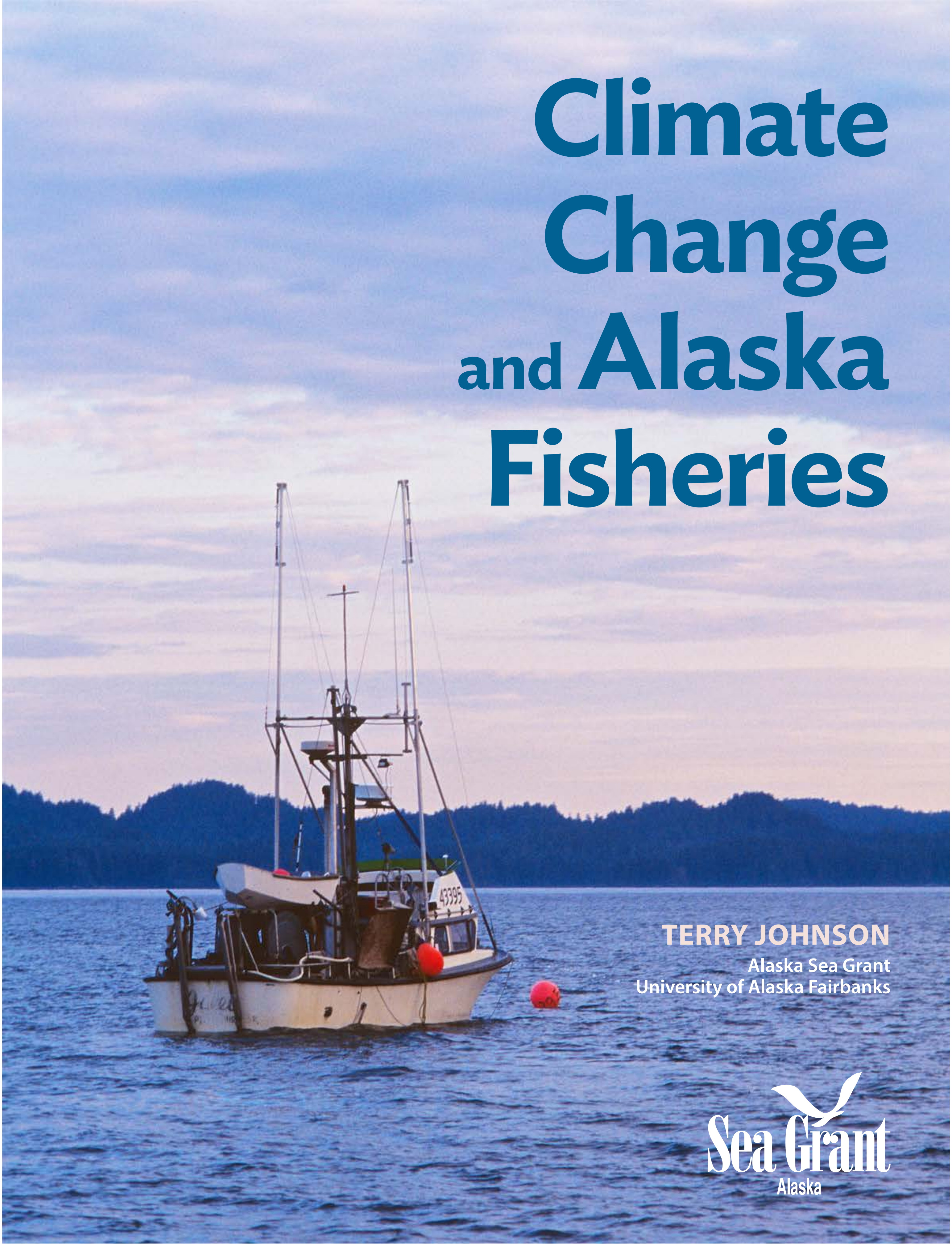

Climate Change and Alaska Fisheries

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ABSTRACT

This report summarizes the current state of knowledge on North Pacific Ocean climate change and its anticipated effects on Alaska's fisheries through the middle of this century. It is based on results of scientific research, and observations recorded by the public and industry. The publication focuses on fisheries effects attributable to progressive long-term warming and also looks at effects of transitory climate variability phenomena like El Niño and Pacific Decadal Oscillation, as experienced in Alaska waters and in waters of US West Coast states and British Columbia. It also considers effects of changes in ocean chemistry, commonly referred to as ocean acidification.

The first sections describe categories of climate-related change and the final two sections address human adaptation responses in the public sector and by private industry and individuals.

Take-home messages

- The sea is changing—it's getting warmer (overriding decadal scale variations), sea level is rising, sea ice is decreasing, and water chemistry is changing.
- Invasive species, harmful algal blooms, and disease-causing pathogens already are becoming more common and are harming indigenous fish and shellfish and threatening human health.
- Commercially valuable fish stocks are undergoing changes in distribution, abundance, and behaviors. Any projections for stock abundances in the future are very tentative, and observed trends may be specific to regions or locations. Major abundance shifts, if they do occur, will develop over a period of decades.
- Hard times may be coming for Bering Sea pollock and some crab stocks and the fisheries that depend on them.
- Most Alaska salmon stocks probably will continue to prosper and some may increase or expand their range.
- Exploitable halibut biomass may increase from current levels.
- Other species, including Pacific cod and some flatfish, may experience range extension or stock level increases but changes will be highly variable from one stock to another.
- Research and regulatory agencies are preparing for "climate ready" fisheries management, though regulatory options for climate change adaptation are limited. Some fishermen and fishing communities have begun to apply adaptive measures but in the future they may have to make bigger changes in the way they do business.

Note: This report focuses on progressive long-term climate change, not anomalous weather, nor inter-annual or multi-decadal climate variability. For example, the 60-year gradual upward trend in air temperatures can be viewed as climate change, while El Niños raise temperatures dramatically but temporarily, and occur sporadically. Likewise, ocean climate regime shifts, which are characterized by warmer or cooler (plus or minus 2 degrees C) seawater temperatures, persist over periods of 7–10 months to as much as 30–40 years and may reflect warm ("positive") and cool ("negative") phases of the Pacific Decadal Oscillation. While there are indications that the frequency and intensity of these events are driven by long-term climate change, they are not manifestations of long-term climate change per se.

Scientists create statistical models intended to predict future effects of long-term change based on data derived from these more transitory climate phenomena. Similarly, observing biological effects of climate on the US West Coast states and British Columbia, which also are experiencing higher temperatures, may provide clues about what to expect in Alaska when long-term temperatures here reach levels now extant in the Northwest.

INTRODUCTION

"It is very difficult to judge at a global level who the main losers and winners will be from changes in fisheries as a result of climate change, aside from the obvious advantages of being well-informed, well-capitalized and able to shift to alternative areas or kinds of fishing activity (or other non-fishery activities) as circumstances change."

—Keith Brander, Technical University of Denmark (2010)

Alaska is home to the nation's largest commercial fisheries, with an average of $1.5 billion annually in ex-vessel value and $3.6 billion in processed value, and drives an estimated $5.8 billion in economic activity. A small but growing shellfish mariculture industry adds up to a million dollars annually. Alaska's oceans support vital subsistence and personal-use fisheries, and through sport fishing they contribute substantially to a more than $1 billion recreation and tourism industry.

At the same time Alaska is on the front line of climate change. Over the last 60 years Alaska has warmed more than twice as rapidly as most of the United States. The US Environmental Protection Agency reports that average annual temperatures in Alaska have risen 3.4 degrees F (winter temperatures have risen 6.2 degrees F) during that period and some projections call for another 2–4 degree increase by the middle of this century (Chapin et al. 2014, ch. 22). Most of that warming occurred around the 1976 "regime shift" when the North Pacific Ocean climate transitioned from a cool to a warm phase. The more recent return to a cool phase during the period 2006-2013 moderated the trend somewhat in the North Pacific but the warming resumed in 2014. The Arctic is warming more rapidly than the middle latitudes, and this warming manifests itself dramatically in a decrease in Bering Sea and arctic sea ice coverage and in the timing of sea ice advance and retreat.

Scientists say 90–95% of the accumulated increase in heat on this warming planet is contained in the oceans, most of it so far in the upper 2,300 feet of the water column, although scientists recently have documented heat penetration to lower layers. Because of the immense capacity of the ocean to absorb heat, the seas are not warming as quickly as the atmosphere but the heat is in the water and is being distributed around the globe, with unknown future consequences.

Ocean acidification—a phenomenon related to atmospheric carbon dioxide (CO_2)—is showing up in Alaska's coastal waters. Consequences for the fisheries could be severe if worst-case scenarios are realized.

Despite the increasing volume of climate- and CO_2-related data, however, **observable impacts of long-term climate change on Alaska's fisheries so far have been few and for the most part relatively mild.** In a few cases there have been more dramatic responses to short-term climate variation and those events indicate a capacity for resilience to short-term perturbation. Most commercially important stocks continue to prosper and most sport and subsistence resources remain within the normal range of variation. There are some notable exceptions, such as the widespread decline of Chinook salmon and the dramatic decrease in halibut recruitment and size-at-age, but so far neither has been attributed directly to climate change or ocean acidification.

However, stakeholders in fisheries-related industries and fisheries-dependent communities are looking for ways to understand, prepare for, and adapt to changes that they know are certain to come.

Conclusions in this report are preliminary since the science is constantly advancing. At the same time human ingenuity is rapidly developing technologies and behavioral responses to new challenges.

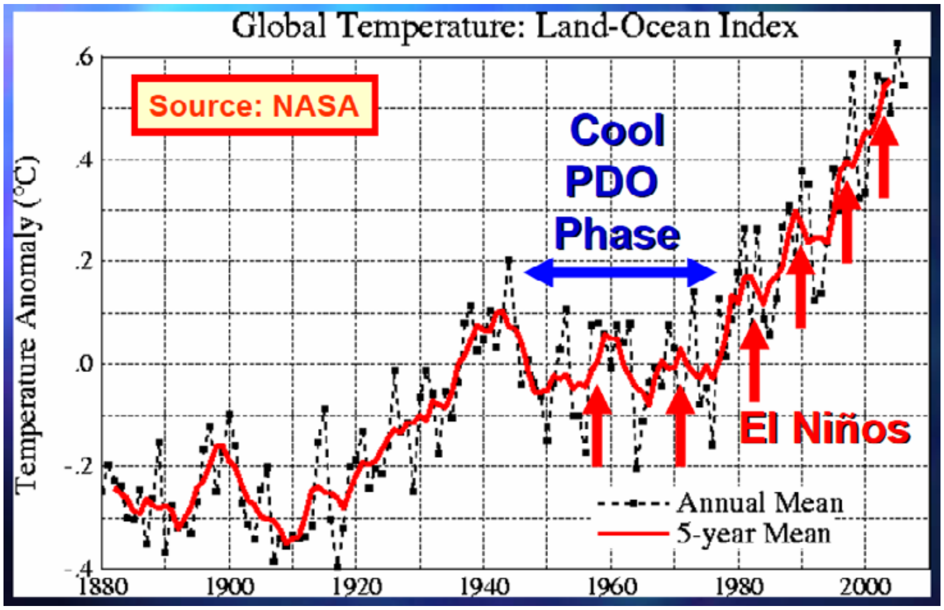
1 OCEAN TEMPERATURE AND CIRCULATION

> *"There are three basic ways that a species can survive climate change. It can move, it can adapt, or it can hunker down—that is, hang out in whatever remnants of its former range are still suitable."*
>
> —Michelle McClure, NOAA fisheries biologist

The changing climate affects the ocean environment physically, chemically, and biologically. The **ocean is warming.** The global sea surface temperature (SST) has increased about 1.1 degree F since 1950 and the North Pacific winter temperature is on track to increase another 1.8–2.9 degrees F by 2050 (National Wildlife Federation 2011). Researchers studying the Gulf of Alaska in 2014 recorded surface temperatures 1–5 degrees F warmer than the long-term average (Card 2014). Most of the ocean warming since the dawn of the Industrial Revolution has occurred in the last 20 years. If atmospheric scenarios from the Intergovernmental Panel on Climate Change (IPCC) prove accurate, the long-term rate of ocean warming will continue to accelerate. (See the section below on effects of transitory temperature variations.)

Atmospheric warming at higher latitudes increases freshwater inputs and the potential for temperature and salinity stratification in the water column, which can disrupt primary productivity of the system, particularly phytoplankton (microscopic plants that are the base of the marine food web) production due to lack of nutrient replenishment. The number of oxygen-depleted "dead zones" worldwide is increasing (Holmyard 2014, p. 7). Since the warmer the water the lower its capacity for holding oxygen, **hypoxia** or oxygen starvation has depressed some fish stocks on the US Pacific Coast, and dead zones have rendered expanses of the ocean off the three Pacific coast US states devoid of commercially valuable fish resources.

Increased energy in the atmosphere from warmer temperatures causes changes in pressure cells and the accompanying wind currents that can increase the **frequency and intensity of storms** (Haufler et al. 2010, p. 12). Satellite altimeter radar data indicate that mean significant wave height in the Pacific-arctic region is increasing by about 1 inch per year (NOAA National Climate Assessment). On the Pacific Northwest coast storm wave heights have increased by as much as eight feet and deliver 65% more force when they batter the shore (Tillman and Siemann 2013). Coastal battering accompanies erosion, storm surges, and



Despite periodic cooling phases, long-term average temperatures over the last century have increased. Source: NASA.

flooding/inundation. Storms also bring extreme precipitation events and can drive surface ocean currents in atypical patterns, affecting migration routes and primary productivity, both of which influence the abundance of fisheries resources.

While precipitation is increasing, more of it comes in brief and intense episodes that cause **flooding and streambed scouring**. At the same time the soil is becoming drier, **stream flows are diminishing, and stream temperatures are rising.** In some regions lakes are drying up.

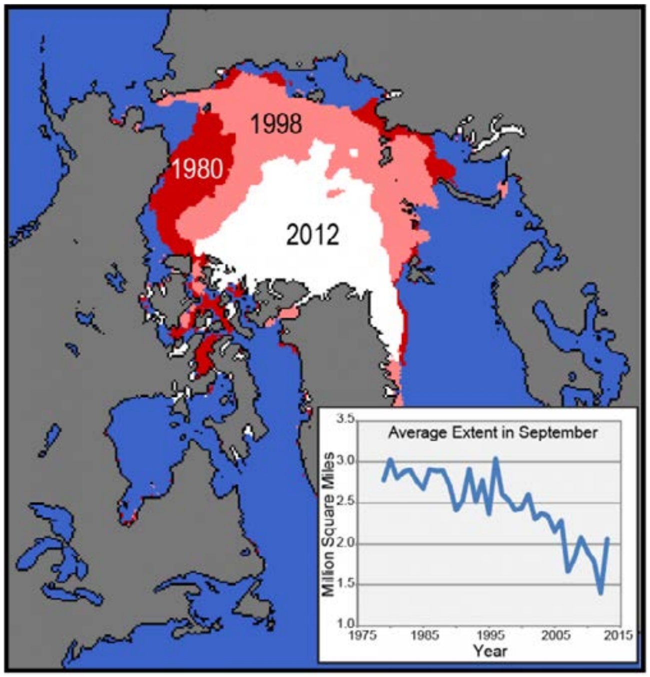
(Drier landscapes and increased precipitation are not mutually exclusive. In a drier world more precipitation falls as rain rather than snow, and more often in episodic severe storm events. Most of the water flushes rapidly out of streams and rivers; at the same time higher temperatures increase evapotranspiration and evaporation during a longer frost-free season, leaving soils drier most of the year. Severe storms and flooding are harmful to salmon spawning and rearing success and damage stream habitat.)

The warming climate also means shorter winters (or the number of days in which air temperatures are below 32 degrees F). This may cause winter precipitation to shift from being mainly snow to rain, particularly on the Gulf of Alaska coast. Most snow is stored in the mountains until spring and summer melt, when it can reach the ocean. If temperatures are above freezing for much of the winter the rain drains rapidly into the ocean because of the steep, short watersheds. This changes the timing of the river discharge cycle, which may have huge implications for the Gulf of Alaska shelf. Freshwater runoff is much lighter than saltwater so this runoff stratifies the coastal ocean. The spring phytoplankton bloom requires stratification, but this bloom may occur earlier if the ocean stratifies earlier, and it may not be available to the zooplankton that migrate onto the shelf in the spring. Thus the zooplankton may show up "anticipating" the spring bloom and find that it has already occurred. This would make the zooplankton population less productive and this decrease in production would be reflected in the fisheries that depend on zooplankton (Tom Weingartner, University of Alaska Fairbanks, personal communication).

Sea level is rising globally by about one-eighth inch per year, and the rate is increasing. For now, this rise is imperceptible in most of Alaska because most of the coastal land is still rebounding after the retreat of the glaciers. But some low-lying areas in western and northwestern Alaska are experiencing increased flooding during storm events. Sea level rise is caused both by thermal expansion of ocean water and by melting of glaciers and ice sheets over land. Scientists predict world sea levels eventually will be higher than they are now by three feet or more. Little is known about the net effect of sea level rise on fisheries resources; it can affect either negatively or positively the productivity of estuaries, which are important fish and shellfish rearing areas.

In the Arctic and Bering Sea the extent and thickness **of sea ice is diminishing,** with formation coming later and ice pack retreat coming earlier than only a few decades ago. The rate of decrease is expected to accelerate. Seasonal ice coverage has diminished by nearly 12% per decade since the 1970s (US EPA undated) and by 2050 seasonal ice coverage is expected to have diminished by 40% from current values. Floating ice reflects solar radiation back into space (the albedo effect) so decreased ice coverage means more solar energy is absorbed by the sea, increasing the rate of ice coverage loss and ocean temperatures.

Sea ice suppresses storm waves and when land-fast ice forms late in the fall storm season



Minimum annual sea ice extent has been decreasing. Source: NSIDC 2012.

the result can be increased beach erosion and flooding of low-lying coastal villages. Free-floating sea ice serves as a resting and foraging platform for various important marine mammal (e.g., walrus and polar bears) and seabird species. On the other hand, decreased sea ice allows more sunlight penetration and increases production of some kinds of plankton, and affords fishing vessels increased access to potentially productive waters.

Storms also can have the **beneficial effect of improving water column mixing,** which brings nutrient-rich water to the photic zone where sunlight penetrates, stimulating plankton growth.

How winds and temperature influence currents and biological productivity

Most species of fish and shellfish cannot tolerate significantly elevated temperatures. Sensitivity may relate to dissolved oxygen levels in the water, to diseases, or simply to temperature-related physiological stress. Temperature effects can begin at the base and work up the food chain.

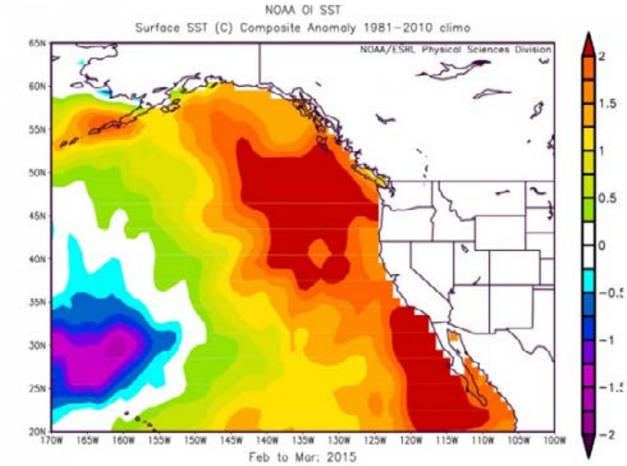
Phytoplankton—the microscopic "plants" that form the basis of the oceanic food web—need nutrients and light energy from the sun. Strong winds, which are most frequent in fall and winter, bring nutrients into the photic zone—the surface layer where solar energy is intense enough to support a phytoplankton bloom. This nutrient mixing fosters high primary productivity if matched with adequate spring and summer solar energy input. However, if summer temperatures are too warm thermal stratification occurs, which blocks nutrients from the ocean depth from reaching phytoplankton near the surface. Timing and intensity of mixing and subsequent phytoplankton blooms must match the abundance of zooplankton, and the eggs and larvae of fish and crustaceans, for optimal transfer of energy to higher levels of the food web and maximum fisheries productivity. Phytoplankton production in the Chukchi Sea has increased significantly in recent decades, apparently due in large part to the decline in seasonal ice coverage that allows more sunlight to get into the water (Pickart 2016).

Two recurrent climate patterns influence this timing and abundance. El Niño/La Niña, otherwise known as the El Niño/Southern Oscillation (ENSO), is a pattern of opposing climate variability that occurs on two- to seven-year cycles, driven by atmospheric forces in the central Pacific. El Niños tend to bring anomalously warm temperatures, above average precipitation on the Gulf of Alaska coast (lower precipitation on the Bering Sea), and temperature stratification that can be detrimental to fisheries productivity. An extreme El Niño can cause shifts in plankton production that causes, for example, massive seabird die-offs for a year or two. La Niñas bring cooler temperatures and more normal ocean climates. Effects of ENSO are more pronounced on the Gulf of Alaska coast than elsewhere in the state.

The other pattern, known as Pacific Decadal Oscillation (PDO), is characterized by longer term periods of cooler or warmer water along the Gulf of Alaska coast, each of which ends with a "regime shift." (A warm phase is warmer along the coast but cooler in the central Gulf.) These regimes, though separated by only a couple of degrees in water temperature, can have profound long-term effects on productivity and favor some species and disfavor others. The 1977 shift to a warmer climate regime in the North Pacific was well studied. It was accompanied by an increase in zooplankton and ushered in a new era of high salmon, cod, and pollock production, but also brought steep declines in forage fish, crab, and shrimp. Less pronounced regime shifts occurred in the late 1990s, 2007, and apparently a return to another warm regime in 2014.

While it is not proven that long-term climate change is causing El Niños or warm PDO phases, there is concern that eventually the long-term prevailing conditions will come to approximate those effects on fisheries productivity.

The **Blob** is an ocean water temperature anomaly. The term was coined by Nicholas Bond, of the NOAA Pacific Marine Environmental Laboratory, to describe an expanse of the North Pacific where upper layer sea temperatures are unusually high. The Blob developed in the summer of 2013, persisted through that winter, expanded and intensified during 2014, and expanded again in 2015 to reach parts of the Gulf of Alaska coast. It consisted of three separate but related areas of warm water spread over more than 2,000 miles between Baja California and Alaska. Along the central Gulf of Alaska coast water temperatures in 2015 were reported to be as much as 4.5 degrees F higher



The Blob, a sea surface anomaly in the northeastern Pacific Ocean, appears in red. In recent years it comprised several distinct areas of anomalous temperature zones. Source: NOAA 2016a.

than normal. By late fall 2015 the Blob was reported to be breaking up but had not yet vanished.

Scientists believe the Blob was caused by a static high pressure cell over the North Pacific that prevented cloud formation and rain, resulting in greater heat absorption and diminished loss of heat into the atmosphere. This blocked winter storms and diminished water circulation, forming a static surface layer of water down to 300 feet. This combination forces more warm water from southern latitudes into the North Pacific (Bond et al. 2015). Scientists are not yet certain whether the emergence of the Blob and other forms of climate variability such as El Niño and Pacific Decadal Oscillation are being driven by climate change in the Pacific Ocean.

The Blob is associated with the appearance of tropical fish and with seabird die-offs in British Columbia and Alaska waters, including a dramatic murre mortality event on the Gulf of Alaska coast and sea lion deaths in California (see harmful algal blooms below). A major concern is the effect the warm water was having on **development and availability of phytoplankton and zooplankton,** which form the foundation of the food chain supporting commercially important fisheries. The warm surface waters form a thermal barrier that inhibits nutrients from being mixed into the surface layer to fuel production of phytoplankton. Furthermore, warm-water currents off the Pacific Coast bring southern varieties of zooplankton, particularly copepods, which have low lipid (fat) content and are less nutritious to fish and birds than the normally available northern varieties of copepods and krill. So far, northern copepods and krill have not disappeared from Alaska waters but if they did it could be devastating for some Alaska fisheries because they provide high-energy nutrition to important commercial species like pollock and some salmon. University of Alaska professor Russ Hopcroft found a marked absence of pollock larvae surviving into late summer in the Gulf of Alaska, associated with the Blob.

The ice algae/plankton connection

A complex relationship exists between sea ice and the fortunes of many stocks of commercially important fish and shellfish in the Bering Sea. **Ice-associated algae growing on the underside of sea ice,** and phytoplankton (such as diatoms) growing in the water column under the ice, bloom in the spring as the ice melts. The blooms support communities of microzooplankton and zooplankton, such as dinoflagellates, ciliates, copepods, and euphausiids (krill), which are the prey of larger predators such as forage fish that in turn feed commercially important species. During cold periods the early primary productivity falls to the bottom where it provides nutrition to benthic organisms but is out of reach to most commercially valuable fish.

Some kinds of krill feed extensively on ice algae, so a decrease in ice coverage equates to a decrease in krill. Timing is important—if the ice melts too early in the spring much of that plankton productivity drops to the seafloor, where it is lost to most finfish.

The large zooplankton appear to **grow and survive more successfully in cold years.** A Bering Sea ecosystem study funded by the National Science Foundation and the North Pacific Research Board found that colder water favors production of large, lipid-rich copepods, an important prey of juvenile pollock. In warm-water years plankton growth and development are faster but overall food web success is lower, possibly because warm winter temperatures may cause them to exhaust energy reserves sooner. Pollock larvae grow quickly during those warm years but like the plankton they appear not to survive the winter due to lower energy reserves.

The silver lining

Concerns over negative impacts of climate change are at least partially balanced by positive outcomes. In cold water regions a modest temperature rise normally increases primary productivity. It tends to improve survival and spur growth up the food chain. Some models indicate an increase in fishery yields of 30–70% in the high latitudes, which would include Alaska (Holmyard 2014, p. 10). However, each specific species and stock responds differently, as mentioned in following sections of this publication. Warming is correlated with improved aquaculture production. Milder winter weather can be a boon to freshwater survival and growth of anadromous fishes such as salmon.

Warmer temperatures, and milder sea conditions that sometimes accompany them, may improve safety and reduce costs for harvesters and processors. Expanded or shifted ranges can bring new fishery resources into a region, or increase abundance of those already there.

Diminished arctic sea ice coverage already is allowing increased vessel access, including more shipping and hydrocarbon exploration, although this development also increases threats of pollution, spills, disruption of subsistence activities, and transport of invasive species.

2 OCEAN ACIDIFICATION

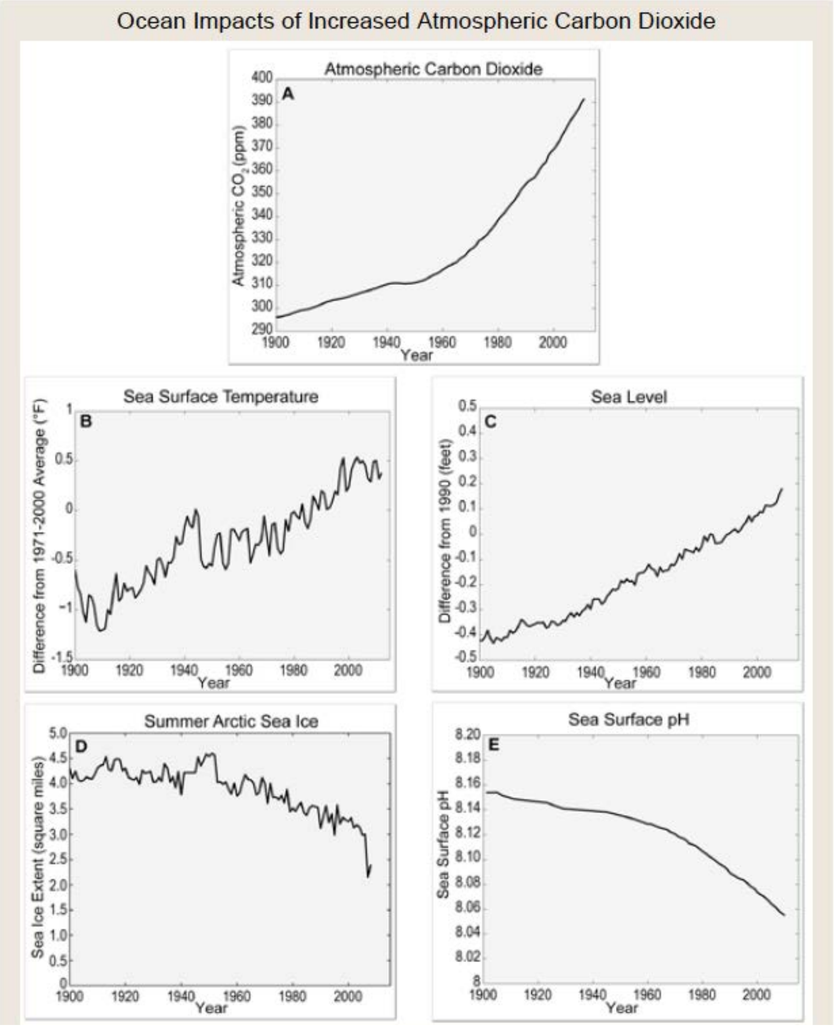
"The oceans always will be productive. The question is, what will they be productive with?"
—Jeremy Mathis, NOAA Arctic Research Office

Ocean acidification is an atmospheric carbon–related phenomenon that is starting to have profound effects on the oceans. It results from the absorption of atmospheric carbon dioxide (CO_2) by seawater. Atmospheric CO_2 has been increasing since the dawn of the Industrial Age and scientists positively correlate it with emissions from burning fossil fuels and other possible sources. Ocean acidification **may bring serious problems to the fisheries.**

The name ocean acidification is somewhat misleading—the ocean isn't acidic, not even close. To scientists "acidification" means that the ocean's pH—that is, the acid-base balance—has shifted slightly from mildly basic to a little closer to neutral. The pH scale goes from 0 (battery acid) to 14 (very strong base such as liquid drain cleaner) with pure water neutral at a pH of 7. Although the pH of freshwater can vary widely depending on the mineralization in the drainage it comes from, freshwater tends to be closer to neutral and rainwater usually has a pH of less than 7. The average ocean pH stands at about 8.1, down from 8.2 since the dawn of the Industrial Revolution, so it remains basic but less so than previously. In some places seawater is more acidic than in others—within the ocean waters of different pH values flow like rivers at different depths.

The pH scale is logarithmic and a 0.1 drop means a 30% increase in "acidity." Scientists predict that under projected levels of atmospheric carbon emissions, the oceans will experience an additional decrease to an average pH of about 7.8 by the end of this century (Ocean Acidification Research Center, undated). Increases in freshwater in the ocean due to glacial melt or increased runoff have the effect of increasing acidification. Freshwater in streams has less concentration of dissolved ions (alkalinity) that can neutralize added acidity of seawater.

Cold water absorbs more CO_2, and some of the highest concentrations of dissolved CO_2 have been measured on the Bering Sea shelf and in the Chukchi and Beaufort Seas. Cold water there, which is also very "old" and has accumulated a lot of CO_2 and nutrients due to bacterial respiration that converts organic material to CO_2 and nutrients, up-



Ocean impacts of increased atmospheric carbon dioxide. Source: Doney et al. 2014.

wells from the deep ocean. Scientists predict that within 15 to 30 years some of those waters will sustain pH levels low enough to be detrimental to survival of some important marine species. Still, Alaska's waters are unlikely ever to become acid.

From king crab to bivalve mollusks to tiny planktonic plants and animals that form the base of the food chain, many marine organisms need calcium carbonate to build and maintain their shells. Normally carbonate ion concentrations are saturated in seawater, and those organisms precipitate either calcite or aragonite they need from the calcium carbonate. But seawater with lower alkalinity can become under-saturated with those compounds. When there isn't enough available calcium carbonate the organisms can't build the platelets and shells they need to grow, and if the saturation level is low enough their shells can actually begin to dissolve, hence the expression "corrosive." Laboratory experiments have produced this result in several species. Jeremy Mathis, a leading ocean acidification scientist, says that by the end of the century "all of the waters around Alaska" will be corrosive at the levels demonstrated in the experiments (Mathis 2014).

"Acidic" or low-pH waters, flow up the continental slope from the deep ocean ("upwelling") and spread across Alaska's highly productive continental shelves. The Bering Sea is particularly vulnerable to acidification due to oceanographic characteristics, and NOAA scientists predict its waters will no longer be sufficiently saturated with calcium carbonate for key species to build and maintain their shells by the year 2044 (Mathis et al. 2015). The Arctic may reach that stage even sooner.

Press coverage has focused on Alaska's **king and tanner crabs** because of their commercial value and because laboratory studies show them to be vulnerable to the effects of ocean acidification. Snow crab and Dungeness appear to be less affected. So far no direct effects on any Alaska crab have been reported but NOAA scientists say that the future of red king crab does not look good due to the increasing acidity of Bering Sea waters.

***Clione limacina,* or sea angel, is a pteropod and a key link in the food chain. Though it doesn't build a shell of its own, it feeds exclusively on other species that do. Photo: R Hopcroft, University of Alaska Fairbanks.**

Another object of concern is the tiny planktonic snail known as a **pteropod,** a key food source for salmon and herring, comprising nearly half the diet of juvenile **pink salmon.** Pteropods grow protective shells so they are vulnerable in low pH waters. In laboratory studies pteropods perish in water of the same carbonate chemistry as is currently being measured at some locations off Alaska. Authors of the report *Climate Change Impacts in the United States* say that a 10% decrease in pteropods could cause a 20% decrease in body weight of adult pink salmon, but they add that studies indicate pteropod consumption by juvenile pinks in the northern Gulf of Alaska varies by as much as 45%, which may reflect the salmon's ability to adapt to changes in prey availability (Chapin et al. 2014).

The industry most immediately threatened by ocean acidification is **shellfish mariculture.** Already, an oyster hatchery in Oregon has lost a crop and had to modify its operations, scallop farmers in British Columbia lost 10 million scallops in 2014, and Puget Sound oyster growers are moving nurseries to Hawaii. Alaska's small but growing oyster farming industry and its two oyster hatcheries are in jeopardy if waters unsaturated in calcium carbonate come to predominate (NOAA 2015d). One NOAA report predicts the Alaska shellfish hatchery industry will come to an end by the year 2040. This conclusion is preliminary and research continues.

On the other hand, some kinds of marine **plants** and **algae** are likely to benefit from predicted changes in pH. They use CO_2 as the carbon source for cell growth, so more CO_2 can mean greater productivity as long as sufficient sunlight and nutrients are present. Edible plants and algae, and ingredients in industrial products, could become new sources of income for fishermen and sea farmers in Alaska. Furthermore, wild kelps and seagrasses are important habitat for larvae and juveniles of commercially important species, although some of them—sea urchins, for example—have shells made of calcium carbonate.

Research in British Columbia shows that elevated CO_2 levels in **freshwater** also can be detrimental to pink salmon. Results indicate that pinks developing in high-CO_2 freshwater are smaller and have a diminished sense of smell and response to danger.

3 INVASIVE SPECIES, HARMFUL ALGAL BLOOMS, AND DISEASE-CAUSING PATHOGENS

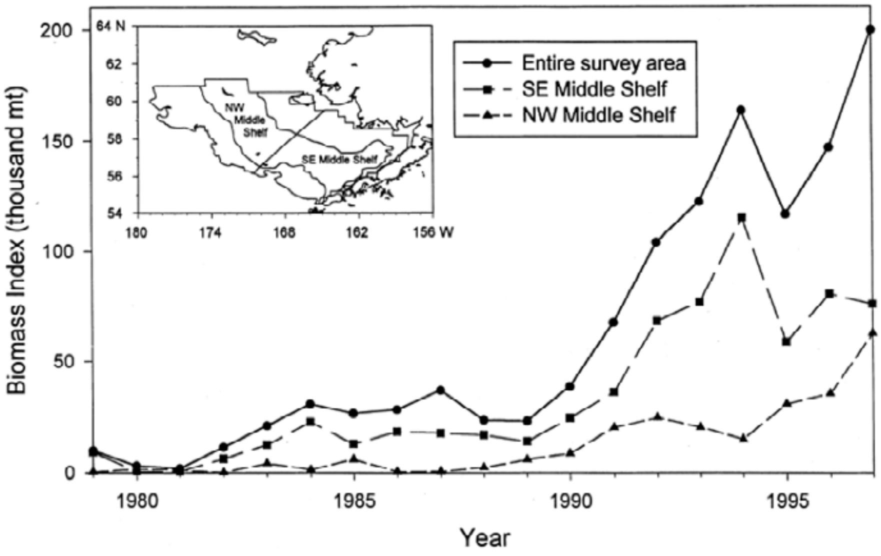
> *"Look down the coast and that's our future."*
>
> —Bruce Wright, marine ecologist, Aleutian Pribilof Islands Association

A warming sea attracts exotic creatures, and can drive an increase in abundance of others that previously were present but not abundant. These can range from the giant ocean sunfish (to 10 feet, 2,200 pounds) to the tiniest microbes. Invasive species and harmful algal blooms (HABs) already have made their mark on the Pacific Coast and are starting to raise concerns in Alaska.

So far Alaska waters seem to support few permanent populations of marine **invasive species** that can be attributed directly to long-term climate change. There is concern about a possible invasion by Chinese mitten crab, European green crab, the tunicate *Botrylloides violaceus,* and the pathogen *Myxobolus cerebralis* that causes whirling disease in salmonids. But of those four only *Botrylloides violaceus* has turned up in Alaska's marine waters, and it is not known to have caused any harm. Green crab is causing the greatest concern because it has the potential to decimate local species, particularly bivalves. It is advancing northward at a steady pace, and now is known to be in northern British Columbia waters (Gary Freitag, University of Alaska Fairbanks, personal communication). Atlantic salmon show up occasionally but their existence is attributed to escapes from mariculture pens in British Columbia and is unrelated to climate. The most vexing actual arrival to date is a colonial tunicate known as *Didemnum vexillum,* a species of sea squirt that suddenly appeared in a Sitka boat harbor a few years ago and has proven difficult to eradicate. Biologists consider *Didemnum vexillum* a threat because when it becomes established it smothers other marine life on the seafloor. But it is believed to have arrived on an aquaculture pen towed up from British Columbia, rather than migrating north in response to a warming sea (NOAA 2015c).

Various pelagic sharks, tuna, and other finfish appear from time to time in Alaska waters with temporary warm-water currents but they haven't become established. Mackerel have come as far north as British Columbia waters and are believed to be competing for prey with juvenile king salmon.

A report from the Arctic Research Centre at Aarhus University in Denmark suggests that the natural biological barrier posed by the harsh arctic climate and extremely cold oceans separating the Atlantic from the Pacific may be breaking down. **This could result in an exchange of fish species, bringing Atlantic stocks previously unknown in the Pacific to Alaska waters** (Wisz et al. 2015). But considering current flow through the Arctic, the reverse is more likely. People in Greenland have found pink salmon in their waters. Ecological and commercial consequences cannot be predicted. The last time the two ocean basins were biologically connected was three million years ago.



Biomass index of jellyfish caught in bottom trawl surveys on the eastern Bering Sea shelf, 1979-1997. Source: Brodeur et al. 1999.

Some indigenous species have experienced a dramatic increase in abundance, such as the gelatinous zooplankton (medusa or jellyfish) of the Bering Sea. From 1982 to 1997, a period of gradually increasing sea surface temperatures, the biomass of medusae increased tenfold. Scientists think changes in seawater circulation patterns related to diminished sea ice improved conditions for the jellies. The dominant species *Chrysaora melanaster* (northern sea nettle or brown jellyfish) preys on pollock larvae and zooplankton (Brodeur et al. 1999). Medusa biomass in the Gulf of Alaska quadrupled over the same time period. Jellyfish abundance has increased in the majority of the world's coastal and ocean ecosystems (Brotz et al. 2012).

Another example of change is the arrowtooth flounder, which has become more abundant in both the Gulf of Alaska and the Bering Sea. It is a predator on and competitor with juvenile halibut.

Harmful algal blooms are of immediate concern. Alaska always has suffered occasional outbreaks of paralytic shellfish poisoning **(PSP),** which is caused by various compounds collectively known as saxitoxins that are produced by the dinoflagellate alga *Alexandrium.* PSP illness usually results from eating infected clams or mussels, and also can come from eating crab viscera. PSP events, which sometimes kill people, apparently are becoming more frequent, though greater awareness and more reporting could partially account for the surge. The years 2014 and 2015 saw record high levels of PSP toxin in some locations. PSP was documented along the entire Gulf of Alaska coast and as far north as the central Bering Sea. There is some indication that decreased populations of marine mammals and of Yukon River Chinook salmon can be explained by PSP: all of the affected species feed on forage fish, such as sand lance, which are known to concentrate PSP toxins from eating zooplankton (Bruce Wright, Aleutian Pribilof Islands Association, personal communication).

A big problem on the US West Coast and a growing threat in Alaska is **domoic acid,** a sometimes fatal neurotoxin that can cause an ailment known as amnesiac shellfish poisoning (ASP). The agent of domoic acid is a group of microscopic diatoms in the genus *Pseudo-nitzschia,* which are ingested and concentrated in shellfish and finfish. Domoic acid is linked to deaths of seabirds and sea lions in California, and even implicated (though not proven) in an unusual mortality event of baleen whales in Alaska. On the Pacific Coast important bivalve and crab fisheries were closed in 2015 due to widespread outbreaks of domoic acid, and the public was warned against eating anchovy and sardines (NOAA 2015e). The toxin was reported as far north as Kachemak Bay, and the commonality in the domoic acid outbreaks was abnormally warm seawater.

According to a 2016 paper published in the journal *Harmful Algae,* domoic acid and saxitoxins are prevalent in 13 species of Alaska marine mammals, including various whales, porpoises, seals, sea lions, and sea otters, based on samples taken from harvested or stranded animals along virtually the entire Alaska coast from Dixon Entrance to the Beaufort Sea (Lefebvre et al. 2016). Another article in the same journal (Roncalli et al. 2016) reports that on the US East Coast a toxic dinoflagellate has been shown to suppress egg production and viability of a highly nutritious calanoid copepod. A dramatic die-off of murres and other seabirds on the Gulf of Alaska coast during 2015–2016 is attributed to starvation; one hypothesis is that there may prove to be a link between the die-off and effects of HABs on the seabirds' food supply (Bruce Wright, Aleutian Pribilof Islands Association, personal communication).

Disease-causing pathogens

Another threat is the bacterium *Vibrio parahaemolyticus,* which causes severe but usually not fatal gastrointestinal infection in people. It is in the same family as the cholera-causing bacterium and is found in raw oysters when sea temperatures rise. ***Vibrio*** outbreaks have occurred at Alaska shellfish farms in recent years. Alaska oyster farmers are conducting careful temperature monitoring to respond proactively.

Consumers of shellfish on the Pacific coast face the threat of another harmful algal malady, known as diarrhetic shellfish poisoning (DSP), produced by the alga *Dinophysis.* So far DSP has not been identified in Alaska.

Outbreaks of PSP, domoic acid, and possibly *Vibrio* in 2015 coincided with an unusual warm water phenomenon on the West Coast dubbed the Blob.

4 FISHERIES EFFECTS—GROUNDFISH AND CRAB

"There are always winners and there are always losers in a changing system, but who those winners and losers will be is hard to predict."

—Phyllis Stabeno, NOAA Pacific Marine Environmental Laboratory

Organisms generally respond to changes in their environment in one or more of the following ways: changing distribution (in space or time), changing productivity, and adaptation—behavioral or physiological (Hollowed et al. 2013).

Changes in oceanographic conditions can affect physiology, growth, reproduction, distribution, and mortality of individual species, or can impact ecosystem structure, food webs, and primary productivity (Brander 2010). This section outlines possible climate change effects on Alaska fisheries resources in general, and specifically on pollock, halibut, and crab. Section 5 addresses salmon.

Worldwide, warmer seawater temperatures are causing a **range displacement or extension** of many species, and in the Northern Hemisphere that is mainly to the north. The southern range limits of some species have not measurably shifted but the stocks are spread out over a greater latitude range (range extension), and the center of the biomass is shifting to the north. Range displacement can result either from migration or from differential productivity between more northerly and southerly components of the populations (Hollowed et al. 2013).

In the southeastern Bering Sea, species that had shifted northward during the warmer water period of the early 1980s to early 2000s include eulachon—20 miles, arrowtooth flounder—28 miles, halibut and flathead sole—33 miles, snow crab—54 miles, and Greenland turbot—60 miles (Sigler 2012, from Mueter and Litzow 2008). Snow crab have both shifted northward and have decreased in abundance. Atka mackerel, normally concentrated in the Aleutians, have turned up at Nome. Many of these shifts reversed during recent cold years associated with heavy ice (2007–2013), but are expected to resume as temperatures increase.

Displacement by latitude isn't the only option fish have for seeking cooler water; they can change depth. A NOAA study in the Gulf of Alaska using acoustic, longline, and bottom trawl survey data found different responses by species, with some, such as Pacific cod, shifting abundance to deeper water in warm years.

Some species will increase in abundance and individual growth will accelerate. Changes may be modest and highly variable by region; in most cases less than 10% with a mean of plus 3.4%, according to estimates by Barange et al. (2014). However, University of Cambridge scientists are predicting a 30–70% overall biomass increase at high latitudes globally, along with a 40–60% decrease in the tropics (Holmyard 2014). Some scientists speculate that regions like the eastern Bering Sea with seasonal ice coverage will experience increased productivity due to greater light penetration and a longer plankton growing season.

Adaptation generally is a slower process than changing abundance or productivity, and more difficult to document. Distribution changes can be viewed as a form of behavioral adaptation, as can changing prey, and there is evidence of those kinds of adaptation in some cases. Less clear is whether physiological adaptations are occurring in Alaska marine species so far. Certain Alaska stocks of salmon (see next section) may have adapted physiologically to warmer stream conditions, but these changes are not proven.

Predation, competition, and disease are likely to have a greater negative impact as northern seas warm. Three common species of sharks inhabit Alaska waters regardless of temperature—salmon shark, sleeper shark, and spiny dogfish. Other visitors (e.g., great white sharks, thresher sharks) come in particularly warm years and are very effective predators on salmon and herring. Great white sharks are not common now but may be more so as ocean temperatures rise (Bruce Wright, Aleutian Pribilof Islands Association, personal communication). Pomfret, and possibly mackerel, have appeared in Alaska waters; they prey on juvenile salmonids and are aggressive competitors for the same prey resources.

One possible explanation for the decreased halibut recruitment during the last decade is competition for prey from a dramatically increased biomass of **arrowtooth flounder,** which appear

Arrowtooth flounder preys on and competes with halibut. Arrowtooth abundance appears to be increasing.

to thrive during periods of above normal water temperatures. Researchers are investigating this possibility. Arrowtooth abundance in the Bering Sea has increased eight-fold in the last three decades (BEST-BSIERP, undated) and about quadrupled in the Gulf of Alaska (Spies et al. 2015).

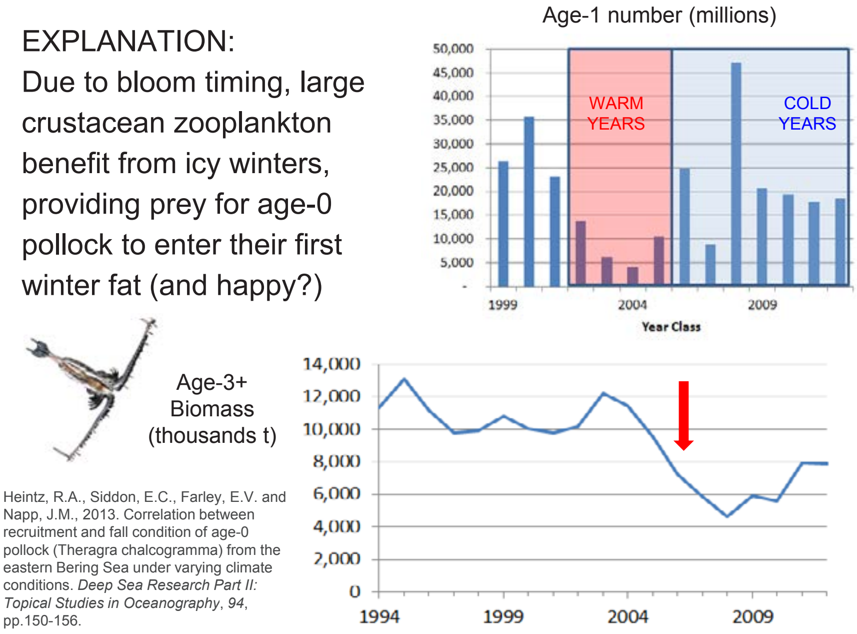
Many waterborne disease pathogens thrive in warmer water, and fish disease outbreaks are documented around the world. Salmonids are especially susceptible to a range of diseases, particularly in their freshwater stages. Chinook salmon runs in the Yukon River have plummeted, and there has been a correlation noted between decreased Chinook abundance and infection caused by a parasite known as *Ichthyophonus,* which appears to be more prevalent with warming conditions. *Ichthyophonus* infection in the Bering Sea is not well studied and it is unclear whether it is more common or if fish succumb to the infection because they are experiencing other temperature-related stresses (Sullivan, undated).

Bitter crab syndrome, a crustacean disease caused by the parasitic dinoflagellate *Hematodinium,* kills snow crab in the Bering and Chukchi Seas and Tanner crab in the Gulf of Alaska. Some evidence suggests the warmer water during the most recent ocean warm phase has caused or contributed to increasing *Hematodinium* disease in the North Pacific (Morado 2007).

Pollock

Walleye (Alaska) pollock in the Bering Sea supports the biggest single-species food fishery in the nation with annual catches averaging 1.5 million metric tons, worth more than $500 million ex-vessel to more than $1 billion first wholesale value.

The strength of individual pollock year classes is a function of several factors, including predation and the quantity and quality of prey, which determines the accumulation of sufficient energy reserves to provide for winter survival (Hollowed and Sundby 2014). Following a recent



EXPLANATION:
Due to bloom timing, large crustacean zooplankton benefit from icy winters, providing prey for age-0 pollock to enter their first winter fat (and happy?)

Heintz, R.A., Siddon, E.C., Farley, E.V. and Napp, J.M., 2013. Correlation between recruitment and fall condition of age-0 pollock (Theragra chalcogramma) from the eastern Bering Sea under varying climate conditions. *Deep Sea Research Part II: Topical Studies in Oceanography*, *94*, pp.150-156.

Walleye pollock abundance dramatically fell in the early 2000s, leading to a 40% drop in quota for the largest single fishery in the US, and then rebounded. This was believed to be due to bloom timing. 0-age pollock feed on crustacean zooplankton to gain fat reserves to carry them through their first winter. Source: NOAA 2016b.

period (2002–2005) of above-average Bering Sea temperatures, the abundance of adult pollock declined. In response NOAA Fisheries lowered the pollock quotas from 1.5 to 0.8 million metric tons in 2006–2010. In subsequent years temperatures decreased and when stock surveys indicated an increase, the pollock quota was increased.

Research results suggest that while pollock larvae and juveniles respond to warmer water with faster growth and lower mortality, a decreased availability of high-quality prey and increased predation lead to lower recruitment into the fishery (Mueter et al. 2011). Scientists found that the large crustacean zooplankton that age-0 pollock depend on are less available in warm years.

Scientists have correlated the pollock decline with the decrease in sea ice cover and resulting shift in plankton species makeup available to juvenile pollock. Years of more extensive and later melting ice cover appear to favor production of **lipid-rich plankton,** especially euphausiids and *Calanus marshallae* copepods, which provide the young fish the energy they need to survive the long winter. The leaner small copepods that predominate during low ice (warmer) years have less than half as much lipid content (Hunt and Stabeno 2002).

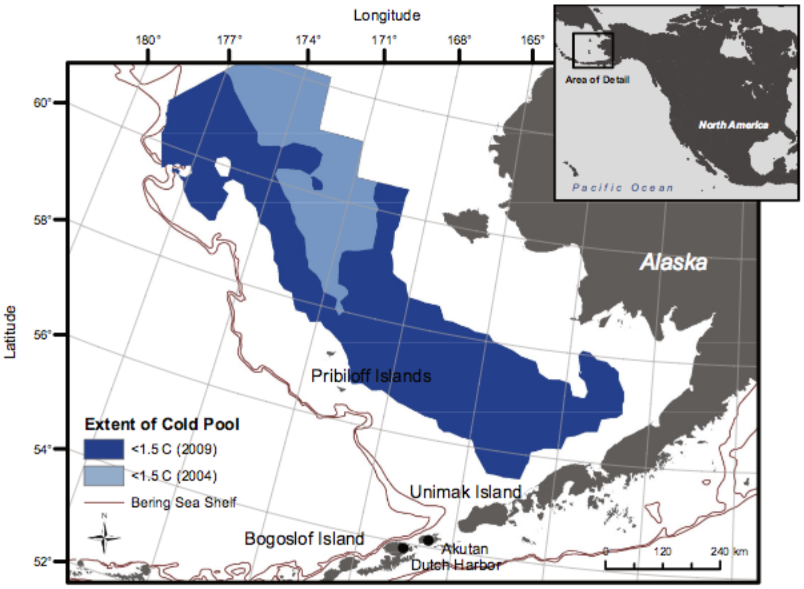
Ron Heinz at the Ted Stevens Marine Research Institute has found that both pollock and their prey tend to be leaner during relatively warmer water years, while during cooler water years more of the fatter juveniles survived to recruit into the fishery. Krill (euphasiids) are also important prey for pollock and other fish, and research shows that krill are more abundant in cold water years. Furthermore, since fish metabolism increases in warm water, it takes more krill to support fish growth. In colder water, when krill are more abundant, fish need less to support metabolism so there is more energy to support growth. Warm conditions that accelerate fish metabolism also increase the overwintering energy demands. When waters returned to a cooler phase and prey conditions improved after 2005 the pollock stock quickly rebounded (Hunt et al. 2011).

During the same warm water period, **juvenile pollock were heavily preyed upon** by adult pollock, arrowtooth flounder, and salmon. In the absence of the large, lipid-rich copepods and krill, the higher level predators turned to juvenile pollock to meet their nutritional needs. This predation decreased when the water cooled and the richer zooplankton again became available (Coyle et al. 2011).

***Calanus* is a group of abundant, lipid-rich copepods that are an important food source for juvenile pollock. Photo: R Hopcroft, University of Alaska Fairbanks.**

Bering Sea walleye pollock respond to changes in the size and location of the “cold pool,” which is an ever shifting mass of super-chilled water that remains on the shallow Bering Sea continental shelf. The Bering Sea is divided by a transition zone at about 60 N latitude; bottom waters north of that line are colder, serving as a sort of thermal barrier for pollock and some flatfish, preventing them from extending their range into the Arctic. While adult pollock typically avoid colder waters, the more cold-tolerant juveniles advance into the cold pool. Scientists speculate that the cold pool provides them a temporary refuge from those predators. Warmer water may deprive them of some of that refuge effect, contributing to lower survival during warmer years (Van Pelt 2015). Pacific cod also seem to be limited in their northward expansion, but in warm years they concentrate in the northern Bering Sea near the cold pool.

NOAA scientists say that by 2040 water temperatures recorded during the abnormal warm period of 2002–2005 could be normal for the Bering Sea if the climate continues on its current trajectory. At the same time, oceanographers pre-



The extent of the cold pool in 2004 (a warm year) and 2009 (a cold year), as measured by the annual summer bottom trawl survey in the eastern Bering Sea. Source: Haynie and Pfeiffer 2013.

dict that the Bering Sea cold pool will persist, preventing pollock from expanding their range into the Bering Strait and Chukchi Sea where they could escape the warming water.

Based on these factors, fishery scientists expect the biomass of harvestable **pollock in the Bering Sea to diminish** significantly over the next quarter century. Franz Mueter and his co-authors (2011) predict that by the middle of this century pollock recruitment will decline by 32% to 58%.

An additional concern is that as the population shifts northward over the shelf and slope of the northern Bering Sea it spreads across the maritime boundary into Russian waters, making more fish available to the Russian fleet and less to Americans (Strong and Criddle 2013). The Russian fisheries management agency has estimated that 35% of the pollock biomass on the US side eventually will be available to the Russian fleet.

So far there is little indication of water chemistry effects on pollock. Lab research with pollock larvae using elevated levels of dissolved CO_2 indicated no significant harm and researchers say the results suggest that the growth potential of early life stages is resilient to the effects of ocean acidification (Hurst et al. 2013).

Pacific cod appear to respond to water temperature changes similarly to pollock but also they have been found to migrate to deeper water during warm-water years. Work by NOAA scientists suggests that the Bering Sea longline cod fleet experiences decreased CPUEs (catch per unit of effort) related to the size of the Cold Pool and the amount of travel required to find harvestable concentrations of cod.

Halibut

Halibut recruitment and growth have fluctuated widely in the last century and scientists say that environmental variability is largely responsible. Indications are that, at least in Alaska, the halibut biomass responds to some of the same cues as juvenile salmon, which are influenced by the abundance of plankton, meaning that it has responded positively to warmer water. During positive (warmer) Pacific Decadal Oscillation (PDO) regimes halibut productivity tends to be high in the Alaska Gyre (Clark and Hare 2002). In concert with salmon, halibut landings gradually diminished during the cool phase of the 1960s and 1970s, bottomed out at around 15 million pounds, and then surged up to as high as 60 million pounds in the warmer phase years immediately following the 1977 regime shift.

Ocean climate, especially during the year of spawning, influences halibut recruitment. Year class strength depends on either the transport of eggs and larvae by currents to nursery grounds on the continental shelf, or on plankton production that varies with climate and weather. On the other hand, growth appears to vary with changes in halibut stock size with little influence of climate (Clark and Hare 2002). Ongoing research is focusing on factors that influence size-at-age, and some results indicate that size-selective fishing is a significant factor in reductions in size-at-age since the 1980s (Jane Sullivan, University of Alaska Fairbanks, personal communication).

Halibut typically spawn in January, and by July the larvae are settling on the bottom nearshore and growing into juveniles. When atmospheric conditions produce winds that drive currents that transport halibut larvae more rapidly onto the continental shelf where they encounter more agreeable rearing conditions, increased productivity as expressed by increased recruitment occurs (Cathleen Vestfals, Oregon State University, personal communication). PDO positive regimes tend to produce those currents. A positive PDO phase brings conditions believed to be similar to what would prevail during a long-term warming of the North Pacific.

Currently the halibut biomass is fairly large with many fish, but the abundance of legal size fish is relatively small. (Abundance is the number of individual fish, biomass the total weight of the stock.) If growth is slow, fewer halibut reach the minimum legal size and recruit into the fishery. Recruitment in recent years has been smaller than observed during the 1980s and 1990s.

The few available analyses seem to point to a possible **improvement in halibut biomass and recruitment** in a future of moderate increases in atmosphere and water temperature. But the average size of individual fish is likely to remain smaller than in the past, with high densities of predatory arrowtooth flounder and competition for prey within an increased halibut biomass.

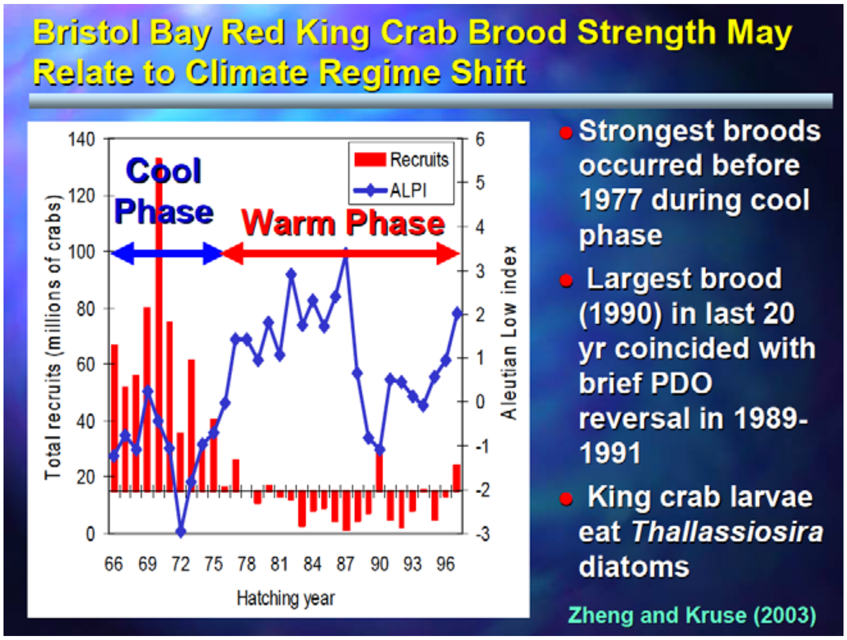
Crab

In general, Alaska stocks of red **king crab, Tanner, and snow crab currently are in a prolonged period of decline.** Scientists believe that crab stocks respond to surface and subsurface seawater temperature, vertical mixing, currents, atmospheric pressure, and subtle variations in sea level. Studies link these forcing agents to the location and intensity of the Aleutian Low atmospheric pressure center, which appears to correlate with Pacific Decadal Oscillation. A warm PDO phase tends to support a more northerly Aleutian Low, bringing warmer temperatures to the Bering Sea.

Crab stocks tend to be supported by a few very strong year-classes separated by several years of low productivity. Factors seem to include distribution of larvae by the currents, availability of suitable plankton prey for larvae, particularly a group of diatoms in the genus *Thalassiosira,* and the biomass of predators, especially cod. King crab productivity appears to be controlled by availability of suitable prey and by whether currents carry larvae to prime or unsuitable habitats. Conditions that support a large population in the northern Bering Sea, for example, may bring failure to another in the southern Bering Sea or the Gulf of Alaska (Zheng and Kruse 2000).

Past warm phases of the PDO provide a preview of the future. During the first four years following the last strong cool phase the snow crab population in the Bering Sea decreased substantially, while the center of the biomass contracted and shifted to the north (Sigler 2012). Juvenile king crab productivity has plummeted by about 70% (Kruse 2007). One study has found that the biggest factor in snow crab abundance is winter sea ice extent as determined by climate warming (Mueter and Litzow 2008).

Tanner and snow crab in Alaska are susceptible to bitter crab syndrome, caused by the parasitic dinoflagellate *Hematodinium.* The disease is so-named because live and apparently healthy crabs are inedible due to a bitter aftertaste in their meat.



Bristol Bay Red King Crab Brood Strength May Relate to Climate Regime Shift

- Strongest broods occurred before 1977 during cool phase
- Largest brood (1990) in last 20 yr coincided with brief PDO reversal in 1989-1991
- King crab larvae eat *Thallassiosira* diatoms

Zheng and Kruse (2003)

Bristol Bay red king crab brood strength has been shown to correlate with climate regimes. Source: Zheng and Kruse 2003.

Bitter crab syndrome in Alaska was first reported in 1987 in Tanners from Southeast Alaska but is now found as far north as Norton Sound and the Chukchi Sea (Morado 2007). While no definitive link to climate change has been proven, the disease first appeared during a general warming period following the 1977 regime shift.

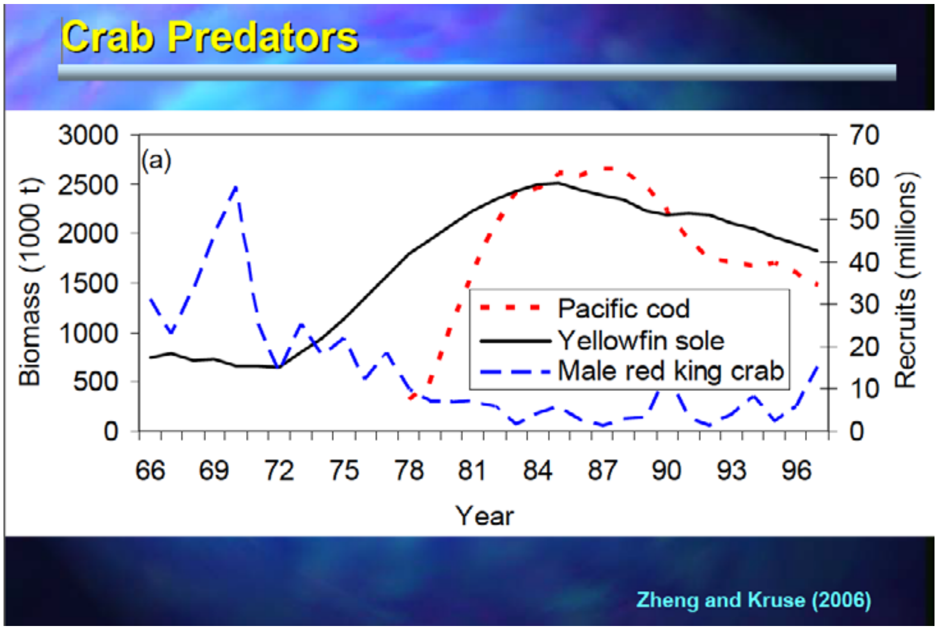
Crab also are threatened by ocean acidification. While "very low" pH water eventually could cause corrosion of adult crab shells, it is more likely that larvae would be unable to form shells due to lack of available calcium ions in the water and would not survive to maturity. In research by NOAA scientists, juvenile king crabs exhibited slower growth and higher mortality when held in water at a pH level equivalent to what will predominate in crab rearing habitat within a century.

Some recent research suggests that Dungeness crab are threatened by the effects of ocean acidification, at least at levels projected for the latter part of this century. However, Dungeness as a species is adapted to lower pH waters since they typically live in estuaries with a greater freshwater component, so projections for Dungeness responses to ocean acidification are preliminary and speculative.

NOAA scientists have projected an accelerating decline in king crab biomass culminating in **total cessation of commercial fishing by the year 2100.** Less is known about snow crab population dynamics, but there is little reason to think the scenario will be better.

If there are any silver linings they are: (1) **Crab may be able to migrate** into the Arctic and new habitat. Recent surveys indicated increases in snow crab in the Arctic. (2) Crab can be **hatchery-raised.** A massive hatchery program could allow "stocking" the ocean with young crabs that already have passed the point of greatest vulnerability to acidification. This concept is controversial because of the problems related to separating hatchery from wild stocks. (3) NOAA scientists say they have documented evidence that both Tanner and blue king crab have some **capacity to adapt** to low pH waters. They found that the longer juveniles were exposed to acidic water the less likely they were to die.

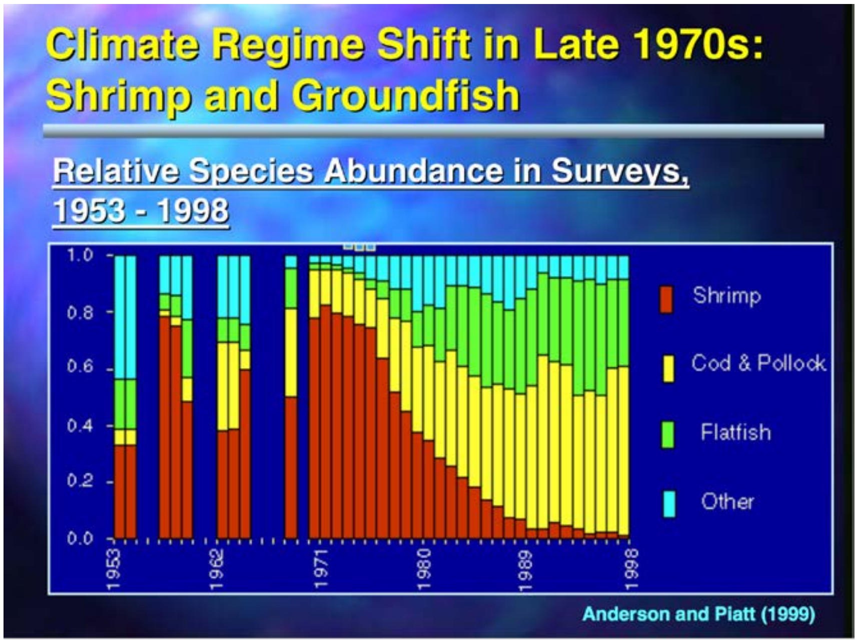
So far there is little information about the effects of temperature or acidification on **Dungeness crab.** Dungeness production on the US West Coast has always fluctuated from year to year, but in general has continued strong during recent years. Since Dungeness commonly occur in estuary areas with high freshwater content, which naturally has a lower pH than ocean water, they may be more resistant to acidification. Lab studies



In the mid 1970s the king crab crash coincided with an increase in abundance of Pacific cod and yellowfin sole. Source: Zheng and Kruse 2006.

have shown some decrease in developmental parameters such as spine length in Dungeness larvae, but no difference in mortality (Descoteaux et al. 2012).

Shrimp abundance also is closely linked to ocean climate, particularly northern pink shrimp *(Pandalus borealis)* (Gordon Kruse, University of Alaska Fairbanks, personal communication). Gulf of Alaska pink shrimp production peaked at 58,000 tons in 1976; it then went into precipitous decline and landings have been negligible for years. At the same time, king and tanner crab stocks collapsed in the same waters. Those events coincided with a big increase in cod and pollock—the timing of both major changes corresponded to the 1977 regime shift. Since it takes several years for a living resource to progress from egg and larvae stage to recruiting into the fishery, those changes actually manifested a few years later.



Climate Regime Shift in Late 1970s: Shrimp and Groundfish

Relative Species Abundance in Surveys, 1953 - 1998

Anderson and Piatt (1999)

Climate regime shift in the late 1970s: shrimp and groundfish. This graph illustrates the shrimp decrease and groundfish increase in abundance in response to the 1976-1977 regime shift. Source: Anderson and Piatt 1999.

5 FISHERIES EFFECTS—SALMON

Alaska has many distinct salmon populations and each responds in its own way to environmental change. With two freshwater phases and extensive ocean migrations, salmon are subject to many environmental influences.

So far Alaska salmon have exhibited few changes in abundance, distribution, or behavior directly attributable to long-term climate change. NOAA researchers have concluded that increased salmon abundance in recent decades can be attributed to variations in the ocean physical characteristics accompanying the PDO, which is brought about by shifts of the Aleutian Low pressure system. Stock productivity has been significantly higher since the 1976 shift to warmer ocean climate conditions in the North Pacific. They speculate that storm events and upwelling may have increased biological productivity that benefited salmon survival. The more subtle cooling shift after 1996 is believed to have contributed to sharp declines in some salmon stocks, particularly Chinook.

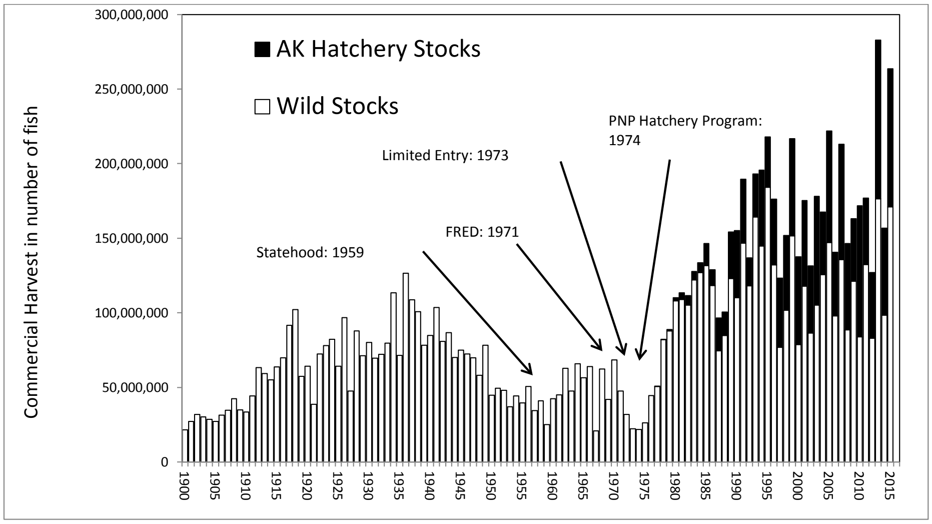
Documenting changes to salmon runs in the Pacific Northwest and studying the effects of temporary climate shifts on Alaska salmon may be useful but sometimes produce conflicting hypotheses, as seen below.

How Pacific Northwest salmon respond to elevated temperatures and drought

Warm PDO phases and El Niño tend to produce low snowpack, lower summer stream flows, high stream temperatures, more fall and winter streambed scouring, and warmer ocean temperatures. All these factors tend to negatively affect salmon productivity.

Copepods are important food for juvenile salmon. A warmer ocean supports “southern” species that are less nutritious than northern species that predominate during cooler ocean periods. Adult Chinook and coho returns from brood years that enter the Pacific during warm years tend to be poor. Plankton trawls on the Gulf of Alaska out of Seward during the warm summer of 2015 recorded a larger than normal occurrence of southern zooplankton.

An extreme interpretation of models based on climate change scenarios is expressed in a 2011 paper, which predicts that by 2100 the ocean winter habitat of Pacific Northwest sockeye salmon would decrease by 38% and summer habitat for Chinook by 86%, sockeye by 45%, 30% for coho, 30% for pinks, and 29% for chums. Projected losses would be greatest in the Gulf of Alaska and



Commercial salmon harvest in Alaska, 1900-2015. Alaska salmon stocks rebounded dramatically after the 1976-1977 regime shift. Source: Stopha 2015.

western and central subarctic North Pacific, and may include nearly complete loss of habitat for sockeye (Abdul-Aziz et al. 2011).

Another states, “Simulations predict that rising water temperatures will thermally stress salmon throughout Washington’s watersheds, becoming increasingly severe later in the 21st century” (Rosenberg et al. 2010).

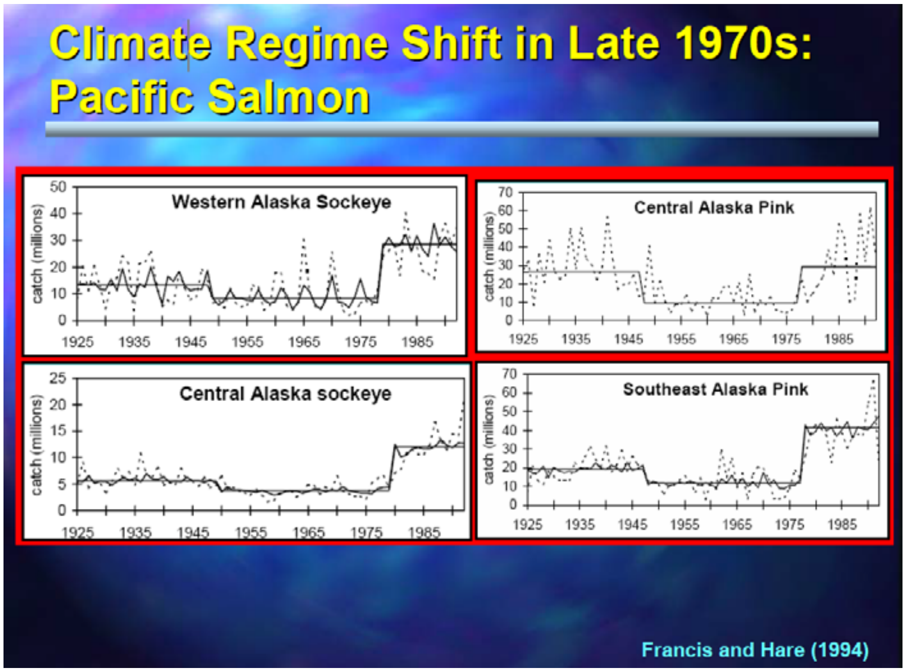
The year 2015 produced unusually warm stream temperatures and reduced flows as well as above normal ocean temperatures. Here are some observations recorded during that summer:

- More than a quarter million adult sockeye salmon died in the Columbia River and its tributaries because of warm river waters. NOAA says the loss could come to 80% of the run.
- Sockeye also died in the Deschutes River, most from columnaris, a bacterial infection associated with low oxygen and warm water (ODFW 2015b).
- Spring Chinook died in the Middle Fork of the John Day River in water temperatures that hit the mid-70s F. Fish become stressed at 68 and stop migrating at 74 (Associated Press 2015).
- The 2015 coho return to Washington’s Skagit River was the lowest on record—only 12% of the recent decade average—and returning coho were only half the normal size. Biologists attributed these effects to the Blob (Seattle Times 2016).
- Spring Chinook died in the Willamette earlier in 2015. They start getting stressed at 60F and at 70F there were significant mortalities. Willamette River temperatures in June were 74F (ODFW 2015a).
- On the other hand, the Columbia experienced a very strong fall Chinook run in 2015, with 200,000 spawning at Hanford Reach, the most since construction of the big dams.

Current knowledge about climate and Alaska salmon

The paleo record shows that salmon abundance has fluctuated significantly over the past 2000 years in response to climate regimes (Finney et al. 2002).

Alaska Chinook and coho abundance generally are out of phase with British Columbia and the US West Coast. Periods of warm temperatures tend to be associated with improved returns in Alaska



Climate Regime Shift in Late 1970s: Pacific Salmon

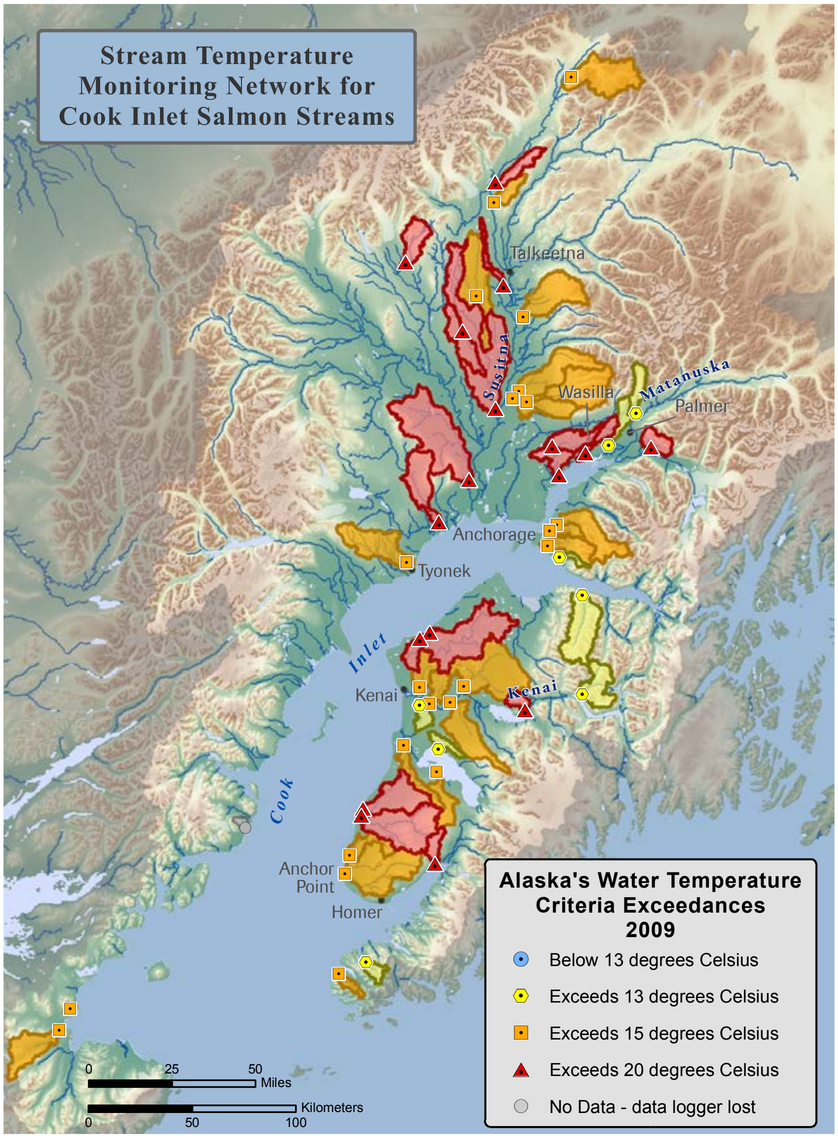
Francis and Hare (1994)

Salmon abundance has correlated with North Pacific oceanic regimes. Source: Francis and Hare 1994.

and poor runs in Washington (Mueter et al. 2002), probably related to the zooplankton available to juvenile salmon.

Pink, chum, and sockeye salmon tend to have similar long-term abundance trends (Beamish and Bouillon 1993). Pink and chum have brief freshwater phases and juveniles don't spend a summer in streams; most sockeye rear in lakes and also have a relatively short stream residence. All may benefit from increased primary productivity associated with warmer ocean temperatures. Coho and Chinook, on the other hand, rear a full year or more in streams or rivers so they are more susceptible to elevated stream temperatures and low flows. Since the 1977 regime shift to a warmer phase, pink, chum, and sockeye have been more productive, while coho and Chinook did not respond so positively. Scientists who looked at sockeye, chum, and pink salmon found that survival (rather than run size) was positively associated with temperature conditions during their early marine phase in Alaska. The increase in those three species is attributed to warm marine conditions, although warm freshwater is beneficial as well.

Alaska salmon tend to prosper during years of intensified and more easterly positioning of the wintertime Aleutian Low over the northern Gulf of Alaska (Finney et al. 2002, Adkison and Finney 2003), which drives wind currents that affect ocean currents, water column mixing, distribution



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map by: Cook Inletkeeper & The Nature Conservancy

Stream temperatures monitored in the Cook Inlet basin, Alaska. Nearly all exceeded maximum tolerance levels for salmon at least part of the summer. Source: Mauger 2013.

of larvae and juveniles, air temperature, and thus primary productivity and salmon production.

Predictions differ for the future of Alaska salmon. For example, in northern latitudes cool water tends to produce higher quality prey than warmer, which leads some scientists to say that continued warming may result in reduced fitness of sockeye and reduced marine survival (Yasumiishi et al. 2015). On the other hand, in years with warm water juveniles of some sockeye stocks feed mainly on juvenile pollock, in cold water years mainly on euphausiids, copepods, and juvenile sand lance, and other scientists say that juvenile sockeye growth rate is better and they have higher survival in years with warm water on the eastern Bering Sea shelf. Since the Bering Sea likely will continue to warm, the implication is that Bristol Bay sockeye probably will continue to do well. However, if summer sea temperatures increase to 9 degrees F higher than the 2002–2005 average there could be a decrease in juvenile pollock, reducing juvenile Bristol Bay sockeye fitness, and causing increased overwintering mortality (Farley et al. 2011).

The critical period for marine survival is the early ocean stage (first few months in saltwater). Smolt migration timing evolved to coincide with normal peaks in plankton availability. A change in plankton blooms or migration timing could deprive juvenile salmon of nutrition essential for growth. Large body size is important for escaping predators and for surviving the first winter at sea when food is scarce.

Salmon are particularly vulnerable to temperature while in freshwater. They may suffer reduced survival of eggs and fry, reduced growth rates due to increased respiration and metabolism, premature smolting causing decreased ocean survival due to small size or lack of synchronicity with plankton blooms, greater vulnerability to pollution, and greater risk of predation and disease (Mauger 2016).

Alaska has temperature criteria for each freshwater life stage, including spawning and incubation of eggs, smoltification (seaward migration), and anticipated adult mortality due to heat stress or oxygen depletion. However, records indicated that most streams in the Cook Inlet Basin exceed those levels for extended periods each summer (Mauger 2013).

Salmon in the Arctic

According to KM Dunmall and co-authors (2013), “The future of Pacific salmon in the Arctic looks promising; geographic distribution is increasing and trends suggest higher abundances.”

Pink and chum salmon spawning populations currently exist in the Arctic and the numbers, though small, appear to be slowly increasing. Currently the range of pink salmon extends east beyond Canada’s Mackenzie River and presumably “vagrant” (stray, nonlocally spawning) pinks have been caught as far away as the east coast of Greenland. Note that pinks have been introduced into many systems in Scandinavia, Russia’s Kola Peninsula, New England, and the Great Lakes but scientist don’t believe any of those stocks to be the source of eastern Canadian arctic pinks. Natal (local spawning) pinks also occur as far west as the Lena River of north-central Siberia. Chums are well established in several streams on the arctic coast of both Alaska and Canada and also appear to be increasing, though it’s not known whether they are colonizing additional spawning streams. Factors limiting pink and chum in the Arctic include sea ice coverage, freshening due to runoff, acidification, and river freezing (Nielsen et al. 2013). Chinook, coho, and sockeye are not established in the Arctic, although recent reports place Chinook in the Mackenzie delta and increasing numbers have been caught along the Beaufort Sea coast of Alaska. A few sockeye also have been documented in the Arctic. These fish are believed to be non-spawning strays that NOAA attributes to the effects of climate change.

Trends in Alaska salmon stocks

- Juvenile pink salmon are migrating earlier from Auke Creek near Juneau. Adults are returning two weeks earlier than 40 years ago.
- Coho returns to Berners River near Juneau decreased 61% during a cooling period in 2005–2013. Several factors contributed to this decline including competition by pink salmon for armhook squid, an important food for coho (Shaul and Geiger 2015).
- Over last 30 years Chinooks have gotten smaller in all 10 rivers around the state studied by the Alaska Department of Fish and Game Chinook assessment.

- The State of Alaska's maximum water temperature criterion for protection of fish is 13 degrees C (54F). During 2008–2012 more than half of the significant salmon-producing streams in the Cook Inlet region exceeded that level more than 30 days per year (Mauger 2013).
- The average size of sockeye returning to Bristol Bay in 2015, a year of warm ocean temperatures and the Blob in the North Pacific, was unusually small.
- Aleknagik Lake (northern Bristol Bay) spring breakup has averaged four days earlier over last 40 years. Earlier breakup supports increased summer densities of *Daphnia* and other crustacean zooplankton, which improves rearing conditions for Aleknagik sockeye (Schindler et al. 2005).
- Pink salmon abundance statewide began to increase in 1976, the time of a large scale regime shift to warmer sea temperatures in the North Pacific (Azumaya et al. 1998, Ishida and Azumaya 1999.)
- Salmon bycatch in the pollock trawl fishery appears to increase during years of warmer temperatures (Stram and Ianelli 2009).
- The historical and paleontological records indicate that warm sea surface temperatures and intensification of the Aleutian Low correlate with increased salmon production in Alaska (Finney et al. 2000).

What these observations suggest for Alaska salmon

- Different species and stocks respond differently to climate and other environmental changes.
- Salmon stocks always have fluctuated in response to natural climate variability.
- Most stocks in Alaska may benefit from increased primary productivity in the ocean, related to higher temperatures and changes in sea currents and water column mixing, even though results of some research suggest that higher quality prey, like the more lipid-rich copepods that predominate during cooler water phases, tend to produce higher salmon survival. Different species and stocks are likely to respond differently. Some scientists predict that primary productivity will decrease, in part due to lower nutrient runoff.
- Sockeye could benefit from increased plankton productivity in lakes.
- Pinks and chums could benefit from increased ocean productivity if shifts in migration timing and plankton bloom timing do not get out of phase.
- Trends indicate a gradual decline of Alaska Chinook and coho, at least those that spawn and rear in small streams. They have had good years during warming periods in the past but are more affected by elevated stream temperatures and decreased flows. Chinook, with longer ocean rearing time, are more susceptible to changes in food supply, harmful algal blooms, predation, and bycatch that could result from a changing ocean climate.
- Salmon may be threatened by ocean acidification, but so far the threat hasn't been realized.
- Some stocks may spread into or become more firmly established in arctic waters with warming temperatures.

6 ADAPTATION—RESEARCH AND MANAGEMENT

"In practice, the response of fishery management to climate change so far is extremely diverse, i.e., some managers assume that natural variability already encompasses climate change, others deny that climate change is occurring in ways that could affect fisheries, while still others are stymied in developing a response because of lack of information, capacity and high level uncertainty."

—David Fluharty, University of Washington (2011)

Human responses to environmental change fall into three categories—**research and monitoring, mitigation, and adaptation.** (Some observers suggest there is a fourth category—denial.) Research and monitoring are ways to collect information that can inform adaptation planning. Climate change mitigation involves actions to reduce release of greenhouse gases into the atmosphere. Adaptation means taking steps to preserve individual or community resilience in the face of change.

Adaptation is not the same as coping. Coping is a short-term response to a temporary phenomenon such as a storm or a poor fish run. Adaptation is a long-term or permanent change in behavior in response to long-term environmental change.

Adaptation can be "bottom-up" or "autonomous" by individuals and communities, or "top-down" policies or regulations applied by governments and agencies. Adaptation can be **planned** or **proactive,** but usually is **reactive** to changes that already have occurred.

With evidence that climate change and ocean acidification are starting to affect Alaska's fisheries and will do so more dramatically in the future, there is opportunity for planned adaptation by research and resource management agencies. This is sometimes called **"climate-ready"** fisheries management.

The academic and agency literature abounds with suggestions for top-down adaptation, including:

- Promote fuel efficient and otherwise environmentally friendly fishing practices.
- Increase climate change education and promote greater public awareness.
- Conduct vulnerability and risk assessments.
- Increase adaptive capacity of stakeholders.
- Promote shift to aquaculture, particularly herbivore (plant eater) aquaculture.
- Foster adaptation planning processes.
- Divert fishing effort from traditional stocks to new or underutilized target species.
- Invest in landing sites, vessels, and alternative gear to improve access to other resources.
- "Decouple" individuals and communities from dependence on the local fisheries.

In the United States there are problems with these prescriptions: No group or agency is tasked or authorized to carry them out. There is no funding or implementation mechanism. Stakeholders (commercial fishermen, seafood companies, fisheries-dependent communities) in many cases are unlikely to accept and support them.

What exists instead is a fishery management process that is constrained by law and practice to a very narrow range of measures centered mainly on regulation of fishing effort or harvest levels. **"Reducing fishing mortality"** often is the first if not only recommendation for adaptation to climate change mentioned. Fisheries managers may address changes in ecosystem productivity and fish abundance, changes in fish distribution, interactions with nontarget species, and habitat (Morrison et al. 2015), and they should consider the cumulative effect of multiple stressors including fishing and pollution. Generally they recognize that fish stock resilience is enhanced if other stressors such as fishing pressure and pollution are minimized. But the range of potential actions remains based on restricting either harvest effort or landings. The structure of both state and federal management is such that industry players have to be convinced that measures are justified and likely to be successful before any can be taken.

Two recommended principles for getting best results are these (Knapp et al. 1998):

- Conduct long-term forecasting and planning. The better managers anticipate changes the better they can plan for and adjust to changes. The key is "long-term" as opposed to season by season.

- Incorporate mechanisms for adjusting to harvest changes in management and political institutions. Management organizations and political agreements should be flexible enough to accommodate changes to stock and harvest levels.

Two management agency responses

In the federal waters off Alaska fisheries management planning is done by the North Pacific Fishery Management Council, based on data and analysis by the National Marine Fisheries Service, otherwise known as NOAA Fisheries. In state waters policies and allocation are determined by the Alaska Board of Fisheries, with scientific input and implementation by the Alaska Department of Fish and Game.

Both the Alaska Department of Fish and Game and NOAA Fisheries have written climate change plans. **ADFG's Climate Change Strategy** is broad in scope. It includes identifying effects, assessing vulnerabilities, conducting research and monitoring, incorporating climate change in management plans, and addressing statutory changes, budget issues, and partnerships, as well as developing communication and outreach programs (ADFG 2010).

ADFG has been introducing adaptive management practices that accommodate changes in fish behavior related to climate. For example:

- ADFG has allowed changes to crab season start and end dates to take into account changes in timing of the molt because molting crab experience high mortality and are less valuable in the market.
- In some salmon fisheries ADFG has transitioned from relying entirely on run timing as an indicator of run strength to emphasizing genetics and pre-season forecasts due to increasing unreliability of in-season run timing as an indicator of run strength (Jeff Regnart, Commercial Fisheries Division, Alaska Department of Fish and Game, personal communication).

NOAA Fisheries provides a number of science-based services including data support and advice to the regional fishery management councils. NOAA focuses on research and monitoring to predict the status of fishery stocks and harvest rates and to analyze the effects of proposed catch levels on the stocks and their habitat (Link et al. 2015). In February 2016 NOAA released its five-year regional action plan, called **Climate Science Strategy for the Southeastern Bering Sea** (Sigler et al. 2016). Objectives include "Identify appropriate, climate informed reference points" for managing fisheries, "Identify robust strategies…," "Design adaptive decision processes" for responding to climate change, "Identify future states of coastal, marine and freshwater ecosystems" in a changing climate.

One feature of the plan is a "climate vulnerability assessment" that analyzes the dependence of Alaska communities on their fisheries and characterizes their economic vulnerabilities to fishery disruptions. It also highlights "a comprehensive, multi-disciplinary modelling approach to project abundance estimates for key fish stocks under varying climate conditions." The Alaska Fisheries Science Center is funded at about $9 million a year to conduct ecosystem monitoring, process studies to understand ecological relationships, and modelling and retrospective studies to promote understanding of the results of the ecosystem monitoring and process studies.

Using NOAA Fisheries stock assessment data, the North Pacific Fishery Management Council is adding environmental variables to stock assessments, and as part of the harvest specifications process for each assessment there is consideration of the appropriate time period representing current environmental conditions for recruitment (Diana Evans, North Pacific Fishery Management Council, personal communication).

Two actions by the NPFMC serve as examples of federal regulatory responses to climate change effects on Alaska fisheries. As noted earlier, using NOAA monitoring data that showed decreased zooplankton, more predators, and lower pollock productivity, the council reduced the fishing quotas in the Bering Sea by nearly half. The following year when data on those environmental conditions improved the quotas were increased (Pinsky and Mantua 2014). In another example, the council closed all arctic waters under its jurisdiction to commercial fishing and halted expansion of trawl fisheries, an expression of the precautionary principle in the face of northward shift in fishing effort.

7. ADAPTATION BY INDUSTRY, INDIVIDUALS, AND COMMUNITIES

"Anthropogenic climate change is nearly certain to change fishing opportunities available to communities. Progressive ecosystem changes will require adaptive responses which may include increased travel to new fishing grounds, fishing new species, or transitioning out of fishing altogether."
—ML Pinsky and NJ Mantua (2014)

The vulnerability of an individual or community to environmental change is based on three factors: the extent of their exposure to the consequences of change, the severity of the potential impacts, and their capacity for adaptation to change. Fishermen and fishing communities vary greatly in their vulnerability. As long as they remain dependent on the fisheries they have limited options for reducing exposure and severity, but they have a wide range of choices for increasing adaptive capacity.

Flexibility is the key to individual and community resilience in the face of climate change effects on fisheries. Although scientists and academics make this assertion, they offer little in the way of specific recommendations.

Experts with the United Nations Food and Agriculture Organization (FAO) provide some general examples of climate impacts and suggested adaptive responses (FAO 2008):

- Reduced productivity and yields—>Increase fishing power, access higher value markets.
- Increased variability of catches—>Diversify livelihoods, develop insurance programs.
- Decreased profitability—>Reduce operating costs, diversify livelihoods, leave fishing for other livelihoods.
- Changes in distribution of stocks—>Migration of fishing effort and processing facilities.
- Increased risks, danger—>Get insurance, improve weather warning systems, buy better vessels.

Other potential adaptive measures based on experience and general knowledge:

- Employ selective fishing gear in order to keep fishing for abundant target species while avoiding depleted stocks.
- Move to new fishing grounds.
- Get into aquaculture as an alternative to commercial fishing.
- Press for changes in fishery management that accommodate changing realities in the fisheries. For example, halibut fishermen could request a return of the minimum size limit to 26 inches from the current 32 inches. This would allow harvest of smaller fish not yet recruited into the fishery under the current regulations and prevent their loss to predation, bycatch, and release handling mortality.

Four strategies may be applied to adaptation planning by fishermen and processors:

1. Diversify fisheries with multiple permits/quotas, and combination vessels that have greater range and multi-fishery capacity. However, existing regulatory structure sometimes is a barrier to fishery diversification due to constraints such as limited entry and exclusive area registration. Diversify income by taking training and developing skills that lead to good paying jobs during the off-season.
2. Get higher value for the catch through alternative or direct marketing, or by improving product quality through advanced handling or better refrigeration and storage technology.
3. Mitigate risk through measures such as cooperative fisheries, cooperative processing, and expanded and alternative insurance coverages.
4. Reduce uncertainty by systematically gathering and analyzing all available information as it becomes available and incorporating results into planning.

Some fishermen are exhibiting **adaptive behaviors,** whether they realize it or not. For example, the center of vessel fishing effort during the summer "B" pollock season shifted steadily north during the period 2002–2008, from about 56.8 to 59.4 N latitude in response to the shift in pollock biomass (Haynie and Pfeiffer 2013).

Since **shellfish farmers** are particularly vulnerable to effects of temperature and acidification, they have incentive to take adaptive measures. Some already have found they can effectively avoid the threat of toxic algal blooms by configuring their sets so that they can be lowered to put the oysters they are raising into cooler water where toxic blooms are less threatening. A newly developed device called the Burkolator helps shellfish hatcheries monitor seawater pH, and the Alutiiq Pride Shellfish Hatchery in Seward is experimenting with controlling CO_2 levels in hatchery rearing tanks.

Non-commercial users of fisheries and marine resources have their own adaptation issues. For example, since subsistence shellfish harvesters face the threat of disease caused by harmful algal blooms, they can minimize risk by demanding programs to monitor and test shellfish for HABs.

Other adaptive measures are not specific to climate effects but improve overall resilience. Alaska's private nonprofit salmon hatchery program is a proactive adaptation to a range of environmental stressors. Recent developments in marine industry–related vocational training through the University of Alaska system and other institutions have opened new opportunities for supplemental incomes or alternative careers for fishermen. Alternative product development and byproduct utilization are methods processors use to get greater value out of limited volumes of product. All forms of energy efficiency and capital efficiency improvements help increase profitability. Fishermen, particularly in the federal waters trawl fisheries, are working on ways to reduce bycatch, including improving communication between individuals to help avoid high bycatch areas, as well as gear development and changes in fishing practices. These measures may help the industry weather coming changes, whether directly from climate or from other environmental or economic forces.

IN SUMMARY

"The future ain't what it used to be."
—Yogi Berra

During the working lifetime of younger fishermen currently in the industry, effects of long-term climate change on the fisheries probably will turn out to be profound but not cataclysmic. In 30 years most existing fisheries will continue to be productive. Some will be smaller than they are now and others will flourish. The late 1970s saw the Bering Sea king crab boom, which subsequently crashed, probably as a result of climate-related factors; the volume and value of the harvest has not returned to what it was, but a profitable crab industry remains. After a nadir in the late 1970s Alaska's salmon fisheries came roaring back from near oblivion to become a productive industry today, a turnaround that resulted at least in part from climate trends that continue and likely will into the future.

To survive and prosper industry participants will need to keep up to date on climate science and observable changes in the environment as well as on advances in technology, finance, and the politics of resource management. Fishermen and communities will need to develop adaptive strategies that may include, among other approaches, looking for new opportunities that arise out of climate related changes.

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CLIMATE CHANGE
AND ALASKA FISHERIES

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Alaska Sea Grant, University of Alaska Fairbanks

This book summarizes knowledge of North Pacific climate change and its anticipated effects on Alaska fisheries through the middle of the 21st century. Based on scientific research and observations by the public and industry, the publication focuses on fisheries effects caused by long-term warming, looks at effects of climate variability phenomena, and considers ocean acidification. Author Terry Johnson concludes that during the working lifetime of today's younger fishermen, effects of long-term climate change on fisheries probably will be profound but not cataclysmic. In 30 years most existing fisheries will continue to be productive, with some becoming smaller and others flourishing. To survive and prosper, the industry must keep up to date on climate science, environmental changes, and advances in technology, finance, and the politics of resource management. Fishermen and communities will need to develop adaptive strategies.

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