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Impacts of climate change on fisheries and aquaculture

Synthesis of current knowledge, adaptation and mitigation options



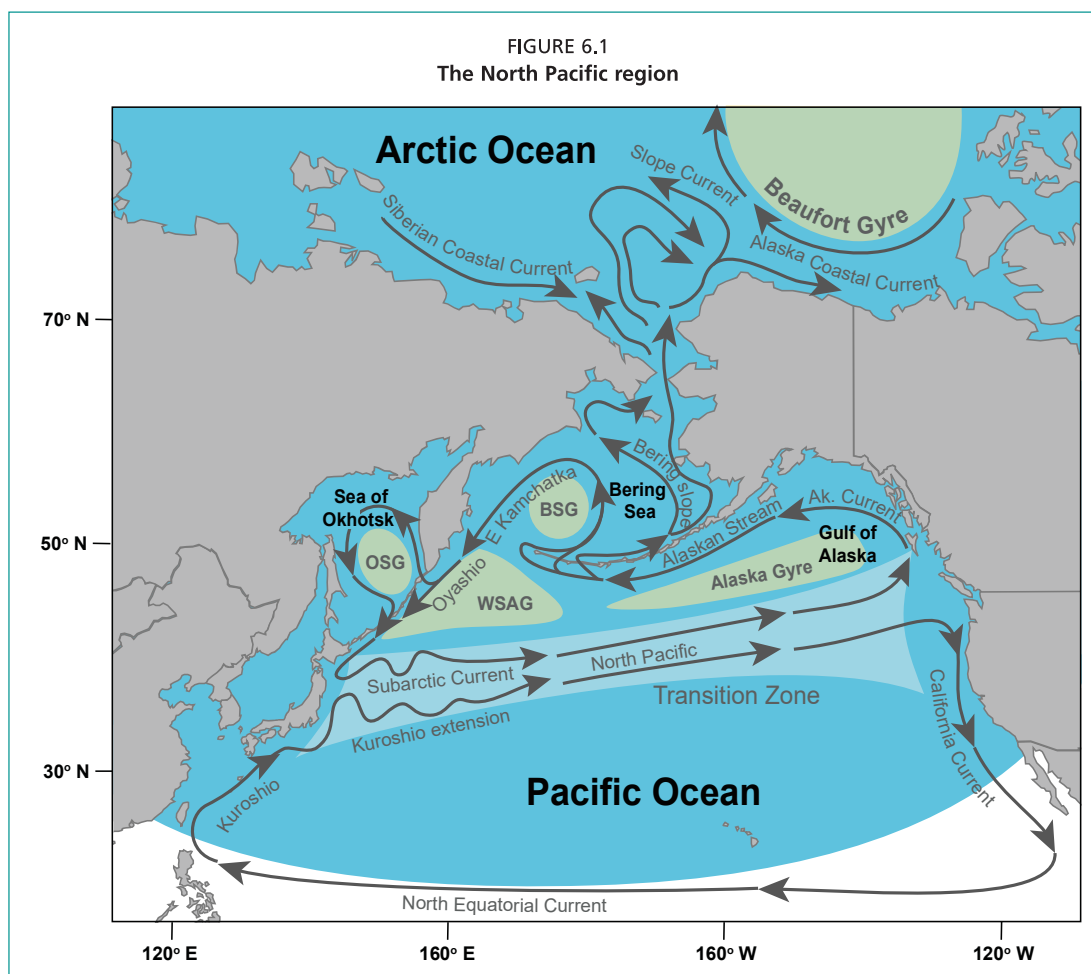
Chapter 6: Climate change impacts, vulnerabilities and adaptations: North Pacific and Pacific Arctic marine fisheries

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KEY MESSAGES

- The North Pacific has experienced disturbances in recent years that are very likely driven in part by anthropogenic climate change, including the persistent anomalously warm conditions in the Northeast Pacific from 2014 to 2016.
- Extreme events are expected to become more frequent and longer in duration across the North Pacific under unmitigated CO₂ scenarios (medium confidence).
- There is high confidence that extreme events will directly or indirectly induce disturbances to some existing fisheries, while others may be unaffected.
- Some demersal fish and crab stocks in multiple regions, as well as Chinook salmon in the Northeast Pacific, may decline as a result of ocean acidification, warming waters, and phenological mismatch and shifts in prey resources (medium confidence).
- There is high confidence that centroids of biomass for some fish and crab species in the Bering Sea will shift northward into northern Bering Sea waters, where commercial fishing is limited.
- There is high confidence that small boat fisheries (catcher vessels in Alaska, saury fishing vessels) as well as shore-based subsistence and recreational fishers are the most vulnerable to future climate change.
- Realized impacts of climate-driven changes on fisheries will depend on constraints to, or opportunities for, adaptation from non-climate pressures such as fishery dependency and diversity, global socio-economic drivers, pollution, non-climate-driven habitat loss, sea level rise, evolving scientific understanding, and technological advancements.



Map of the North Pacific and Pacific Arctic region and key oceanographic features, including major currents (arrows) and major gyres (green polygons); Okhotsk Sea Gyre (OSG), Western Sub-arctic Gyre (WSAG), and Bering Sea Gyre (BSG).

6.1 REGIONS AND FISHERIES OF THE NORTH PACIFIC

Roughly half of all fish captured globally each year come from the North Pacific (FAO, 2016) which is comprised of diverse marine ecosystems (Figure 6.1) that include the following:

6.1.1 The Northwest Pacific

The Northwest Pacific is one of the most productive areas in the world and with an annual catch of more than 21 million tonnes harvested in the region, represents 25 percent of worldwide capture fisheries production annually (FAO, 2016). Key fisheries include walleye pollock (*Gadus chalcogrammus*, formerly *Theragra chalcogramma*), Japanese anchovy (*Engraulis japonicus*), Pacific chub mackerel (*Scomber japonicus*), largehead hairtail (*Trichiurus lepturus*), forage fish species, scads (family *Carangidae*), crab, shrimp and molluscs. Oceanographic features of the western North Pacific are largely characterized by two western boundary currents (WBCs): Kuroshio (subtropical WBC), which transports warm and oligotrophic water, and the Oyashio (subarctic WBC), which transports cold and nutrient-rich subarctic water (Figure 6.1). Where these currents meet, mixing promotes biological production and sustains high fishery production in the western North Pacific. In addition, strong temperature gradients between the Oyashio and Kuroshio delineate a variety of species habitats.

6.1.2 The Northeast Pacific

The Northeast Pacific is characterized by productive boundary currents and upwelling zones that support large fisheries for migratory bluefin (*Thunnus orientalis*) and albacore tuna (*T. alalunga*), small pelagics, Pacific halibut (*Hippoglossus stenolepis*) and other groundfish, and a number of Pacific salmon (*Oncorhynchus* spp.) stocks, as well as valuable crab, shrimp and squid fisheries with a collective average annual value to Canada's Pacific economy of about USD 230 million (DFO, 2013). Important non-migrant fish stocks include rockfish species, characterized by slow growth rates, high longevity, and low recruitment rates, potentially making them more vulnerable to climate change (Bograd *et al.*, 2016). Marine recreational fisheries are also very important and contribute over USD 90 million annually to Canada's Pacific economy (DFO, 2013).

6.1.3 The Pacific Arctic

The Eastern Bering Sea (EBS), Beaufort, and Chukchi seas that comprise the Pacific Arctic are dynamic, shallow, ice-driven ecosystems (Sigler *et al.*, 2016b) that support some of the most productive fisheries in the world and are critical to regional and national economies and food security. With more than 2.5 million tonnes landed in 2015, and a total landings revenue of about USD 1.7 billion (2015 values), more than half of all domestic landings in the United States of America came from Alaska fisheries in the EBS for groundfish (including walleye pollock, Pacific cod, Pacific halibut, rockfish, and flatfish), crab and Pacific salmon, including the largest wild salmon fishery in the world for Bristol Bay sockeye salmon. Subsistence harvest of fish and marine mammals is a significant feature of Arctic fisheries and is critical to long-term sustainability of local communities. Climate drives regional productivity and fisheries; in particular, ice extent and persistence in the Arctic influences the distribution of fish and marine mammals and the subsistence harvest of fish and marine mammals by local communities (Huntington *et al.*, 2013; Moore and Stabeno, 2015). In the EBS, winter sea ice structures the formation of the summer "cold pool", a body of dense, cold bottom water (less than 2 °C) that influences food web interactions on the shelf through divergent tolerance of predators and prey of cold pool conditions, determines the relative strength of top-down versus bottom-up controls, and promotes lipid-rich trophic pathways that enhance recruitment of multiple groundfish and crab species during cold years (Sigler *et al.*, 2016b).

6.1.4 The Central Pacific

The Central Pacific region transitions from warm-water oligotrophic coral ecosystems to cool-water pelagic ecosystems and supports a diversity of fish species and fisheries. More than 14.5 million tonnes were landed by fisheries in the central Pacific in 2014, most of which were harvested in the western central region (12.8 million tonnes; FAO, 2016). In the Hawaiian Islands, the marine ecosystem supports a strong subsistence harvest, a recreational fishery for reef and open-water fish, and a commercial longline fleet for tuna and swordfish (Pooley, 1993). In 2015, USA commercial fishery landings revenue totalled about USD 111 million with bigeye tuna accounting for at least 50 percent of Hawaii's landings revenue each year from 2006 to 2015 (NMFS, 2017a). As of 2012, 80 percent of fisheries revenue came from large-scale commercial longlines compared to smaller-scale fisheries (Lowther and Liddel, 2014). A roughly 1 500 000 km² fishery closure area surrounding the northwest Hawaiian Islands is one of the largest marine protected areas in the ocean. Many commercial fisheries target the highly productive North Pacific Transition Zone (NPTZ, approximately between 32°N and 42°N; Figure 6.1), where both commercially fished species and marine predators take advantage of the mesoscale oceanographic features that aggregate prey at the transition from the subarctic to subtropical frontal zones. As such, potential bycatch of protected species remains a concern for these open-ocean fisheries (Howell *et al.*, 2015).

6.2 OBSERVED AND PROJECTED IMPACTS ON THE MARINE ENVIRONMENT

Over the next century, significant environmental change is anticipated for the North Pacific under unmitigated as well as moderate CO₂ future scenarios (IPCC, 2013, 2014). Changes in water temperature, circulation, oxygen conditions, and ocean pH may alter species distributions and interactions in ways that yield novel system dynamics and whole ecosystem reorganization (Poloczanska *et al.*, 2016). Within the North Pacific, the largest potential climate impacts on fisheries include changes in temperature and ice conditions, which can alter the flow of energy to upper trophic levels; changes in the location, timing and magnitude of coastal upwelling, which can impact lower trophic productivity and predator-prey interactions; changes in ocean circulation, which can impact the characteristics of source waters to the region and alter advective pathways; and changes in ocean biogeochemistry, including the supply and stoichiometry of nutrients, alterations in the depth and strength of stratification, reduced oxygen content at mid-ocean levels, and increasing acidification (IPCC, 2013, 2014).

6.2.1 Physical and chemical changes

Warming ocean temperatures

Across the North Pacific, temperatures increased by 0.1 °C/yr to 0.3 °C/yr from 1950 to 2009¹, although the California Current System (CCS) and Northwest Pacific have shown greater rates of increase (0.6 °C to 1.0 °C and 0.3 °C to 0.6 °C, respectively; Poloczanska *et al.*, 2013). Continued sea surface warming is anticipated for the entire North Pacific over the next century (Figure 6.2). Relative to 1956 to 2000 average conditions, projected increases for the 2050 to 2099 period range from a total of 1.4 °C to 2.2 °C (moderate CO₂ scenarios; hereafter RCP4.5) to 3.0 °C to 3.2 °C (unmitigated CO₂ scenarios; hereafter RCP8.5) for the EBS and Western Bering Sea, Sea of Okhotsk, and Gulf of Alaska (GOA; Figure 6.2). Projected total increases in sea surface temperatures (SST) for the Arctic range from 0.6 °C to 1.4 °C and 0.8 °C to 2.4 °C (RCP4.5 and RCP8.5, respectively; 2050 to 2099 relative to 1956 to 2005), but represent an eight-fold increase in variability over 1956 to 2005 levels. In the EBS and Arctic, increased temperatures represent a relatively larger change than in warmer central Pacific regions. Average summer bottom temperatures in the EBS historically averaged between 2 °C to 4 °C but under unmitigated scenarios are projected to increase by about 3 °C (2 °C to 4 °C) by 2099; summer SST across the region, which has historically ranged between 2 °C and 10 °C may increase by as much as 4 °C to 8 °C by 2099 (Figure 6.3). Multi-year periods of cooler than average conditions, typical over the last two decades in the EBS and associated with high productivity in the system (Sigler *et al.*, 2016b), are expected to decline in frequency, duration, and magnitude (Hermann *et al.*, 2016), and are absent in multiple unmitigated scenarios after 2050.

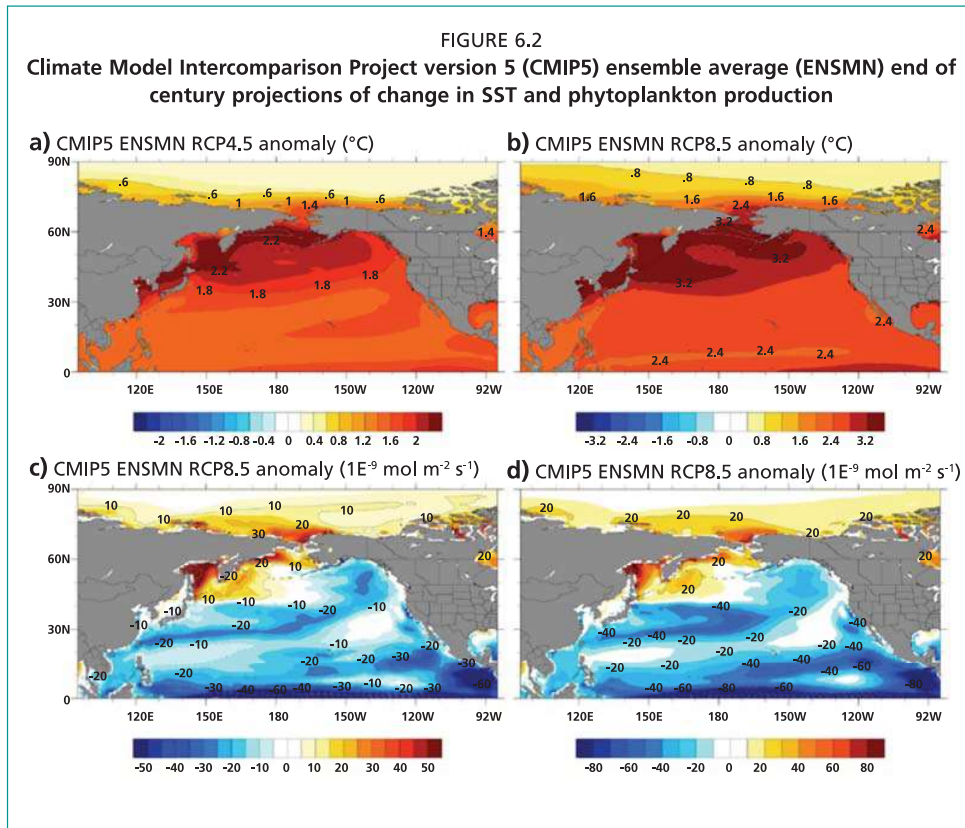
Decreasing and more variable ice cover

Sea ice extent and thickness has shown consistent declining trends in multiple regions of the North Pacific. In the high Arctic, sea ice extent declined between 1979 and 2017 at a rate of between 2.5 percent and 13.2 percent per decade (April and September, respectively; approximately 86 100 km² per year for September; Ding *et al.*, 2017). Decline is especially apparent for the oldest, thickest sea ice (4+ years) which constituted approximately 150 000 km² in 2017 compared to over 2 million km² in the mid-1980s². September 2017 Arctic sea ice volume calculated using the Pan-Arctic Ice

¹ For this report historical, present, and projection reporting periods may vary by study.

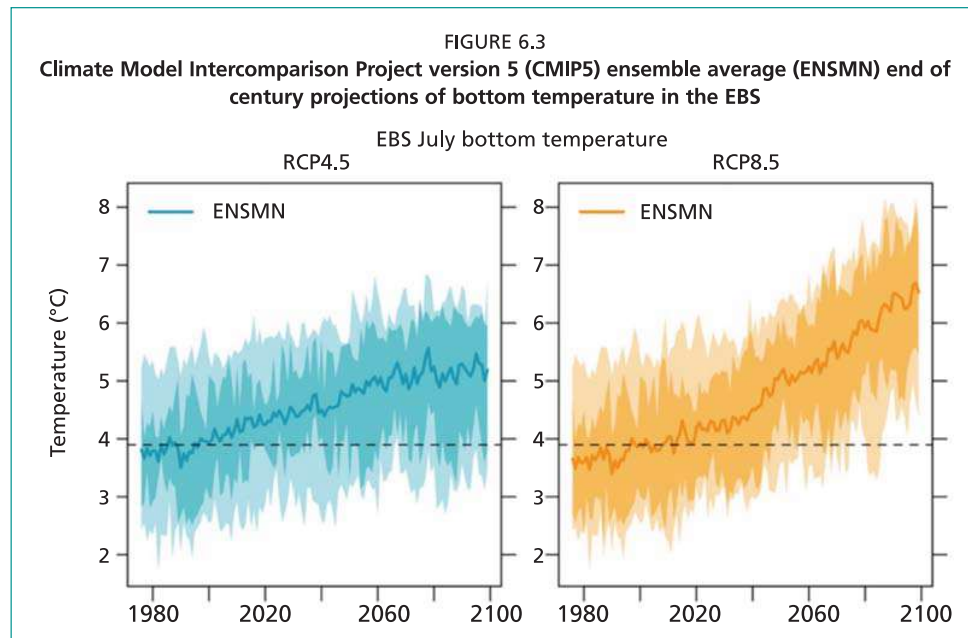
² National Snow and Ice Data Center <http://nsidc.org/arcticseaicenews> based on Tschudi, M., Fowler, C., Maslanik, J., Stewart, J.S. & Meier, W. 2016. *EASE-Grid Sea Ice Age, Version 3*. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. <http://dx.doi.org/10.5067/PFSVFZA9Y85G> [Cited 15 October 2017].

Ocean Modeling and Assimilation System at the University of Washington (PIOMAS³) was 72 percent lower than the August 1979 maximum. Sea ice cover also showed decreasing trends in the Sea of Okhotsk: reconstructed sea ice production decreased by 11.4 percent from 1974 to 2008 (Kashiwase, Ohshima and Nihashi, 2014) mainly as a result of warmer autumn air temperatures.



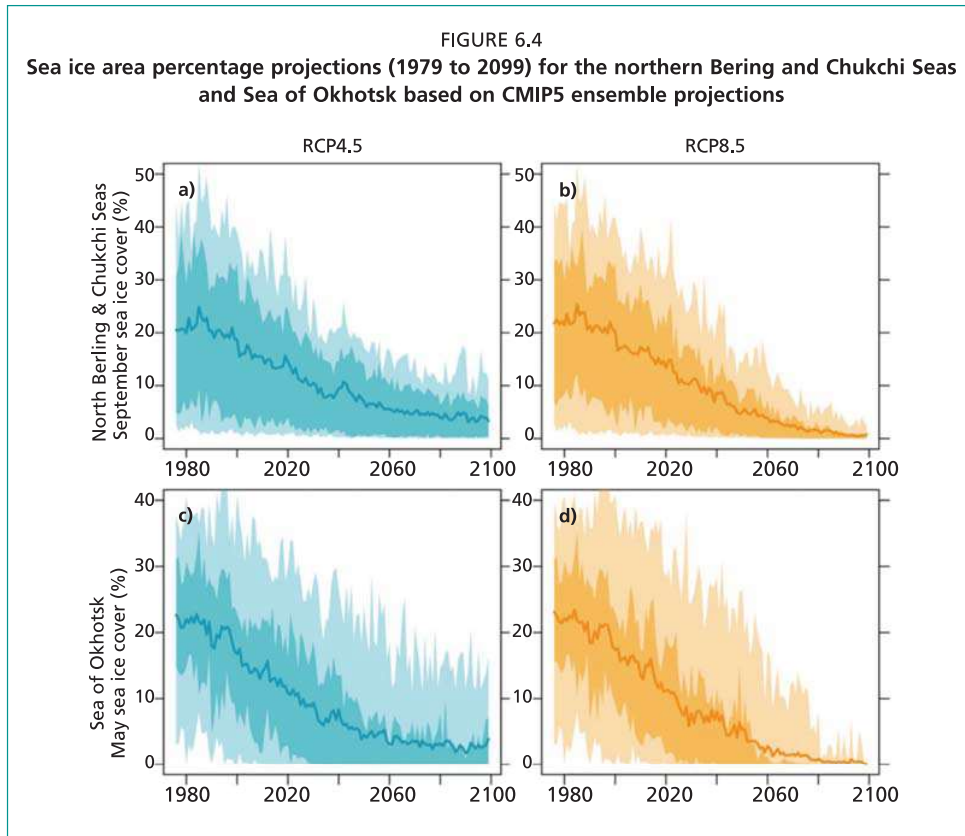
Changes in (2050 to 2099) annual mean SST (a, b) and annual mean primary organic carbon production (c,d) under moderate CO₂ scenarios (RCP4.5; a, c) and unmitigated CO₂ scenarios (RCP8.5; b, d) relative to 1956 to 2005. Image courtesy of the United States Department of Commerce, NOAA Earth System Research Laboratory Climate Change Portal www.esrl.noaa.gov/psd/ipcc/ocn/. Projection data from the fifth phase of the Climate Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012).

³ <http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/>



The simulations are forced using historical emission (1976 to 2005) and future projection (2006 to 2099) under moderate (RCP4.5; left) or unmitigated CO₂ (RCP8.5; right) emission scenarios. A one-year running mean is applied. Figures show the ENSMN ensemble mean (solid lines), and in light shading and dark shading, 80 percent and 50 percent of the spread of all the CMIP5 members, respectively. Based on data and images provided by the United States Department of Commerce, NOAA Earth System Research Laboratory Climate Change Portal <http://www.esrl.noaa.gov/psd/ipcc/ocn/timeseries.html>. Projection data from the fifth phase of the Climate Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012).

While the Pacific Arctic will likely continue to experience ice formation during the winter, ensemble projections indicate the Arctic may be ice-free in the summer by mid-century (Figure 6.4). Under both moderate (RCP4.5) and unmitigated CO₂ scenarios (RCP8.5), the extent, thickness, and date of sea ice retreat is projected to decrease. According to ensemble Climate Model Intercomparison Project version 5 (CMIP5) projections, May sea ice percentage cover in 2085 in the Sea of Okhotsk is likely to decline more than 50 percent relative to historical (1986 to 2005) ice conditions, with greater declines projected for unmitigated CO₂ scenarios (Figure 6.4). September sea ice extent over the EBS shelf (Figure 6.4) and the area of the summer cold pool is projected to decline to near zero by 2055 under unmitigated CO₂ scenarios (Figure 6.4; Hermann *et al.*, 2016; Hermann, unpublished data).



Projections of September sea ice cover in the Northern Bering & Chukchi Seas (a,b), and mean annual sea ice cover in the Sea of Okhotsk (c,d). The simulations are forced using historical emissions (1976 to 2005) and future projection (2006 to 2099) under (a,c) moderate (RCP4.5) or (b,d) unmitigated CO₂ (RCP8.5) emission scenarios. A one-year running mean is applied. Figures show the ENSMN ensemble mean (solid lines), and in light shading and dark shading, 80 percent and 50 percent of the spread of all the CMIP5 members, respectively. Based on data and images provided by the United States Department of Commerce, NOAA Earth System Research Laboratory Climate Change Portal <http://www.esrl.noaa.gov/psd/ipcc/ocn/timeseries.html>. Projection data from the fifth phase of the Climate Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012).

Upwelling and ocean circulation

There is evidence of upwelling intensification in some eastern boundary currents, including the CCS, although coastal wind observations are too short to definitively attribute trends to climate change (Sydeman *et al.*, 2014; Wang *et al.*, 2015). Global climate models project an increase in coastal upwelling in the northern portion of the CCS (only) and a general lengthening of the upwelling season (Rykaczewski *et al.*, 2015) while enhanced stratification may limit upwelling-driven nutrient delivery to the euphotic zone (Bakun *et al.*, 2015). The net ecosystem effects are uncertain, and likely to be highly variable in space and time (Jacox *et al.*, 2015).

Recently, subtropical western boundary currents have undergone rapid warming at a rate three times faster than the global mean surface ocean warming rate (Wu *et al.*, 2012). The accelerated warming is associated with a synchronous poleward shift and/or intensification of global subtropical western boundary currents in conjunction with a systematic change in winds over both hemispheres. The Kuroshio also showed intensification, while the Oyashio responded to the multi-decadal shift in the wind stress field by contracting northwestward (Kuroda *et al.*, 2015). This shift was observed by repeated hydrographic observations over 19 years but is likely part of multi-decadal oscillations and not indicative of a long-term trend.

Sea level rise

During the period 1993 to 2016, sea level in the mid-North Pacific and Western Tropical Pacific had risen 3.0 mm/yr to 7.0 mm/yr (Lyu *et al.*, 2017), while the Northeast Pacific showed slower or negative sea level rise of -1.0 mm/yr to 3.0 mm/yr (Lyu *et al.*, 2017; Thompson *et al.*, 2017). The east-west pattern in sea level change can be explained by decadal and quasi-decadal variability that resulted in the strengthening of trade winds and a predominantly negative phase of the Pacific Decadal Oscillation (PDO) during much of the altimetry period, and which reversed during the 2012 to 2016 El Niño-Southern Oscillation (ENSO) leading to rapid sea level rise in the Northeast Pacific of 20 mm/yr to 40 mm/yr and concomitant decreases in the Western Pacific. In 2016, sea level across the North Pacific was 5 cm to 15 cm above the 1993 average and the number of days where stations reported extreme high water increased by one to over five days for multiple stations in the Northeast Pacific, Hawaii, and Arctic, but decreased by one to two days in the Western Pacific (Thompson *et al.*, 2017). Thermal expansion of oceans, increased sea ice melt, and changes in sea surface pressure are projected to further contribute to continued sea level rise across the North Pacific at rates exceeding historical observations (Nerem *et al.*, 2018), but with differing regional estimates in magnitude over time because of the effect of ENSO events, which can impact sea level.

Continued sea level rise may particularly impact nearshore habitats along North Pacific coasts and ecosystems at the freshwater-marine interface. Qiu and Zhu (2015) found that the intensity of saltwater intrusion and degree of stratification may increase with sea level rise, and estimated 48 percent and 28 percent changes in freshwater volume in spring- and neap-tides respectively in the Yangtze River estuary by 2100. Evaluations of coastal vulnerability to sea level rise indicate that 37 percent of mangroves in the Guangxi Province (China; mostly along the coasts of Dandouhai and Beihai where sea level rise exceeds low sedimentation rates) and 5.8 percent of coastal wetlands in the Yangtze Estuary may be low to moderately vulnerable to sea level rise under unmitigated CO₂ scenarios (A1F1 rise of 0.59 cm per year; Cui *et al.*, 2015; Li *et al.*, 2014); additionally, 6.9 percent of coastal wetlands in the Yangtze Estuary might be highly vulnerable to sea level rise by 2100 (Cui *et al.*, 2015).

Changes in ocean chemistry, oxygen, and pH

In the Northwest Pacific, freshening in the subtropical gyre at a rate of about -0.001 practical salinity units (psu)/year over the last 50 years has accelerated to -0.008 psu/year in the last two decades (Oka *et al.*, 2017). Water exchanges between subarctic and subtropical areas appear to cause freshening through subduction processes and differential freshening trends in subarctic subsurface and surface layers have been observed (Kuroda *et al.*, 2015). While freshening trends can be mostly explained by displacement of isopycnals (vertical distribution of water density) in the Oyashio accompanied by a multi-decadal shift of the wind stress field, subsurface salinity has an additional freshening trend that may be caused by increasing precipitation in the subarctic region and decreasing sea ice formation in the Sea of Okhotsk (Ohshima *et al.*, 2014).

It is estimated that the ocean is 30 percent more acidic today than it was 300 years ago and global oceans have absorbed roughly 26 percent of the 10.2 (+/-0.7) Pg C/yr released globally during the 2006 to 2015 period. Net carbon uptake in 2016 was greatest in the North Pacific, central Pacific and Arctic, and lowest in the Northwest Pacific. The oceans are expected to continue to absorb atmospheric carbon and surface ocean pH across most of the North Pacific is expected to continue to decline by 0.12 (pH units) over the next century, well beyond the natural variability observed to date (i.e. 0.002 to 0.01 pH units for the North Pacific). Acidification is expected to occur faster and to be more severe in the cold waters of the Pacific Arctic compared to lower

latitudes. The response of marine species to lower pH is highly variable and difficult to disentangle from temperature (Poloczanska *et al.*, 2013), making it challenging to identify ocean acidification impacts to date or predict the full range of potential future ecosystem impacts.

Along the eastern boundary of the North Pacific, seasonal hypoxic events (low oxygen, less than 1.4 mL/litre) are becoming increasingly common on the outer continental shelf and slope off the west coast of the United States of America (Connolly *et al.*, 2010). Since 1980 there has been an observed decline in total dissolved oxygen (DO) content in mid-waters throughout much of the eastern North Pacific (Booth *et al.*, 2014), although recent declines followed increasing trends in DO from 1950 to 1980, thus recent declines cannot yet be definitively attributed to anthropogenic climate change (Crawford and Peña, 2016).

6.2.2 Biological and ecological changes

Primary production is projected to increase five percent to eight percent in the historically productive Sea of Okhotsk and Bering Sea, while ten percent to 20 percent declines in primary production are projected for the Northeast and Central Pacific relative to 1956 to 2005 levels (Figure 6.2). In addition, the location of the North Pacific Transition Zone (NPTZ; Figure 6.1) has been recorded as moving northwards resulting in an expansion of oligotrophic tropical waters (Polovina, Howell and Abecassis, 2008). Climate simulations under anthropogenic warming predict the trend will continue, potentially affecting the connectivity of the Western and Eastern Pacific (under RCP8.5; Hazen *et al.*, 2012).

Extreme events

In the boreal winter of 2013/2014, a marine heatwave of strongly positive SST developed in the Northeast Pacific Ocean (Bond *et al.*, 2015) and persisted through a large El Niño in the winter of 2015 (Jacox *et al.*, 2016), yet the persistent warming resulted in a different extratropical expression of El Niño compared to similar magnitude El Niños during 1997/1998 (Jacox *et al.*, 2016). The El Niño conditions, along with preconditioning of waters during 2014/15, and anomalous atmospheric circulation in early 2016 resulted in warm ocean anomalies in the Bering Sea in 2016 that cannot be explained without anthropogenic climate warming (Walsh *et al.*, 2018). Similarly, for the period 2006 to 2020, Oliver *et al.* (2018) found that the intensity and duration of extreme heatwaves in the Bering Sea and GOA were respectively 7.3 and 7.4 times more likely under climate change as compared to the natural world (i.e. under RCP8.5 versus historicalNat⁴). They also found that the return time of such events increased from one in greater than 120 years to one in five years under climate change (RCP8.5 versus historicalNat). Based on this they concluded that it was unlikely that natural variability alone led to the observed extreme marine heatwave in the EBS and GOA in 2016.

Climate change may also increase the intensity and size of storms in the North Pacific. Increases in tropical cyclone intensity with global warming have been confirmed from both historical data studies and theory. Future projections indicate fewer but intensified typhoons in the North Pacific with maximum wind speeds higher than 80 m/s (Tsuboki *et al.*, 2015).

A large harmful algal bloom (HAB) event in the Northeast Pacific during the 2015/2016 period may have contributed to coast-wide mortality of fish, bird, and marine mammal species and caused a prolonged closure of the Dungeness crab (*Metacarcinus magister*) fishery along the entire west coast of the United States of America. Projection of HABs in the Northeast Pacific is an active area of research but

⁴ HistoricalNat - representing historical conditions without anthropogenic influence (Oliver *et al.*, 2018).

studies indicate HAB outbreaks may be linked to climate-scale warm ocean conditions (McKibben *et al.*, 2017).

6.3 CLIMATE CHANGE EFFECTS ON STOCKS SUSTAINING THE MAIN FISHERIES

6.3.1 Changes in biomass and condition

Changes in ocean temperature can have direct impacts on fish metabolic demands, distribution, and growth. Following the anomalously warm conditions in the GOA and EBS during 2014 to 2016, below average fish condition (i.e. lighter fish for a given size) were observed for multiple groundfish species including pollock and Pacific cod (Zador and Siddon, 2016) as well as Chinook salmon (Daly, Brodeur and Auth, 2017). Increased metabolic demand can also intensify predation and lead to high mortality rates of adult and juvenile fish. Increased predation during warm years may partially explain low recruitment and increased juvenile mortality of pollock in the EBS (Mueter *et al.*, 2011; Spencer *et al.*, 2016) and reduced marine survival for Chinook salmon in the Northeast Pacific (Holsman *et al.*, 2012). Thermal stress associated with a recent marine heatwave in the central and western Pacific may have contributed to mortality and starvation of adult Pacific cod in the GOA and a subsequent large reduction in the GOA Pacific cod biomass and recommended harvest (approximately 80 percent decline from 2015 to 2017; Barbeaux *et al.*, 2017). While Pacific cod declined in the GOA, the biomass of Pacific Ocean perch (*Sebastes alutus*) and sablefish (*Anoplopoma fimbria*) remained stable or increased (NPFMC, 2017). During the same period, the EBS also experienced the warmest conditions on record. Yet, while warm conditions in Southern EBS may have contributed to reduced biomass and low recruitment of EBS populations of Pacific cod (NPFMC, 2017), cold water in the Northern EBS may have provided a bioenergetic and foraging refuge that mitigated impacts on juvenile pollock (Duffy-Anderson *et al.*, 2017). These disparate patterns indicate that species responses to sudden and persistent warm conditions may be species-specific and mediated by changes in food web dynamics and access to thermal refugia.

In the Central and Western Pacific, the impact of warming ocean temperatures on coral reefs may be widespread and significant. Thermal stress contributed to coral bleaching events in 2016 that impacted a large proportion of reefs and dependent fish communities in the Central and Western Pacific, and may be indicative of expected change and biological response over the next century (van Hooidek *et al.*, 2016; Kayanne, 2017).

Warming conditions may also present novel opportunities, especially in northern regions. Anomalously warm summer SSTs in the Chukchi Sea in 2007 were associated with high abundances of juvenile pink and chum salmon in the area (Eisner *et al.*, 2013). These salmon returned as adults to coastal regions in relatively high numbers during 2008 (pink salmon) and 2009/2010 (chum salmon) as reported by subsistence users in coastal communities. The loss of ice and a longer ice free season may bring opportunities for new development and increased shipping activity in the Arctic, but also imply increased risks to fish populations, to the broader ecosystem, and to subsistence users and commercial fisheries from disturbance to species, interruption of hunting and fishing access, accidental oil spills, contaminants, and other impacts (IPCC, 2014).

6.3.2 Shifting fish and shellfish distributions

In response to warming conditions, fish may move to reduce thermal stress, escape increased predation, or follow shifting prey resources. Shifting distributions may be more apparent in the Northeast Pacific than the Northwest Pacific because latitudinal SST gradients are steeper in the Northwest Pacific at the convergence of the subtropical

and subarctic WBCs. Therefore, while warming may manifest in the WBCs, latitudinal shifts of marine biota in the Northwest Pacific may be difficult to detect (Masuda, 2008).

In contrast, the stretch of continuous coastline in the Northeast Pacific from the cold waters of the EBS and GOA to the warm waters of the Baja Peninsula represents a migration corridor where some of the earliest evidence of climate-induced range-shifts in the region may emerge. Northward shifts are anticipated for many southern species. Indeed, temperature-correlated shifts in distribution are evident in the EBS (Pinsky *et al.*, 2013; Poloczanska *et al.*, 2013), but are often confounded by changes in size composition and abundance (Barbeaux and Hollowed, 2018; Thorson, Ianelli and Kotwicki, 2017). Anomalously warm conditions across the Northeast Pacific in recent years (2014 to 2017) were associated with shifts in fish and shellfish distributions, including large declines in Pacific cod in the GOA and southern EBS and concomitant increases in survey catch per unit effort of Pacific cod, blue king crab (*Paralithodes platypus*) and walleye pollock in the Northern Bering Sea (Siddon and Zador, 2017). Further south, the 2014 to 2016 warming had strong negative effects on anadromous species such as Pacific salmon, yet had positive effects on the southern California sportfish community by bringing new predatory fish into the region. While shifting distributions are apparent and increasingly documented, the degree to which shifts are the direct result of climate-driven changes versus cumulative outcomes of fishing pressure, changes in prey resources, autocorrelated demographic patterns, or other unmeasured habitat features remains an active area of research (Thorson, Ianelli and Kotwicki, 2017).

Significant changes in fish and shellfish distributions are projected for the entire North Pacific region, with regional differences expected (Pinsky *et al.*, 2013). In the Northeast Pacific, pelagic marine communities are projected to shift poleward at a rate of approximately 30 km/decade (Cheung *et al.*, 2015), which would result in range expansions into the northern EBS, and range contractions in the Aleutian Islands and California Current ecosystems. It is important to note however that these projections do not account for demographic effects that influence realized distributions (see Barbeaux and Hollowed, 2018; Thorson, Ianelli and Kotwicki, 2017). Climate change may also impact the distributional ranges of fish species in the Yangtze River and Yellow River estuaries (Shan *et al.*, 2016). Bioclimatic envelope model projections based on the Geophysical Fluid Dynamics Laboratory projections of global water temperatures under low, moderate, and high CO₂ scenarios (RCP2.6, RCP6.0 and RCP8.5, respectively) suggested increases in fish abundance and distribution (particularly for demersal fish) under high CO₂ scenarios (but without considering fishing and other human activities). Projections include a shift in abundance from the northern Yangtze River estuary in 2030 to southern waters by 2050, and a more uniform offshore distribution with the centre of abundance mainly around Chongming Island coastal waters. For the Yellow River estuary, projected abundance was highest outside of the estuary, and lower in Laizhou Bay and coastal waters of the Yellow River estuary (Shan *et al.*, 2016).

In addition to latitudinal shifts in distribution, many species are projected to move into deeper cooler water as conditions warm. Indeed species moved deeper and northward in response to the marine heatwave of 2015/2016, although depth and age-specific metabolic constraints may limit realized patterns of groundfish redistribution within each region (Deutsch *et al.*, 2015; Rutterford *et al.*, 2015). The realized extent of depth redistributions will likely be shaped by oxygen conditions, which are projected to decline at depth for many areas in the North Pacific and may limit species to shallower habitats (Deutsch *et al.*, 2015). Current envelope models that do not include ontogeny or other constraints such as oxygen and pH may underestimate the impact of climate-driven changes as the scope for behavioural adaptation may be less than expected because of age-specific physiological limitations.

6.3.3 Changes in phenology and mismatch

Changes in ocean circulation in combination with changes in food availability and predator distributions may increase the probability of spatial mismatch of species with habitats and prey resources and reduce juvenile recruitment and survival. This may be the case for crab species such as the Bristol Bay red king crab (*Paralithodes camtschaticus*), which are expected to decrease under climate change based on observations of low recruitment in warmer conditions, transport of larvae beyond their prime habitats in warmer years with more on-shelf transport, and poor feeding conditions for crab larvae during early ice melt years (Zheng and Kruse, 2006). Spatial mismatch during warm years has also been observed for juvenile walleye pollock and their key prey in the Bering Sea (Siddon *et al.*, 2013). Changes to upwelling dynamics in marine nearshore environments as well as alteration of freshwater flow and differential rates of warming between natal streams and marine environments could result in changes to outmigration timing of juvenile Northeast Pacific salmon and potential phenological mismatch with marine prey and predator refuge during a critical early-marine population bottleneck (Bakun *et al.*, 2015; Holsman *et al.*, 2012).

Mismatch under climate change may particularly impact species with narrow bioclimatic envelopes (e.g. width of the timing interval in which individuals must enter the breeding habitat), those where the relative rate of change within a bioclimatic envelope exceeds the inherent phenological plasticity of the species, and migratory species whose timing is cued by photoperiods or other non-temperature cues (Anderson *et al.*, 2013). In these cases, population size might not be a reliable indicator of sensitivity, rather variability in average individual condition across years may be a better indicator of extinction risk under climate change (Anderson *et al.*, 2013).

6.3.4 Ocean acidification impacts

One of the potentially significant, yet uncertain, impacts of climate change on marine ecosystems in the North Pacific is ocean acidification. The Northeast Pacific region naturally has low pH waters near the surface, and may be more vulnerable to acidification than other regions. Shellfish resources are probably most sensitive (Haigh *et al.*, 2015), especially juvenile stages of shell-forming species like red king crab (Long *et al.*, 2013).

Fish-killing algae such as *Heterosigma akashiwo* may gain a competitive advantage under ocean acidification, causing blooms to be more frequent and threatening the commercial British Columbia salmon fishery (Haigh *et al.*, 2015). Ocean acidification also negatively affects some ecologically important components of the food web, in particular shelled planktonic organisms such as pteropods (Bednaršek *et al.*, 2012), which can serve as important prey for fish (Armstrong *et al.*, 2008). However, pteropods may be more resilient than previously believed (Peck *et al.*, 2018) and the food web effects of such impacts are highly uncertain. Although ocean acidification has been shown to affect the growth, survival, sensory abilities and behaviour of some fish species, studies of walleye pollock and Pacific cod did not find direct effects on growth or survival (e.g. Hurst, Fernandez and Mathis, 2013).

6.3.5 Cumulative climate-driven impacts

Projected changes in ocean circulation and upwelling in the Northeast Pacific CCS may have significant ecosystem impacts, as evidenced by the pan-trophic ecosystem disruption observed in the CCS in 2005 as a result of delayed upwelling (Barth *et al.*, 2007). Along the eastern boundary of the North Pacific, a warming of the upper ocean could lead to an increase in water column stratification and increased probability of low oxygen conditions in the CCS. Ecosystem impacts of deoxygenation may include more frequent mortality events, particularly for benthic organisms, habitat compression, distributional shifts, and reduced species diversity (Keller *et al.*, 2015). Impacts from

declining oxygen levels will be exacerbated by ocean acidification, especially in the Northeast Pacific, where upwelling of “corrosive”, low pH waters frequently occurs (Ekstrom *et al.*, 2015; Feely *et al.*, 2008). A modelling study by Kaplan *et al.* (2010) estimated a 20 percent to 80 percent decline in the abundance of some commercially valuable West Coast groundfish as a result of ocean acidification, primarily because of the loss of shellfish prey.

The ability for species to adapt and respond to changing conditions will be governed by the compound constraints posed by multiple pressures and stressors as well as the physiological tolerance and genetic plasticity of individuals. Small populations that have been bottlenecked or genetically homogenized are more susceptible to stressors. Hatchery raised Pacific salmon lack genetic diversity, and spawning with wild populations can reduce a population’s genetic fitness and ability to cope with stressors such as increased temperature. Genomic scans have been used to identify the genetic architecture of disease resistance, particularly in Pacific salmon (Miller *et al.*, 2014) and have illustrated a genetic basis for species’ intolerance to disease.

Ecosystem health and productivity may also be impacted by climate change. Shan, Chen, and Jin (2017) evaluated future fishery ecosystem health (based on environmental conditions, fishery community structure, and ecosystem function and service) of the Yangtze River and Yellow River estuaries and found that ecosystem health indices gradually decreased with increasing greenhouse gas emission levels. By 2050, ecosystem health indices were roughly three times higher in highly mitigated CO₂ scenarios (RCP2.6) than unmitigated CO₂ scenarios (RCP8.5).

6.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

6.4.1 Fishing and post-harvesting operations

Changes in the location of fish resources could impact fishery access and cost, especially for small vessel and shore-based fisheries that may not be able to track climate-driven changes in species distributions and centroids of biomass. In Canada’s Pacific waters, biological impacts from climate change, such as ecosystem and fisheries degradation and damage, changes in biological resources, and species reorganization and displacement, have been proposed as the greatest risks to the region (DFO, 2013). Shifting distributions of some important fish species may especially pose a challenge to shore-based fisheries where harvest allocations are tied to central ports and fisheries are limited in their capacity to follow fish redistributions (Pinsky and Fogarty, 2012). For example, in Alaska some commercial fish and crab species may expand summer feeding migrations into the northern Bering Sea and Chukchi Seas. However, the shallow shelves of the Arctic will continue to cool to near-freezing for extended periods each winter, potentially excluding most boreal species from the region and limiting the establishment of new spawning areas for southern species (Hollowed *et al.*, 2013). Moreover, northward expansion of the commercial fishery, and the establishment of new fisheries, are limited in the northern Bering Sea and are prohibited in the United States of America portions of the Chukchi Sea and Beaufort Sea by existing national laws and in the central Arctic Ocean under an international agreement. Fishing in these areas is presently composed of limited non-trawl commercial fisheries and subsistence harvest of salmon and other fish species in addition to hunting activities, which have been disrupted by changes in ice extent and thickness (Fall *et al.*, 2013; Huntington *et al.*, 2013). Northward movement of fish populations in combination with loss of sea ice may increase trip time and fuel cost for shore-based commercial vessels (which are presently based in the southern EBS) and reduce access to commercial fishery resources (as fish move into fishery closure areas).

In addition to temperature, changes in ocean circulation and primary production may alter fish distributions. For example, projected expansion of the North Pacific Transition Zone may result in further distance travelled for fisheries from the Hawaiian islands, and redistribution of species richness and carrying capacity for marine taxa (Hazen *et al.*, 2012; Woodworth-Jefcoats, Polovina and Drazen, 2017). Similarly, in the Northwest Pacific the path of the subarctic Oyashio recently shifted northeastward (Kuroda and Yokouchi, 2017) shifting fishing grounds of Pacific saury to the northwest and across transboundary lines, presenting a significant problem for small fisheries which do not have rights to cross the international border and are limited in their ability to travel to distant fishing grounds.

Ocean acidification may directly impact shellfish fisheries. Projections that account for the effects of anticipated changes in ocean pH on red king crab larval survival (and assume no acclimation to acidic waters) suggest substantial declines in the harvestable biomass in coming decades (Punt *et al.*, 2014). The welfare loss of ocean acidification on one major red king crab stock (Bristol Bay) to Alaska households has been estimated at USD 500 million to USD 1 billion over the period from 2010 to the end of this century but may be underestimated because the authors only included effects on juvenile stages (Seung *et al.*, 2015). Ocean acidification also affects the hatching success and larval growth and survival of Tanner crab (*Chionoecetes bairdi*) in Alaska and projections that account for these effects suggest a more than 50 percent reduction in catch potential and profits within 20 years (Punt *et al.*, 2016).

Shifting prey resources and conditions can also impact the quality and value of harvested fish. Low fish condition and quality was reported for EBS pollock in 2016, where water temperature was the highest on record, and may have contributed to adult Pacific cod mortality in the GOA (Barbeaux *et al.*, 2017). Warm conditions in 2014/2015 were also associated with poor Chinook salmon condition and size (Daly, Brodeur and Auth, 2017). Similarly, in the Northwest Pacific, saury size is decreasing and future projections indicate further northward shift in distribution and continued reduction of the size of fish (Ito *et al.*, 2013). Since the price of fish strongly depends on fish size and quality, these impacts are serious concerns for fishers.

6.4.2 Communities and livelihoods, and wider societal and economic implications

Differential changes to species productivity and distribution may have disparate impacts on fisheries sectors and fishing communities. For example, commercial groundfish fleets in Alaska can generally be characterized as either catcher vessels, which deliver harvest to shoreside processors and have a large proportion of Alaska-based boats, or at-sea catcher processors that sell processed product directly to first-wholesale market and whose fleet and crew is largely based more than 2 000 km south in Seattle, Washington (Fissel *et al.*, 2017). In the Bering Sea, on average roughly 59 percent of groundfish landings are retained by catcher processors, while in the GOA 86 percent of landings are retained by smaller shore-based catcher vessels. Because of their dependence on discrete processing sites, reduced trip distances, and smaller vessel size, catcher vessels may be less able to adapt to shifting species distributions or increased variability in catch. Salmon harvest similarly is largely conducted by smaller vessels and local fleets out of numerous coastal Alaskan communities, which support the largest salmon fishery for Pacific salmonids. In contrast, larger catcher processors may be able to follow shifting groundfish distributions, and therefore reduce impacts on the Seattle-based fleet.

In addition to tracking changes in fish distributions, fishers that participate in more than one fishery (commonplace in the Northeast Pacific) can adapt to climate-driven change by redistributing effort between different fisheries (Fuller *et al.*, 2017). Such “fisheries connectivity” can help buffer fishing communities from large-scale changes,

so long as central key fisheries remain intact. At the same time, changes to a core fish species (e.g. Dungeness crab in the CCS) can have widespread indirect impacts on connected fisheries. Fuller *et al.* (2017) evaluated fisheries connectivity across ports in the CCS and found that ports such as Santa Barbara (United States of America), which have high diversification across fisheries, are likely most resilient to change despite a high reliance on a central fishery (squid). CCS fisheries are typically generalists and therefore more resilient to sudden change given current fisheries structure. Fishing communities with less diversification may be most vulnerable, as climate-driven loss in individual fisheries could reduce the adaptive capacity of fishers and increase sensitivity to future perturbations (Fuller *et al.*, 2017).

Climate-driven changes in the abundance and distribution of resources impact subsistence harvest success and access and may shape long-term trends for indigenous communities in Alaska. While commercial harvest is currently prohibited in the Northern Bering, Beaufort, and Chukchi seas, subsistence harvest is essential to sustaining indigenous communities in the area (Fall *et al.*, 2013; Haynie and Huntington, 2016; Moerlein and Carothers, 2012). In particular, subsistence harvest in the Northern Bering Sea is influenced by social and ecological conditions that impact the cost of fuel, interactions with and participation in commercial fisheries, the duration and predictability of storms, sea ice extent and thickness, and the location of resources (Fall *et al.*, 2013). Historically, communities have adapted to climate-driven changes, but increasing uncertainty facing local communities in Alaska will shape future adaptation (Fall *et al.*, 2013; Moerlein and Carothers, 2012). Indigenous and First Nations communities throughout the Northeast Pacific and Pacific Arctic are disproportionately at risk to climate-change because of their high reliance on shore-based subsistence and commercial fisheries within traditional territories.

6.4.3 Consequences for fisheries management

Rapid changes in abundance and distribution of fish within a region may impact the ability to assess and manage resources effectively. Fish may move out of survey areas, impacting estimates of abundance and size composition. Climate-driven changes may impact fisheries connectivity and the ability for fishing communities to adjust to rapid change (Fuller *et al.*, 2017). Novel fishery opportunities may emerge that will require rapid development of new fishery management plans. Similarly, new transboundary agreements may need to be developed to help co-manage stocks that shift distributions in response to changing conditions. International coordination on surveys, and joint assessment efforts, like those used presently to manage Pacific halibut and Pacific hake in the Northeast Pacific, may be needed for other mobile fish and crab species. Finally, shifting distributions and changes in abundance may lead to new “choke” fish species (i.e. those with low quotas that are caught as bycatch and limit other fisheries), presenting the need for rapid evaluation of bycatch hotspots, avoidance methods, and technologies to avoid incidental capture. Continued development of ecological forecasting methods, in combination with support for in-season monitoring and regulation (like that used by the groundfish fleets in Alaska to reduce salmon bycatch), is needed to minimize climate impacts on fish species and avoid sudden fishery closures.

Shifting conditions and species phenologies can have direct and indirect effects on fish and fisheries that may be difficult to anticipate but may present novel challenges for fisheries management. For example, entanglements of baleen whales in the CCS reached recorded high numbers in 2015 and 2016 as a result of the combined effects of recovery of humpback whale populations, environmental shifts in distribution of whales, and environmental changes in fishing effort (NMFS, 2017b). The marine heatwave from 2014 to 2016 increased densities of forage fish near-shore, which resulted in a similar shift in foraging humpback whales. At the same time, a large HAB and elevated domoic acid (neurotoxin) levels in invertebrates resulted in a later start

date for the Dungeness crab fishery. A higher fishery effort (compensating for the delayed start of the fishery), combined with the distributional shift in foraging whales, resulted in greater overlap and risk of whale entanglement. As anomalous warm-water events are predicted to increase in the future (Di Lorenzo and Mantua, 2016), unforeseen overlap between protected species and fisheries may create new conflicts, requiring proactive and adaptive approaches to fisheries management.

6.5 VULNERABILITY AND OPPORTUNITIES FOR THE MAIN FISHERIES AND THOSE DEPENDENT ON THEM

Through the highly productive capture fisheries of the region, the North Pacific represents a significant source of provisioning resources for global marine protein. Regional fisheries are also highly integral to the economic and cultural identity of dependent communities and nations in the North Pacific and Pacific Arctic. Multiple climate-driven interacting changes are anticipated for the North Pacific, with outcomes that remain uncertain but may be significant relative to historical conditions. In an updated analysis on the national vulnerability to the impacts of climate change on marine fisheries, which included assessment of aggregate indices for exposure, sensitivity and adaptive capacity, Blasiak *et al.* (2017) ranked China 8th, the Russian Federation 48th, Canada 54th, South Korea 129th, Japan 137th, and the United States of America 142nd out of the 147 countries they examined. As an example of vulnerabilities in Canada, Weatherdon *et al.* (2016) conducted a study of the potential impacts of climate change to the coastal First Nations of western Canada and found that climate change is likely to reduce the availability of marine species that are of nutritional, cultural and economic importance, possibly by up to 49 percent for Pacific herring, with estimates of annual losses between CAD 6 million and CAD 12 million (equal to approximately USD 4.7 million–USD 9.3 million at the time of writing). In addition, the availability of salmon for harvest is predicted to decrease by 17 percent to 29 percent. They concluded that First Nations' territories along the northern and central coasts of British Columbia, Canada, will likely experience less severe declines than communities in southern British Columbia. Similarly, Hunter *et al.* (2014) examined the sensitivity of Canada's Pacific fish stocks to climate change based on assumptions that 1) more productive species will be more resilient; 2) species with higher dispersal ability will be more resilient; and 3) species that do not rely on seasonal environmental cues or multiple habitats for key phases of their life cycle will be more resilient. They concluded that the most sensitive species are elasmobranchs, whereas the least sensitive are flatfishes.

6.6 RESPONSES AND ADAPTATION

Managing resources in a changing environment requires a balance between the trade-offs and benefits of multiple, competing objectives which requires flexible governance and management (King, McFarlane and Punt, 2014). An analysis of the adaptation of the Canadian commercial fishing sector to climate change, as governed by institutional processes and practices, notes that even economically important fisheries within a region vary in their adaptive advantages because of differences in governance regimes. For example, the crab trap fishery was assessed as low–moderate in adaptability as a result of current governance attributes (e.g. allocation agreements) that may act as barriers if the cyclical population dynamics change under climate change. Conversely, the Pacific halibut fishery was assessed as highly adaptive since there are advanced governance arrangements and management attributes that enable adaptation to shifts in productivity. Similarly, in the United States of America recent national and regional strategic initiatives have been aimed at supporting climate-ready fisheries management (Busch *et al.*, 2016; Sigler *et al.*, 2016a) and vulnerability assessments have highlighted vulnerable species and fishing communities (Colburn *et al.*, 2016; Hare *et al.*, 2016;

Himes-Cornell *et al.*, 2016). Highly adaptive fisheries often require governance regimes that include fishery-governance cooperation, stakeholder involvement, and resource co-management; high monitoring and enforcement capacity; compliance with effort, area and time restrictions; complex multi-sectoral fisheries allocation processes and international fisheries governance negotiations; sophisticated stock assessments and harvest control rules that increasingly include management advice for environmental effects; adoption of climate-sensitive policies and timely fisheries management review (Busch *et al.*, 2016).

Measures to promote resilience of fisheries under climate change might include:

- **Continued development of climate-informed management tools** that include flexibility for allocations, ability to switch quota between species, new fisheries management plans, increased foresight into population changes and fishery closures, adjustable rebuilding plans, and re-evaluation of closure areas. Such changes also require pre-specified criteria for when to adjust targets in order to reduce the risk of ratcheting targets that amplify declines.
- **Evaluation of climate-informed management tools** through climate-driven management strategy evaluations and ecosystem risk assessments should be used to help ensure climate-ready fisheries management (Holsman *et al.*, 2017).
- **Increased innovation to help reduce bycatch**, for example through predictive ecological forecasts of conditions and species distributions, flexibility in bycatch allocation measures, and novel incentive structures for reducing bycatch.
- **Continued evaluation and conservation of existing and emergent critical habitats, migration corridors, and spawning areas**, including considerations of dynamic and adaptive closures.
- **Incorporation of projections into business models** and enhanced infrastructure to scope new shore-based processors in the Northern Bering Sea.
- **Increased ability for local communities to adapt** through co-management and updating subsistence permits to include species that are resilient to and favoured by changing conditions. Increased communication with local communities to improve observations of change and predictions of impacts (through local ecological knowledge) and facilitation of local adaptive policies identified by tribal councils and co-managers and regional governing bodies.
- **Continued reduction of cumulative impacts on ecosystems and fishing communities** through policies aimed at increasing ecosystem productivity, fisheries connectivity and diversity, improved community resilience, and increased efficiency to reduce economic burden and cost of fishery harvest.
- **Distribution of carbon taxing** to improve local and individual adaptation policies.

Negative changes in fish production and extreme events are likely to impact coastal communities with high dependence on individual fishery resources, but such impacts are strongly shaped by the flexibility of fishers and hunters to adjust to changing conditions (Fuller *et al.*, 2017; Haynie and Huntington, 2016) and their ability to utilize novel or expanding species. Marine and fisheries management should therefore include policies that increase flexibility, consider fishery connectivity, and remove roadblocks to adaptation, while incentivizing long-term ecological sustainability. For example, Japanese-type management, “resource management by the resource users themselves” is one approach to increase flexibility (Makino, 2017). While increasing flexibility may seem apparent, it is not always intuitively clear, as unintended outcomes can arise from different policies. For example, rights-based programmes (e.g. quotas) have been advocated as a method to increase sustainability under climate change (Costello *et al.*, 2016), yet can also yield unintended outcomes that may reduce climate change resilience. For example, federal management of Alaska commercial fisheries includes

a series of ecosystem-based management approaches, closure areas, and catch share programmes (which represent 75 percent of groundfish landings) aimed at promoting ecological sustainability and economic benefits (NMFS, 2017a; Stram and Evans, 2009). While such programmes increase long-term investment in a given target species, they tend to lead to reduced diversification in fisheries over time through investment, specialization, and management restrictions that reduce switching between target species. This can lead to increased dependency and reduced flexibility for fishers, and potentially increased vulnerability to collapse under future climate change and extreme events (Kasperski and Holland, 2013). The effectiveness of various management approaches also depends on future socio-economic conditions that can influence resources and support for fisheries science and environmental data. Indeed, the optimal mix of fisheries management may include multiple integrated layers of policies that promote diversification and flexibility at multiple scales, enhance management responsiveness, and incentivize stewardship and self-regulation.

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