T),
    SD_M = sd(Mean_Temp, na.rm = T)
  ) %>%
  filter(!is.na(SD_M)) %>%
  mutate(Robust = ifelse((SD_M*2) > Mean_M,"No agreement","Agree"))  %>% # Flags robustness in data
  filter(Robust > 0) %>%
  select(INDEX,Species,RCP,Period,Mean_M) %>% # They all agree except for 4D mid century
  spread(Period,Mean_M) %>%
  mutate( # Estimate the percentage change
    Change_Mid = `Mid Century`/Today,
    Change_End = `End Century`/Today,
    Percentage_Mid = ifelse(round(-(1-Change_Mid)*100) > 100, 100,round(-(1-Change_Mid)*100)),
    Percentage_End = ifelse(round(-(1-Change_End)*100) > 100, 100,round(-(1-Change_End)*100))
    ) %>%
  select(INDEX, Species, RCP, Percentage_Mid,Percentage_End) %>%
    left_join(GB_Coor,
            by ="INDEX")



#   mutate("Percentage Change" = ifelse(Percentage > 100, 100,Percentage)) %>%  # set everything over 1
#   filter(!is.na(Longitude)) %>%
#   filter(Latitude <= 50)

Mean_Data_GoM$Bins <- cut(Mean_Data_GoM$Mid_Century,breaks = 4)
```

```
# unique(Mid_Century$Bins)

# -------------------------------------------------------

# The plot
Seq <- seq(-100,100,10)

Lim_Neg <- min(Seq)
Lim_Max <- max(Seq)

# Use bins and collors yellow orange light red and dark red

# Mean_Data_GoMb <- Mean_Data_GoM %>% # In case you want filter a specific species
#   filter(Species == "Limanda ferruginea")

ggplot() +
  geom_tile(data = Mean_Data_GoM,
            aes(
              x = Longitude,
              y = Latitude,
              fill = Percentage_Mid,
              colour = Percentage_Mid
              # fill = reorder(Bins,-Percentage),
              # colour = reorder(Bins,-Percentage)
            )
  ) +
  # scale_color_manual("MCP % Change",values=c("darkblue","lightblue","red","darkred")) + # for Bins op
  # scale_fill_manual("MCP % Change",values=c("darkblue","lightblue","red","darkred")) + # for Bins opt
  # scale_color_brewer("MCP % Change",type='seq', palette='Reds') + # for Bins option B
  # scale_fill_brewer("MCP % Change",type='seq', palette='Reds') + # for Bins option B
  scale_fill_gradient2("MCP Percentage Change \n(2046-2055)", # If not using the bins
                       limits=c(Lim_Neg,
                                Lim_Max),
                       breaks = Seq,
                       na.value = 'darkred' # NA values are present when the species is no more
  ) +
  scale_colour_gradient2("MCP Percentage Change \n(2046-2055)",
                         limits=c(Lim_Neg,
                                  Lim_Max),
                         breaks = Seq,
                         na.value = 'darkred' # NA values are present when the species is no more
  ) +
  # geom_label(data = Mean_Data_GoMb,
  #            aes(
  #              x = Longitude,
  #              y = Latitude,
  #              label = INDEX
  #            )
  # ) +
  geom_sf(data = GM_Land, colour = "lightgrey") +
  geom_sf(data = eez_GM, fill = NA) +
  annotate("text", label = "United States", x = -70, y = 45, size = 4, colour = "black") +
  annotate("text", label = "Canada", x = -66.8, y = 45.4, size = 4, colour = "black") +
```

```r
  annotate("text", label = "Canada", x = -65.4, y = 44.2, size = 4, colour = "black") +
  coord_sf(xlim = c(-71.0592, -63.33333),
           ylim = c(41,45.5)
  ) +
  ggtheme_map() +
  theme(
    axis.line = element_line(colour = "black", size = .5),
    axis.ticks = element_line(size = .5),
    axis.text.x = element_text(size = 12,
                               angle = 0,
                               face = "plain"),
    axis.text.y = element_text(size = 12),
    legend.key = element_rect(size = 3),
    legend.key.width =unit(8,"line"),
    legend.title = element_text(size = 20),
    legend.text = element_text(size = 18)
  ) +
  facet_wrap(~RCP + Species,
             ncol = 3
  )

Name = paste("Change_GB_26_85_2050.png",sep="_")

ggsave(Name,
       plot = last_plot(),
       width = 20,
       height = 10,
       units = "in",
       path = Path)
```


Aqorau, T., Bell, J., and Kittinger, J. N., 2018. Good governance for migratory species. *Science*, 361 (6408), 1208–1209.

Bjørndal, T. and Munro, G., 2012. The economics and management of world fisheries.

Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., and Vichi, M., 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences*, 10 (10), 6225–6245.

Caddy, J., 1997. Establishing a consultative mechanism or arrangement for managing shared stocks within the jurisdiction of contiguous states. *Australian Society for Fish Biology*.

Cheung, W. W. L., 2018. The future of fishes and fisheries in the changing oceans. *Journal of Fish Biology*, 92 (3), 790–803.

Cheung, W. W. L., Brodeur, R. D., Okey, T. A., and Pauly, D., 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progress in Oceanography*, 130 (C), 19–31.

Cheung, W. W. L., Jones, M. C., Lam, V. W. Y., D Miller, D., Ota, Y., Teh, L., and Sumaila, U. R., 2016. Transform high seas management to build climate resilience in marine seafood supply. *Fish and Fisheries*, 1–11.

Cheung, W. W. L., Jones, M. C., Reygondeau, G., Stock, C. A., Lam, V. W. Y., and Frölicher, T. L., 2016. Structural uncertainty in projecting global fisheries catches under climate change. *Ecological Modelling*, 325, 57–66.

Cheung, W. W. L., Lam, V. W., and Sarmiento, J. L., 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16, 24–35.

Cheung, W. W. L., Reygondeau, G., and Frölicher, T. L., 2016. Large benefits to marine fisheries of meeting the 1.5 C global warming target. *Science*.

Cheung, W. W. L., Watson, R., and Pauly, D., 2013. Signature of ocean warming in global fisheries catch. *Nature*, 497 (7449), 365–+.

CIA, 2017. The US-Canadian Dispute Over the Georges Bank, 1–10.

Fredston-Hermann, A., Gaines, S. D., and Halpern, B. S., 2018. Biogeographic constraints to marine conservation in a changing climate. *Annals of the New York Academy of Sciences*, 367, 49–13.

Gattuso, J. P., Magnan, A., Billé, R., Cheung, W. W. L., Howes, E. L., Joos, F., Allemand, D., Bopp, L., Cooley, S. R., Eakin, C. M., HOEGH-GULDBERG, O., Kelly, R. P., Pörtner, H. O., Rogers, A. D., Baxter, J. M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U. R., Treyer, S., and Turley, C., 2015. Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science*, 349 (6243), aac4722–aac4722.

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H., Benson, S. R., Eguchi, T., Dewar, H., Kohin, S., Costa, D. P., Crowder, L. B., and Lewison, R. L., 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, 4 (5).

IPCC, 2014. *Climate Change 2014 Impacts, Adaptation, and Vulnerability: Summary for Policy makers*. Cambridge: Cambridge University Press.

IPHC Secretariat, 2017. *Fishery statistics (2017): Preliminary*.

IPHC Secretariat and Gustafson, K., 2017. *IPHC Annual Report 2016*. Seattle.

Karim, T., Keizar, A., Busch, S., Dicosimo, J., Gasper, J., Mondragon, J., Culver, M., and Williams, G., 2010. *Report of the 2010 Halibut Bycatch Work Group*. IPHC. No. 57.

Kleisner, K. M., Fogarty, M. J., McGee, S., Barnett, A., Fratantoni, P., Greene, J., Hare, J. A., Lucey, S. M., McGuire, C., Odell, J., Saba, V. S., Smith, L., Weaver, K. J., and Pinsky, M. L., 2016. The Effects of Sub-Regional Climate Velocity on the Distribution and Spatial Extent of Marine Species Assemblages. *PLoS ONE*, 11 (2), e0149220.

Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G., and Sumaila, U. R., 2016. Projected change in global fisheries revenues under climate change. *Scientific Reports*, 6 (1), 1–8.

McCaughran, D. A. and Hoag, S. H., 1992. *The 1979 Protocol To The Convention and Related Legislation*. Seattle. No. 26.

McDaniels, T., Wilmot, S., Healey, M., and Hinch, S., 2010. Vulnerability of Fraser River sockeye salmon to climate change: A life cycle perspective using expert judgments. *Journal of Environmental Management*, 91 (12), 2771–2780.

Merten, W., 2015. *International Agreements Concerning Living Marine Resources of Interest to NOAA Fisheries*. Silver Spring, Maryland.

Miller, K. A., Munro, G. R., Sumaila, U. R., and Cheung, W. W. L., 2013. Governing Marine Fisheries in a Changing Climate: A Game-Theoretic Perspective. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 61 (2), 309–334.

Miller, K. and Munro, G., 2002. *Cooperation and Conflicts in the Management of Transboundary Fishery Resources*. Monterey, California: Proceeding of the Second World Conference of the Second World COngress of the American; European Associations of Environmental; Resource Economics.

Monllor-Hurtado, A., Pennino, M. G., and Sanchez-Lizaso, J. L., 2017. Shift in tuna catches due to ocean warming. *PLoS ONE*, 12 (6), e0178196.

Morley, J. W., Selden, R. L., Latour, R. J., Frölicher, T. L., Seagraves, R. J., and Pinsky, M. L., 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLoS ONE*, 13 (5), e0196127.

NOAA, 2013. Reducing Bycatch in Alaska. [online]. Available from: https://www.npfmc.org/wp-content/PDFdocuments/bycatch/Bycatchflyer913.pdf.

Northeast Atlantic Fisheries Commission, n.d. *Northeast Atlantic Fisheries Commission Objectives.*

Pauly, D. and Cheung, W. W. L., 2018. Sound physiological knowledge and principles in modeling shrinking of fishes under climate change. *Global Change Biology*, 24 (1), e15–e26.

Payne, M. R., Barange, M., Cheung, W. W. L., MacKenzie, B. R., Batchelder, H. P., Cormon, X., Eddy, T. D., Fernandes, J. A., Hollowed, A. B., Jones, M. C., Link, J. S., Neubauer, P., Ortiz, I., Queirós, A. M., and Paula, J. R., 2016. Uncertainties in projecting climate-change impacts in marine ecosystems. *ICES Journal of Marine Science*, 73 (5), 1272–1282.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J., Linnetved, H. I., Martin, V. Y., McCormack, P. C., McDonald, J., Mitchell, N. J., Mustonen, T., Pandolfi, J. M., Pettorelli, N., Popova, E., Robinson, S. A., Scheffers, B. R., Shaw, J. D., Sorte, C. J. B., Strugnell, J. M., Sunday, J. M., Tuanmu, M.-N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E., and Williams, S. E., 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355 (6332), eaai9214.

Pershing, A. J., Alexander, M. A., Hernandez, C. M., Kerr, L. A., Le Bris, A., Mills, K. E., Nye, J. A., Record, N. R., Scannell, H. A., Scott, J. D., Sherwood, G. D., and Thomas, A. C., 2015. Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, 350 (6262), 809–812.

Pinsky, M. L. and Fogarty, M., 2012. Lagged social-ecological responses to climate and range shifts in fisheries. *Climatic Change*, 115 (3-4), 883–891.

Pinsky, M. L., Reygondeau, G., Caddell, R., Palacios-Abrantes, J., Spijkers, J., and Cheung, W. W. L., 2018. Preparing ocean governance for species on the move. *Science*, 360 (6394), 1189–1191.

Pinsky, M. L. and Selden, R. L., 2017. Climate Variability, Climate Change, and Conservation in a Dynamic Ocean. *In*: *Conservation for the anthropocene ocean: Interdisciplinary science in support of nature and people.* Rutgers, The State University of New Jersey, New Brunswick, United States; Elsevier, 23–38.

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., and Levin, S. A., 2013. Marine Taxa Track Local Climate Velocities. *Science*, 341 (6151), 1239–1242.

Poloczanska, E. S., Burrows, M. T., Brown, C. J., Garcı'a Molinos, J., Halpern, B. S., Hoegh-Guldberg, O., Kappel, C. V., Moore, P. J., Richardson, A. J., Schoeman, D. S., and Sydeman, W. J., 2016. Responses of Marine Organisms to Climate Change across Oceans. *Frontiers in Marine Science*, 3 (28), 515–21.

PSC, 2017. Pacific Salmon Commission: About the Commission. [online]. Available from: http://www.psc.org/about-us/.

Rheim, M., Rintoul, S. R., Aoki, S., Campos, E., Chambers, D., Freely, R. A., Gulev, S., Josey, S. A., Kostiany, A., Mauritzen, C., Roemmich, D., Talley, L. D., and Wang, F., 2013. Foreword. *In*: IPCC, Stocker, T. F., Quin, D., Plattner, G. K., Tigor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., eds. *Climate change 2013 - the physical science basis.* Cambridge: Cambridge University Press, v—–vi.

Ross, P. M., Parker, L., O'Connor, W. A., and Bailey, E. A., 2011. The Impact of Ocean Acidification on Reproduction, Early Development and Settlement of Marine Organisms. *Water*, 3 (4), 1005–1030.

Schmidtko, S., Stramma, L., and Visbeck, M., 2017. Decline in global oceanic oxygen content during the past five decades. *Nature*, 542 (7641), 335–339.

Serpetti, N., Baudron, A. R., Burrows, M. T., Payne, B. L., Helaouët, P., Fernandes, P. G., and Heymans, J. J., 2017. Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries. *Scientific Reports*, 7 (1), 13438.

Soboil, M. L. and Sutinen, J. G., 2006. Empirical analysis and transboundary management for Georges Bank multispecies fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, 63 (4), 903–916.

Song, A. M., Scholtens, J., Stephen, J., Bavinck, M., and Chuenpagdee, R., 2017a. Transboundary research in fisheries. *Marine Policy*, 76 (C), 8–18.

Song, A., Temby, O., Krantzberg, G., and Hickey, G. M., 2017b. Institutional Features of US-Canadian Transboundary Fisheries Governance. *In*: Temby, O. and Stoett, P. J., eds. *Towards continental environmental policy.* New York: books.google.com, 156–179.

Spijkers, J. and Boonstra, W. J., 2017. Environmental change and social conflict: the northeast Atlantic mackerel dispute. *Regional Environmental Change*, 17 (6), 1835–1851.

Sumaila, U. R., 2013. *Game Theory and Fisheries.* 1st ed. Routledge.

Sumaila, U. R., 2019. Climate Change: Impact on Marine Ecosystems and World Fisheries. *In*: *Encyclopedia of food security and sustainability.* Elsevier, 218–222.

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., and Herrick, S., 2011. Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, 1 (9), 1–8.

Teh, L. and Sumaila, U. R., 2015. Trends in global shared fisheries. *int-res.com*, 530, 243–254.

United Nations, 1986. United Nations Convention on the Law of the Sea (UNCLOS) - Part V.

Van Der Voo, L., 2016. Conflict threatens to close Bering Sea halibut fishery.

Vuuren, D. P. van, Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K., 2011. The representative concentration pathways: an overview. *Climatic Change*, 109 (1-2), 5–31.

Zeller, D., Palomares, M. L. D., Tavakolie, A., Ang, M., Belhabib, D., Cheung, W. W. L., Lam, V. W. Y., Sy, E., Tsui, G., Zylich, K., and Pauly, D., 2016. Still catching attention: Sea Around Us reconstructed global catch data, their spatial expression and public accessibility. *Marine Policy*, 70, 145–152.