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The ACIA, climate change and fisheries

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Abstract

The Arctic Climate Impact Assessment (ACIA) is a project of the intergovernmental Arctic Council, intended to synthesize knowledge of the effects of climate change on the Arctic. This paper is based on the primary output of the ACIA project, a 1042 page book entitled *Arctic Climate Impact Assessment*. Our concern is with the effects of Arctic climate change on fisheries. To set the stage, however, we first discuss those chapters that logically precede the fisheries discussion, the chapters concerned with past and present climate change, climate modeling and marine systems. The conclusion notes that moderate climate warming will probably benefit most Arctic fisheries. The conclusion also considers the role of anthropogenic causation in climate change and its policy implications.

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1. What is the ACIA

The Arctic Climate Impact Assessment (ACIA) is a project of the Arctic Council, a high-level political body representing each of the eight countries bordering (or with dependencies bordering) on the Arctic: Russia, Canada, United States, Finland, Denmark, Sweden, Norway and Iceland. The goal of the ACIA is to synthesize knowledge of the effects of climate change on the Arctic, with its main product being a large volume of more than 1000 oversize pages [1].[1]

This paper is concerned with those aspects of the ACIA that reflect on Arctic climate change and the fisheries. To set the stage for this consideration, and to help explain the uncertainties reflected in the fisheries discussion, those chapters of the *ACIA* which logically precede the fisheries chapter, i.e., those concerned with present and past Arctic climate change, climate modeling, and marine systems, are discussed first. The discussion of the fisheries chapter then follows.

Although the Arctic is usually defined as north of 60° (22), because of the Labrador current, the waters off Newfoundland have the characteristics of cold Arctic waters, much more so than the Bering Sea and Northeast Atlantic, both of which are much further north (771). Newfoundland is, therefore, for reasons of this study, considered to be part of the Arctic region, despite the fact that St. John's, the capital, is located as far south as 47°N.

The study was motivated by a number of observations [2]:

(a) Inland Arctic areas have warmed by 2.0 °C per decade for the last three decades.
(b) Ozone has been depleted and UV radiation increased during the past decade.
(c) Precipitation at high latitudes has increased in some areas by as much as 15% in 100 years.
(d) Permafrost has thawed.
(e) Arctic glaciers have generally receded during the past century.
(f) There has been soil erosion from storm surges along the coasts of the Bering Sea.
(g) Sea ice thickness has been reduced in the Arctic.
(h) Temperatures in western North America and Siberia have been increasing while those in Hudson Bay and Greenland have decreased.

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[1] Throughout this paper, ACIA refers to the ACIA project, while *ACIA*, in italics, refers to the scientific document prepared by the ACIA [1]. Page references (in round brackets), except where otherwise stated, are to the *ACIA*.

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The greatest fears arising from these observations are that:

1. Sea levels will rise substantially, flooding low-lying areas.
2. Increased ultra-violet radiation will adversely affect human health.
3. Potential changes in the thermohaline circulation could have dramatic effects on the Arctic, and global, climate and on the Arctic economy.

The questions then arising are: what is the state of scientific knowledge regarding the changes; what gaps remain in our scientific knowledge; what changes are natural and which are caused by human activity; and what policies are required to modify human causes and mitigate the effects of such changes, whether natural or caused by human activity. The *ACIA* is divided into 18 chapters. Intended to fully cover the ground, the book moves from a description in Chapter 2 of the Arctic climate—past and present; to Chapter 4 modeling future climate change; to Chapter 5 on changes in ultra-violet radiation; to the anticipated effects of the projected climate change on the life of indigenous peoples, on the cryosphere, the oceans, fisheries, forestry, land animals, etc. Each chapter was assigned one or two lead authors, and a group of technical specialists were to be drawn together, sufficient in number and diversity of interests to cover the discipline.

The project originated with a proposal submitted to Arctic Council officials in 1999. Details of the proposed project, along with general outlines of each chapter were prepared by the "Assessment Steering Committee" in September 2000. The following month, the Arctic Council formally moved to finance the project, which was to result in three documents: the Scientific Document (the *ACIA*) which I have already described; a synthesis document summarizing the information in the *ACIA* in no more than 20 pages; and a policy document. The synthesis document was issued in November 2004 with the title *Impacts of a Warming Arctic* [3]. This book has 139 oversized pages, not 20 as originally foreseen. The policy document, as a set of recommendations by scientists based on the work of the ACIA, has not been published. Apparently, the committee established to prepare the policy recommendations was disbanded and an anemic 6-page policy document was issued in November 2004 by the political body to whom the recommendations were originally to be submitted, the Arctic Council [4].

The lead authors for the fisheries chapter of the *ACIA* were Alf Håkon Hoel, a political scientist at the University of Tromso and Hjalmar Vilhjalmsson, a fisheries scientist at Iceland's Marine Research Institute. There are in effect eight subsections in the chapter, one subsection on the fisheries per se and another on the socio-economic effects of anticipated changes in the fisheries for each of four geographical areas: northeastern Canada; Iceland and Greenland; northeast Atlantic; and the Bering Sea.

The *ACIA* is a compendium of the latest knowledge of areas within its purview. Whatever is written there about the future, however, is of necessity highly tentative. The time frames for forecasts are generally 2020, 2050 and 2080. As economists, we know how cloudy are our crystal balls at the best of times. But these are not the best of times. Consider the chain of projections that must be faced in making the predictions of climate change on socio-economic effects. First atmospheric changes must be predicted, then the effects on the oceans must be identified, then the effects on specific species and stocks must be determined, and then the effects on the human society projected. There is plenty of room for uncertainty.

1.1. Thermohaline circulation

Since it plays an important role in the sequel, and its effects may be crucial but remain unpredictable, a few words on the thermohaline circulation may be in order. Under the thermohaline circulation, warm, saline Gulf Stream water reaches the Arctic in the form of the North Atlantic Current and returns to the Atlantic as cold upper layer and deepwater ocean currents. The process of freezing seawater results in "brine rejection" whereby most of the salt does not freeze into the ice. Whatever brine is frozen ultimately leaches out. The subsurface water increases in salinity because it must accept the resulting excess salt, thereby becoming denser (462). Atmospheric cooling also increases seawater density, and the denser, colder, water in the Arctic sinks. A counterforce exists in that there is a substantial inflow of freshwater in the north, tending to decrease seawater density. "Approximately 11% of global river runoff is discharged to the Arctic Ocean, which represents only 5% of global ocean area and 1% of its volume," (27). The fact that the thermohaline circulation exists is evidence that the forces increasing the density of Atlantic seawater inflows to the Arctic exceed those reducing density. Local variations in the Arctic region also play a role. The Arctic is a large area and the freshwater intake areas are generally located elsewhere than where the ice forms (462). Clearly, if the amount of freshwater inflow increases with global warming, and temperature increases sufficiently to limit the formation of ice, the increasing density of seawater that drives the thermohaline circulation will cease, and so will the circulation. Nobody knows what the effect will be, but it might well be dramatic.

2. Chapter 2—Arctic climate—past and present

The chain of projections begins with an understanding of previous climate changes that have occurred in the Arctic. At one point in their summary (54), the authors state that "the climate of the Arctic is changing." This cannot be read as a deviation from the norm: the Arctic climate has always been changing. They review the evidence from such sources as ice cores, sediments, tree rings and fossils and describe major changes in climate. Then they show how changes do not occur uniformly over the geographic area of the Arctic, and that even within large-scale trend periods, there are subperiods with short-term opposite trends.

Long-term drivers of climate changes have been tectonic processes, changes in the orbit of the earth which occur over tens to hundreds of thousands of years, and changes in the emissivity of the sun which occur over decades, centuries, millennia and much longer periods (46). Major short-term variations might be caused by particularly violent volcanic eruptions such as that of Huanyaputina in Peru in 1600 [5]. One example cited concerns Siberia where the evidence rests on tree growth. Apparently, the most favorable period for such growth was from 9200 years ago to 8000 years ago, when the tree line was at 70°N. Cooling then occurred: for the first 400 years the tree line remained unchanged; for the next 200 years the tree line retreated to 69°N. There was then no change in the tree line for more than three millennia, until, in the short period of 50 years after 3700 years ago, it retreated about 20 km to near where it is today, at least 150 km south of its northernmost limit. Why was there such a rapid retreat? It is speculative, but it may have been "associated" with the eruption of the Thera volcano near Greece which occurred at around that time (52).

Fossil evidence suggests that the Arctic from 120 to 90 million years ago was far warmer than it is now. Only 20,000 years ago, towards the end of the last Ice Age, the Arctic was characterized by intense cold. One estimate is that in the past 1.6 million years (the Quaternary period) there have been as many as 30–50 glacial/interglacial cycles of cooling and warming in the Arctic, probably driven by changes in the orbit of the Earth (47).[2] The last interglacial period lasted from 130,000 to 107,000 years ago. During this period the Greenland Ice Sheet was considerably smaller than at present and probably contributed 4 to 5.5 m to the global sea level.

The cycles, however, are not clearly or uniformly delimited. The last period of glaciation, the last ice age, started about 107,000 years ago, peaking around 20,000 years ago, and ending about 11,000 years ago (the start of the Holocene period). But there was considerable variation: the Laurentide ice sheet, which extended through Canada to the US midwest, reached its maximum extent, depending on location, between 24,000 and 21,000 years ago; one section towards the eastern edge of North America, the Canadian Cordillera, only reached its zenith around 15,000 years ago, long after most of the ice sheet had started retreating. The Eurasian ice sheet did not even start growing until 28,000 years ago (48).

Warming was particularly rapid in Greenland, where temperatures rose by 2 °C per millennium between 20,000 and 10,000 years ago. Even more rapid warming of 10 °C per 50 years may have occurred at various times in parts of North America. According to Greenland ice core studies, during the cold period from 115,000 to 14,000 years ago, there were periods of rapid warming. In some local areas, the full extent of the warming might have been experienced over a period of only a few decades. The subsequent warm periods lasted from a few centuries to as many as 2000 years before the "normal" cold temperatures were restored. The warm period temperatures might have reached as high as 16 °C—not bad during an ice age. The chapter reviews such cycles and anomalies for a number of Arctic areas (49).

The last millennium has been characterized as falling into three periods: the Medieval Warm Period, from roughly the 9th to mid-15th centuries; the Little Ice Age, from the mid-15th to the mid-19th centuries; and a warming period from the mid-1800s to the present which may have been without precedent since the early Holocene (54). In addition to the economic and social factors that led to the Norse migrations during the Medieval Warm Period, the settlement of Greenland and Iceland were stimulated by the "reasonable" climate of those islands at that time. With the coming of the Little Ice Age, the Greenland settlements were ultimately deserted [5, at 9 and 68–69]. Yet average temperatures during the Medieval Warm Period were merely 0.2 °C higher than during the Little Ice Age, and were lower than in the mid-20th century (52). The medieval warmth was not universal, but appears to have been concentrated in the North Atlantic, possibly tied to changes in the thermohaline circulation. The difference between the temperature averaged over the Northern Hemisphere between the Little Ice Age and the present is less than 1 °C. But averages are deceptive and, as I mentioned before, there are considerable differences over time and place, even during a period of global warming or cooling (53). The climate was always changing and there were cold periods within the Medieval Warm Period and warm periods during the Little Ice Age (466).

During the warming period of the last 100 years, the average surface temperature in the Arctic increased by 0.09 °C per decade. But this increase was irregular: there was an increasing trend to the middle of the 1940s, then a cooling period to the mid-1960s, and a warming trend thereafter at a rate of 0.4 °C per decade. Accompanying the warming of the past century, atmospheric pressure has dropped, and is dropping, over the Arctic; total precipitation has increased by 1% per decade; and snow and sea ice cover have declined (54). In the northern North Atlantic and Arctic, there was rapid atmospheric warming in the 1920s and 1930s, with a continuation of warm conditions through the 1960s. This period was followed by one of cooling (in some places rapid cooling) that lasted into the mid-1990s. Then warming resumed (467). The conclusion drawn in the chapter is that if the current warming trend continues, increasing precipitation, snow melt, and freshwater runoff will reduce the cooling effect in the Arctic

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[2] There is an eccentricity to the orbit of the earth with a cycle of 100,000 years; a tilt in the axis of the earth which varies between 22.2° and 24.5° in a 41,000 year cycle; and variations in the position of the Earth in its elliptical orbit during the Northern Hemisphere summer with a cycle of 23,000 years (47).

waters, thus slowing the thermohaline circulation, resulting in increased sea level and reduced upwelling of nutrients. There will be a chilling effect in the North Atlantic region as the warming effects of the Gulf Stream and the North Atlantic Current are reduced (55). The authors of this chapter leave uncertain the role that "anthropogenic" changes (those induced by man) have played, and might play, in climate change.

3. Chapter 4—climate modeling

The ostensible reason for the ACIA program is to evaluate and synthesize current knowledge about Arctic climate, to establish a research agenda, and to provide guidance to governments concerning policy relating to climate and climate change. But to aid in policy making, one needs both to synthesize the current science and to predict what will happen in the absence of government intervention. While there is probably little that can be done to stop or reverse natural changes, and we have already seen that these are, and always have been, occurring, the key question concerns to what degree observed and future changes are anthropogenic. The most publicized concern relates to "greenhouse gases" which are believed to affect ozone protection and climatic warming. The major greenhouse gases are carbon dioxide, sulphur dioxide, methane, and nitrous oxide. Lesser ones are hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride.[3] What could or should be done about them? The questions are important and policy decisions have potentially dramatic economic consequences—witness the current debates over the Kyoto Protocol which was intended specifically to limit the production of these gases.

We have already seen that the authors of *ACIA*'s chapter on current and past climate change conclude that the extent of anthropogenic effects in past climate change is uncertain. Some claim that the global warming seen since the mid-19th century was caused by the industrial revolution. A recent theory states that the anthropogenic effect on climate started 8000 years ago with the development of agriculture. Apparently, according to ice core studies, for 25 centuries before that time, carbon dioxide in the atmosphere had been falling and the trend suddenly reversed. Five thousand years ago, a 6000-year downward trend in atmospheric methane was reversed. According to the theory, these changes were stimulated by developments in agriculture [7]. Be that as it may, scientists are divided on the extent and importance of anthropogenic effects. In 1988, a pair of United Nations agencies, the United Nations Environment Programme and the World Meterological Organization, established the Intergovernmental Panel on Climate Change (IPCC). The IPCC has issued three "assessments" on the status of climate change, and a fourth is expected in 2007. Included in these assessments are syntheses and critiques of the various climate change models. I will not summarize the work of the IPCC. What is important for us is that the IPCC assessments are used as the basis for the ACIA climate projections. Two aspects of the IPCC work are particularly important for the ACIA: (a) a number of models were studied and the conclusion reached that none was clearly preferable to the others (108); and (b) in a major study, 40 scenarios of future greenhouse gas emissions were analyzed, and six were selected as being particularly illustrative of what might occur during the 21st century (119).

Of a number of types of models that have been built of varying degrees of complexity, the most sophisticated for global climate simulations and projections of future climatic states are a series of "atmospheric-ocean general circulation models." These models are believed capable of providing "credible simulations of climate, at least down to subcontinental scales and over temporal scales from seasonal to decadal" (102). They have what is called "low resolution" when it comes to regional (Arctic) details. This is so because topographical features such as coastlines, ice sheets, sea-ice margins and mountains are weakly modeled, if at all, and the models are as yet unable adequately to capture the effects of intense storms and fundamental aspects of regional ocean circulation (136). Enlarging the global models to include these details has so far been impossible because of the enormous computational requirements of such a system. Auxiliary models are used to improve the results (104), but regional Arctic climate models have so far been inadequate to provide much improvement over the results drawn from the global models (130, 136).

The models are coupled submodels of the atmosphere, oceans, land surface, cryosphere (ice and snow covered areas), increasingly with biological and chemical components. Driving forces considered, for instance, in the ocean components of the models include: the interaction of atmospheric heat flows and sea-surface temperatures, brine rejection, freshwater from melting sea ice, and freshwater discharge from land sources (104). Many critical variables are omitted, as we shall see. The atmospheric component allows simulations over time and space of winds, temperature, humidity and surface pressure (105). The ocean component allows simulations of currents (in three dimensions), and temperature and salinity structures (106). The thermohaline circulation falls within its ambit. The land-surface component emphasizes thermal and moisture storage properties with key properties considered being surface roughness and albedo (the land reflectivity, or whiteness). The cryospheric component has, as its primary elements, snow cover, sea ice, and to a lesser degree, permafrost (107).

The ACIA adopted five of the IPCC models for use in its study. The primary criterion for choosing a model was its ability to simulate the evolution of actual global and Arctic climate scenarios over the 20th century. It is fully understood that satisfying such a criterion is no guarantee that

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[3] All but sulfur dioxide are discussed in [6]; for sulfur dioxide, see [1 at 120].

projections into the future will be adequate, but there is little reason to believe that a model that fails to satisfy that criterion will be useful for making future projections.

To provide a foundation for projections into the future, the models were intensively run over a 20-year baseline period from 1981 to 2000. The baseline simulations were run for each of the five models, the average of the results for the five models were computed, and comparisons were made with accepted standards of what actually happened over that period. For surface air temperature, for instance, the differences between the standard and the five-model mean were relatively small compared to the difference among the results generated by the different models (114). For precipitation, the difference between the five-model mean and the standard was greater than with air temperature. The authors speculate that this is caused by measurement error, primarily of precipitation in solid form (115). Similar runs were made for other climatic variables such as surface pressure. Other variables of interest, such as cloudiness, a key variable for climate system feedbacks, and the extent of sea ice and snow cover on land, are still poorly simulated (116–118). Such variables as wind stress, and inter-layer mixing within the water column, critical for nutrient upwelling, are neglected.

The IPCC used the global climate models to work out a number of scenarios of future greenhouse gas emissions. For instance, for use in simulations to the year 2100, IPCC scenarios include an increase in atmospheric carbon dioxide concentrations from the 1990 level of 350 parts per million, to, for the scenario showing the least change, 550 parts per million, and in the most extreme case, 950 ppm. The range for temperature increases from 1990 to 2100 is from 2 °C to somewhat over 4 °C. Two scenarios, labeled A2 and B2 were considered to be of particular interest to the ACIA project. The A2 emissions scenario emphasizes economic development rather than conservation and assumes a continuously increasing population. The B2 scenario, has a greater emphasis on environmental concerns with slower economic and population growth. To keep the project within manageable limits, a single emissions scenario, B2, was chosen for use in subsequent ACIA work (8). The IPCC did not assign probabilities to the future time series associated with each of the six "marker" scenarios (119–120). B2 seems reasonable, and lies in the middle range of the IPCC scenarios (100).

One result of the process that led to this selection, and the chapter is explicit about this, is that the scenario is not to be treated as a prediction; it is a projection based upon a more or less arbitrary, but reasonable, choice of possible future events (100). The results of the modeling exercise, and all the results that follow down the line, including the results concerning fisheries, are based on the results churned out by the five models conditional on the chosen B2 emissions scenario. A major conclusion drawn from the modeling exercise is that it is difficult to determine to what extent temperature changes are natural or anthropogenic, a key issue in the debate over global warming. Two further problems arise. Of great importance to fisheries, some of the five models project substantially reduced thermohaline circulation, while others do not. This makes it difficult to draw conclusions. Second, as referred to above, sea ice is not well handled by the models. This is interesting because the publicity surrounding the release of the synthesis document in November 2004 placed great emphasis on the effects of changes in sea ice (increased maritime shipping in the north; endangering polar bears and ringed seals). With regard to this variable, "expert judgment" is used in conjunction with the model results to draw conclusions (124).

Summarizing some of the simulation results using the B2 emissions scenario and the five atmosphere–ocean general circulation models for projections to the late 21st century (2071–2090), based on the 1981–2000 baseline, we get the following results:

- Surface air temperature: Global mean ranges from increase of 1.4–2.1 °C; Arctic, north of 60°, mean increase ranges from 2.8 to 4.6 °C (121–123).
- Precipitation: For the Arctic, projected increase in precipitation ranges from 7.5% to 18.1% (126).
- Sea-level air pressure: slight decrease (127).
- Cloud cover: slight increase (127).
- Sea-ice and terrestrial snow: decreases (127).
- Precipitation minus evaporation: increase (127).
- River discharge to the Arctic: increase (127).

The chapter ends with the comment that "there could still be surprises … solar variability, the effects of cosmic rays, and volcanic eruptions may all contribute more to Arctic climate change than is presently thought." (144).

4. Chapter 9—marine systems

This chapter opens with the comment that most models focus primarily on atmospheric changes, less on oceans, and that therefore the climate change scenarios for the oceans are highly uncertain. Conclusions drawn in this chapter are based on the atmospheric effects projected by the models, coupled to present understanding of how atmospheric "forcing" affects oceans, together with some results of ocean models (454). The primary mode of transport of climate change to the ocean is through mechanisms of physical oceanography. Key features are upper layer oceanic currents whereby heat is transported from southerly to northerly latitudes, such as by the Gulf Stream and the North Atlantic Drift. On reaching the north, the water in these currents is cooled and is returned south in the form, for instance, of the cold upper layer Labrador and East Greenland currents, as well as deep water currents called "overflows" (463–464). Warm Atlantic water flows into the Arctic Ocean via the Barents Sea and the Fram Strait (between northern Greenland and Spitzbergen) while similar activities occur in the Pacific, where the Bering Strait provides the gateway. Ten to 20 times as much water enters the Arctic from the Atlantic than from the Pacific and the exit from the Arctic is primarily through the Fram Strait and the Canadian Archipelago, a string of islands in the Canadian north (454–455).

The extent and depth of sea ice is a crucial determinant of: (a) the degree to which heat is transferred between ocean and atmosphere (456); (b) the extent of carbon exchange (516); and (c) the amount of light that penetrates to the water, thus affecting "primary production," the growth of phytoplankton (456). Sea ice experiences seasonal fluctuations (a 2:1 difference in sea ice cover March to September), as well as interannual, decadal and interdecadal fluctuations. These fluctuations are primarily the result of changes in atmospheric pressure patterns, associated winds, continental discharge of fresh water and flows of Atlantic and Pacific waters (456). Ice coverage has apparently been reduced by about 3% per decade during recent decades and multi-year ice (ice that does not melt seasonally) may have been reduced by as much as 7% per decade for the last two decades (457). As is so often true, there is division between scientists who believe that the changes are part of the natural changes in the polar climate and those who believe the generation of greenhouse gases by human activity has played the primary role (457).

The cause of the warming of the first half of the 20th century is uncertain, but one hypothesis is that the proximate cause was the increased transport of warm water through the North Atlantic Current. The mid-1960s cooling may have been caused by the displacement of the warm North Atlantic Current by the cold waters of the East Greenland Current (468). These changes reflect modest shifts in the volume and location of these currents. Since the effects of the changed weather patterns that resulted from modest shifts in ocean currents were great, some idea is conveyed of the importance of the factors that affect these currents. If global warming were to limit the formation of sea ice, and reduce the ambient temperature in the north, then the driving mechanism of the thermohaline circulation will be interfered with and the circulation will be modified. The result could be dramatic changes in the world's climate. Whether the resulting changes would be on net negative, or positive, is not clear.

A key question is what governed the temperature changes of the last century. During the irregular decline of temperatures following the 1960s, there were local minima off Newfoundland near the mid-1970s, mid-1980s and mid-1990s. These corresponded to peaks in the North Atlantic Oscillation (468). The North Atlantic Oscillation describes the relationship between the sea level air pressure between an Icelandic low and an Azores high. The North Atlantic Oscillation is considered positive when the pressure differential is large. As the gradient declines, the oscillation becomes negative. Prevailing winds are seriously affected by these pressure changes. There is also an Arctic Oscillation that is less well understood and appears to be highly correlated with the North Atlantic Oscillation. The Arctic Oscillation may, or may not, be a unifying thread between the Atlantic and Pacific Oceans (24–25). A major "mode" of North Pacific climate variability is the Pacific Decadal Oscillation and in the south is the Southern Oscillation, associated with El Niño. The physical origins of these major pressure phenomena are unknown (26). There has been a lot of work attempting to predict changes in the North Atlantic Oscillation and considerable doubt about the consequences. There appears to be consensus that were the Oscillation to increase (i.e., become more positive), westerly winds over the Atlantic would increase, leading to more frequent storms (470).

With the 1990s came increasing temperatures accompanied by changes in the Arctic water column, atmosphere, ice cover and the export of Arctic water to the Atlantic. The chapter's authors consider that their greatest challenge is to distinguish natural from anthropogenic changes. The second great challenge is to relate all of these physical changes to effects on living things, "biota" (469). The authors present tables showing "very likely" changes by 2020, 2050 and 2080. Abbreviated, the maximum projected changes are:

- Annual mean air temperature: increase by 1.5 °C by 2020, 3 °C by 2050 and 5 °C by 2080. Changes are much more substantial in the winter than summer, with a resulting lessening of seasonal variation.
- Net precipitation (precipitation minus evaporation) increases by 2%, 6% and 10% by 2020, 2050 and 2080, respectively.
- Sea level will rise by 5 cm by 2020, 15 cm by 2050 and 25 cm by 2080.[4]
- Cloud cover will increase by 3%, 5% and 8%.
- While substantial changes in winds are expected, there is little consensus on the changes in speed and direction.
- Duration of sea ice: less by 10 days, 20 days and 30 days for 2020, 2050 and 2080.
- Extent of winter ice: reduced by 10% by 2020, 20% by 2050 and by 2080 there will be ice-free areas in the high Arctic.
- Summer extent of ice, by 2080 up to 100% reduction from baseline.

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[4] These sea level figures appear to be at the low end of model simulations. Chapter 6, on the cryosphere and hydrology, discusses sea level changes at length. They assign three causes: vertical shifting of the earth caused either by slow glacio-isostatic expansion resulting from the removal of the ice cover before the start of the Holocene period, or by tectonic land movements; steric rises which refer to increases in ocean volume without changes in mass, caused by thermal expansion or salinity changes; and eustatic rises resulting from changes in mass caused by the melting of terrestrial ice (230). Figures for sea level change cited in this chapter, drawn from the IPCC, are: +120 m in the last 20,000 years, primarily as a result of the melting of ice age glaciers; an average rate of rise of 0.5 mm/yr over the past 6000 years; 0.1–0.2 mm/yr over the past 3000 years; a current rate of 1–2 mm/yr (232–233). Contrary to the results given in Chapter 9, Chapter 6 cites NASA figures stating that the sea level of the Arctic Ocean will rise during the 21st century by 73, 42 cm from thermal expansion and 31 cm from increased freshwater inflow. The same NASA model projects a global increase in sea level of 45 cm (234). The results from alternative models are highly disparate, with strongly differing regional effects.

- Ice export to North Atlantic, no change by 2020 but sharp reduction by 2080.
- Nutrient levels, with reduced ice cover, are expected to increase (470, 476).

As was remarked on earlier, an important factor in determining the global climate is the thermohaline circulation. Yet an important imponderable is how the circulation will respond to increased freshwater flows resulting from ice melting in response to higher atmospheric temperatures. Some of the models predict a weakening of the thermohaline circulation, while others predict virtually no change. Those that predict change, differ on the amount (reduction of 50% by the end of the century, or total collapse) but even these differ on the effects (477–478). While nutrient levels are generally expected to rise, the decline in vertical mixing within the water column resulting from a reduction in the thermohaline circulation will result in less upwelling of nutrients where the North Atlantic Drift enters the Arctic. In addition, a weakened thermohaline circulation will reduce the amount of warm water entering the north. The result would be a cooling, not warming, of that region. Unfortunately, as with most matters concerning the thermohaline circulation, neither the probability of such regional cooling, nor its extent, nor its magnitude, can be assessed (478).

At the very bottom of the food chain, the "primary production" are phytoplankton (481). Next on the chain come herbivorous zooplankton that can range up to 2–5 mm in size. In the Arctic, this trophic level is dominated by crustaceans, primarily copepods. Variations in the quantity of copepods are early indicators of climate-induced change in the North Atlantic and, being the food of young fish, such as juvenile cod, such variations can have severe effects on fish recruitment. Krill, swarming shrimp-like crustaceans, are also important (482).

During the warming decade beginning in 1920, the biomass of Norwegian spring spawning herring increased 10-fold. The population declined starting in the late 1950s. With the cooling of the mid-1960s in the waters off Iceland, the plankton community in the North Atlantic collapsed, and with it went the planktivorous Norwegian Spring Spawning Herring which previously had migrated to Iceland to feed. By 1970, the herring population had almost completely collapsed. This was a cooling period, although the loss of population was disproportionately more than the drop in temperature.[5] Despite a moratorium on the fishing of this species for a decade starting in 1973, the fish did not start to recover until the mid-1980s. With the warming period of the mid-1990s, the herring population has recovered to its peak levels of the early 1940s. Excessive fishing is credited with being the main cause of the population collapse, although environmental change may have been a secondary cause (485, 501, 698).

Climate affects marine biota directly, through temperature, currents, sea ice and snow, and indirectly through processes that affect nutrient availability. The availability of nutrients influences primary productivity and therefore food availability up through the various trophic levels. Sea ice is critical at the upper end of the food chain as a platform for such animals as polar bears and seals to give birth and seek food. It is probably of greater importance lower down the food chain since sea ice, with its snow cover, can reduce the level of light reaching the water surface to a level as low as the light reaching down 40 m, or even more, in an ice-free water column. Primary production (phytoplankton) below sea ice is severely limited, but is stimulated by the melting of sea ice (491). Currents transport zooplankton, and act with winds and freshwater flows to improve mixing in the water column and the upwelling of nutrients. Light, temperature, and the presence of sea ice all affect the amount of phytoplankton. Zooplankton, to provide animals at higher trophic levels with adequate food, must consume sufficient phytoplankton to fill their fat storage organs to capacity. Increased temperatures apparently speed this process. But since zooplankton are passively transported on ocean currents, the timing of phytoplankton blooms, and the transport of zooplankton to the phytoplankton blooms, must be synchronous or the zooplankton will die, thus depriving organisms at higher trophic levels of food. This potential match–mismatch problem exists all along the food chain. Larval cod, for instance, for survival largely rely on the availability at precisely the right time of copepod zooplankton. Temperature, salinity, mixing in the water column, and currents all play a role in determining the timing and location of key events. Too early melting of sea ice can result in an early phytoplankton bloom, which is gone, or largely gone, by the time it is needed by zooplankton. The result is a mismatch with zooplankton and a lack of food at higher trophic levels (494).

In some areas, such as the northern Barents Sea, primary production is highly correlated with the North Atlantic Oscillation, which, when positive, corresponds to warmer winters and minimal sea ice.[6] At such times, oceanic light levels are high and this stimulates early phytoplankton blooms (492). If too early, this could lead to mismatch.

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[5] Although there was a particularly rapid drop in water temperature in the late 1960s, the relevant ocean temperatures had started falling much earlier, in the mid-1940s, at about the same time that the herring populating started to decrease. The herring population reached its minimum around 1970, only a couple of years before the water temperature, but whereas water temperatures started to rise immediately after hitting bottom, the herring population did not start a significant rise until some 15 years later (501). For a detailed analysis of the historical relationships among overfishing, climate change and the biomass of the Norwegian spring spawning herring, see [8].

[6] Since the 1960s, winter temperatures in the Barents Sea and off Newfoundland have been negatively correlated, reflecting opposite responses to the North Atlantic Oscillation (468). Here the reference is to a positive North Atlantic Oscillation resulting in warm temperatures in the Barents Sea. Temperatures off Newfoundland would be cool.

Since fish are ectothermic (cold blooded), water temperature is usually the chief source of environmental impact on fish, governing growth and maturity rates as well as disease. Other environmental factors such as salinity, water mixing and transport processes also play significant roles (494). These factors all affect recruitment, an important concern of fishery science since early in the last century, and still inadequately understood.

What can be said about historic environmental changes and their effects on fish? During the period of warming from the 1920s to the 1960s, which affected Iceland and Greenland especially, there was an increase in the number of species off Greenland and an enormous increase in overall biomass. The changes are considered to have had to be caused by climate change, not fishing levels. The range of distribution of many fish species increased during this period. Note that it was an extension of the range of the fish populations, not a northerly shift in those populations (500). During the first decade or so of this warm period, the range of cod expanded by about 1000 km northward. After peaking at 400,000 metric tons in the early 1960s, the west Greenland cod catch collapsed, due apparently both to overfishing and a cooling climate. The recent warming of the Arctic has not, as yet, had a discernable effect on west Greenland fishing (500).

Barents Sea waters were cold early in the 20th century, i.e., before the warming which started in the 1920s. The particularly cold year of 1902 led to low cod catches which were in poor condition. Seals moved south. Similar events occurred during the cold 1980s when the capelin population, a key food source for cod, collapsed, leading to small catches of relatively small cod in poor condition. Once again, seals moved south (501).

With the cooling of water temperatures in the mid-1960s, capelin off Newfoundland extended its range southward. With a temporary warming in the 1970s, their range shrank northward and with the continued cooling from the late 1980s into the 1990s, the capelin range was again extended southward. Polar cod, which live north of the capelin, experienced similar changes (501).

In response to climate warming, the following long-term ecological trends are predicted as being "very likely" to happen:

- Southern limit of distribution for colder water fish species, e.g. capelin, polar cod and Greenland halibut, to move northward (a shrinkage of range) and decline in abundance (504).
- Distribution of more southerly fish species, e.g. Atlantic cod, herring, walleye pollack and some flatfish, to move northward (an expansion of range) and increase in abundance (504).
- Timing and location of spawning and feeding migrations to alter.
- Wind-driven flow (advection) patterns of fish larvae may be critical in determining whether there will be a match or mismatch of fish to feed on zooplankton.
- With the regional limitation or extinction of seasonal ice, mismatches of phytoplankton with zooplankton may increase.
- The disappearance of perennial sea ice is liable to double (or even quintuple) primary production, by extending the growing season. The actual outcome will depend largely on local conditions: upwelling, wind-driven vertical mixing and freshwater intake. Small salinity reductions can offset the beneficial effects of increased winds on vertical mixing.
- A crucial question regarding fish is that of the match or mismatch of fish to zooplankton. At this point it is impossible to predict whether the occasions of mismatches will increase or decrease (506–507).

Qualitatively, it is safe to say that increased ultra-violet radiation will negatively affect at least some phytoplankton, thus decreasing productivity at the bottom of the food chain. The mechanism for some microalgae is through reduction of fat content, including polyunsaturated fatty acids. Since zooplankton and fish larvae must consume these acids, the indirect effect of excessive ultraviolet radiation on fish can be quite severe. However, quantification is impossible, so how widespread the phenomenon of ultra-violet radiation reducing fat production among the many species of phytoplankton is unknown. For Atlantic cod, a modeling exercise resulted in ultraviolet mortality averaging only 1% (514–515).

The final class of effects considered in the marine systems chapter is the "carbon cycle", largely concerned with the release or absorption of carbon dioxide and methane. Because of its extensive ice cover, the Arctic Ocean has not been considered as a significant carbon sink. With global warming and the retreat of sea ice, the amount of carbon "sequestered" in the Arctic Ocean is liable to increase (516). The net effect on the Arctic, land and sea, however, is liable to be an increase in greenhouse gases because of the release of methane and carbon dioxide from thawing permafrost.

On a worldwide scale, oceans store approximately 50 times as much carbon as does the atmosphere. Most of this storage is in the deep waters of the Pacific Ocean. If the thermohaline circulation were to slow, or stop, the Atlantic would come to resemble the Pacific in this regard and its carbon storage would increase. Greenhouse gases would be stored, i.e., removed from the atmosphere, and this would have a cooling effect. This is a negative feedback, since the warming effect that slowed or stopped the thermohaline circulation in its turn was created by increases in greenhouse gases and climate warming (517). To the degree that warming increases plankton production, there will be an increase in the formation of calcareous shells, requiring that carbonate ions be removed from the water. Ultimately, these shells settle in the bottom sediments, the carbon is permanently entombed and the ability of the ocean to capture atmospheric carbon is increased. This sequence would further reduce greenhouse gases in the atmosphere (518).

5. Chapter 13—fisheries and aquaculture

For each of the four Arctic regions, this chapter provides a description of the fishery, past and present, then considers how the fishery might respond to anticipated climate change. The current role of the fishery in the economy and society of the region is considered, as are the potential response of the economy and society to the projected changes in the fisheries, and the ability of society to cope with the projected changes.

The marine systems chapter makes projections for such variables as surface temperature, cloud cover, precipitation, sea level, and the duration and extent of the sea ice cover. It also makes clear that surface pressure anomalies (e.g., the North Atlantic Oscillation) and ocean currents (e.g., the North Atlantic Current) play critical roles in determining the magnitude and timing of climate change and the ocean's responses to that change. In addition, such factors as upwelling, water mass mixing, temperatures throughout the water column, and primary (phytoplankton) and secondary (zooplankton) production play major roles in the health of a fish stock. Yet none of these factors is included in the scenarios of current climate models (692), and no projections concerning them are presented in Chapter 9. As a result of this missing information, any projections of what will happen to fish stocks, and any projections to the effects on society, must be tentative and highly uncertain. There are three major categories of uncertainty: (a) uncertainty about the causes (natural or anthropogenic) of past changes in fish population; (b) uncertainty about future climate change; and (c) uncertainty about the effects on society of changes in fish populations (693–694).

In fact, the firmest projections throughout the *ACIA* are those relating to atmospheric temperature. Therefore, in Chapter 13, although consideration is given to many factors, the emphasis is on responses to temperature change. Assuming moderate increases in atmospheric temperature, a few general conclusions can be drawn: (a) cold water species (e.g., capelin) will move north and their range will be reduced (740); (b) warmer water species (e.g., Atlantic cod) will enlarge their range by extending it northward; (c) the total effect on fish stocks will depend largely on the quality of fishery policies and their enforcement; and (d) the economic and social impacts depend largely on the ability of the society to react, and adjust, to the changes induced by the modified climate (692).

5.1. Northeast Atlantic

The key fish species in the northeast Atlantic are Atlantic cod, herring and capelin. Recruitment of cod and herring are enhanced by increased inflows of warm Atlantic water that carry zooplankton which serves as food for the larval and fry stages of those fish. Climate warming thus may increase cod and herring populations. Young herring, however, prey on capelin and increasing the population of the former might lead to decline in the latter. Declines in capelin may negatively affect fish (including cod), birds and marine mammals which prey on capelin (696).

The Northeast Atlantic provides an illustration of the uncertainty associated with even the least controversial of the ACIA projections. The global models on which the projections are based estimate an increase in sea surface temperature in the Northeast Atlantic of 3–5 °C by 2070. Yet regional models project an initial cooling of up to 1 °C by 2020, followed by modest warming of 1–2 °C by 2070. Cod recruitment should increase by 2070 with either of these modest temperature increases and the range of cod should be increased as well. Modest warming will help the cod but excessive warming, as projected by some of the global models, will harm cod recruitment. In this event, there may be a totally unpredictable change in species composition in these waters (700). It is unlikely that the projected moderate climate changes in this area during the medium term will have dramatic effects on the fish stocks.

But what is expected is that the cod stock will expand its range, as it did in the early 1990s. This migration took the stock into the "loophole" of the Barents Sea, an area at the time under no management control. Strong fishery management measures, both domestic within the 200-mile zone and internationally, beyond that zone, will probably play a major role in determining the state of the fish stocks after climate change (707).

Fisheries are economically important in northern Norway, but less so in the rest of the country. Subsidies directed at the Norwegian fishery are minimal, but the industry remains subsidized through programs that support northern regional development.

Northwestern Russia, the center of much Russian fishing activity, is not dependent on fisheries for economic viability, and there has been a great reduction in the economic and social significance of the fishery during the post-Soviet period (704).

5.2. Iceland and Greenland

The waters to the south and west of Iceland are warmer than those of Greenland or the Northwest Atlantic, being an extension of the warm and saline water of the North Atlantic Current (709–710). The result is that there are large quantities of zooplankton in the form of copepods and krill and more than 25 commercial stocks of fish and shellfish. Capelin, an important prey fish of cod, spend most of their time in the colder waters north of Iceland, returning to the warmer waters to spawn (711). Temperature changes around Iceland have generally followed the pattern described previously: cooling temperatures to 1920, then increasing temperatures to the mid-1960s, then cooling to 1970. Here the pattern breaks. There were modest increases in temperature and in temperature volatility until a warming trend started again around 1990. The 1920–1964 period was characterized by an increased flow of Atlantic water to the north of Iceland, stimulating vertical mixing in the water column and leading to increased primary and secondary production (716). One major result of these phenomena was that cod spawned in large numbers in the north and east of Iceland, as well as in the more traditional south and west. This is an example of fish expanding (not shifting) their range when the ocean water warms. A second major result was that there was a migration of cod larvae to Greenland, which matured and led to a spawning population and an active cod fishery there. With the cooling trend of the late 1960s, cod no longer spawned off Greenland, and ultimately the cod larvae migration from Iceland ceased. The Greenland cod fishery ended (718–719).

The growth rate of capelin has been positively correlated with temperature and salinity. Attempts to relate capelin recruitment, however, to such factors as temperature, salinity and zooplankton abundance have yielded ambiguous results (718). Because of high fishing pressure, commercial stocks off Iceland are smaller than previously. Effective, rational, fisheries management, especially combined with favorable climate conditions (from no change in temperature to moderate warming) will probably lead to increased abundance of most stocks (720). Were mean temperatures to rise more than 3 °C during the 21st century, there would probably be dramatic changes to the Icelandic marine ecosystem. Of greatest importance, the range of capelin would shift north and shrink, thus reducing the major food source for cod and other species, resulting in a reduction in their abundance (721).

Throughout the 20th century, Iceland averaged a 4% annual GDP growth rate largely driven by the fisheries. There were five major economic depressions during this period, all related either to the state of the fish stocks or to the foreign trade in fish (721). The authors conclude that the Icelandic economy has become more diverse, so that changes in the fishery will not have as dramatic effects in the future as they have had in the past. In addition, it is believed that the fishery management system has made the fishing industry more adaptable to fluctuations in fish stocks (722).

The effects on Iceland's fisheries of climate change over the next century is likely to be positive. Although there will not be dramatic effects on fish populations, some of the most valuable stocks are currently in depressed states and are likely to benefit from moderate temperature increases. An economic analysis with an "optimistic" scenario featuring a 20% increase in fish populations over 50 years will increase GDP in that time period by less than 4%. Even a totally unanticipated and catastrophic drop of 25% in the fish stock would lower GDP by 9% in year eight but would settle on a 3% reduction in the long term. Such a scenario is most unlikely. The authors conclude that a proper harvesting policy would have a greater effect on the economic yield of the fishery than even the most optimistic climate scenario (726). In Greenland, as well as in Iceland, a warming climate trend is likely to improve the state of fisheries, particularly of the cod stock, although increased cod predation would reduce the shrimp population which now dominates the Greenland fishery (728).

5.3. Northeastern Canada

Although several species are fished off Newfoundland, cod traditionally dominated the fishery, with capelin being an important prey fish. With the decline of the cod, northern shrimp and snow crab have come to prominence.

A century-old pattern of fishing for "northern" cod was broken with the arrival of large foreign distant water fleets in the late 1950s and through the 1960s. Catches that traditionally ran to 300,000 metric tons, grew to a maximum of more than 800,000 metric tons in 1968. The stock then declined substantially as a result of overfishing and did not start to recover until the foreign fleets were largely expelled with the extension to the 200-mile limit in 1977. The recovery was cut short in the late 1980s and the stock collapsed in 1992. The ACIA authors note that not only cod, but other demersal fish, including some that are not fished commercially, collapsed at the same time. This fact has been presented as evidence that climate played a role, even the major role, in the cod collapse. This argument is mitigated by the possibility that, though not fished commercially, the other demersal fish were caught as bycatch (733, 736–737).

That the ocean water off Newfoundland in the mid-1980s and early 1990s was particularly cold, correlated with an increasingly positive phase of the North Atlantic Oscillation, also suggests that the climate played a major role in the cod collapse (732–733). Controversy continues as to whether the collapse was caused by overfishing, by climate changes, or both. The question remains open (736). Offshore capelin have also been severely reduced but inshore surveys have not shown similar declines, thus leaving the question of the status of capelin also uncertain (732). It is believed that overfishing was not a factor in any decline of capelin, but rather that any variations have been environmentally driven (738).

The northern shrimp population appears to be healthy, but the snow crab fishery has been used in part to sop up the excess unemployment left by the depleted ground fisheries. While catches and values are still high, there has been pressure to maintain overcapacity in the fishery, which, in turn, provides an incentive to overfish. There are concerns that the resource has declined (735).

A warming trend would probably result in an expanded range for demersal species, including cod. But local differences may outweigh any global trend, and within a trend there may be substantial short-term events running counter to the trend. These short-term events, if severe enough, could be more important than any long-term temperature trend. It might be more important to know what is going to happen to the North Atlantic Oscillation than to predict temperature trends (739–740).

In the absence of future environmental change, the current mix dominated by northern shrimp and snow crab is likely to continue. With moderate warming, there is likely to be a return to the old cod/capelin complex that existed before the 1990s. Warmer sea temperatures are likely to retard shellfish recruitment, but to encourage cod recruitment. Atlantic cod will expand its range northward, and capelin will shift its range northward. On the assumption that warmer temperatures stimulate zooplankton abundance, capelin growth will improve. But rising sea levels will destroy capelin spawning beaches. Capelin can spawn offshore, but survival rates are lower than for beach spawners. Because of the doubts concerning the future of capelin under this scenario of moderate warming, it is uncertain as to whether or not the cod/capelin complex will be restored, but at the moment that is the best guess. In addition, changes in other climatic variables may serve to counteract the increase in temperature; these changes are not being projected in this exercise (740).

Historically, the Newfoundland economy rested on the cod fishery but for the past century there have been repeated attempts to diversify the economy. The fishery remains important, accounting for 3–5% of the provincial GDP, and perhaps 11% of employment. Nonetheless, these are not overwhelmingly large figures. The government, education, health and service sectors of the economy, as well as oil production, account for greater shares of the GDP. Yet rural Newfoundland, despite all efforts to diversify, are still dependent on the fishery. The cod collapse of the late 1980s and early 1990s resulted in increases in unemployment in the tens of thousands and in government transfer payments of more than 2 billion dollars over a decade, largely for income maintenance. The fishery still plays a substantial role in the economy, and even more so in the cultural mythology of the province (741–742).

As we have seen, it is difficult enough, given the basic emission scenarios and the results of the global models, to determine what can be expected to happen to the various oceanographic variables. Thus, the emphasis has been on temperature trends. Recognition of the importance of projections for omitted variables has led to the understanding that there is great uncertainty surrounding nearly all the projections discussed.

When we come to societal reactions, the problems become even worse, at least in the context of Newfoundland. There are historical examples of major shocks, positive and negative, to the Newfoundland fisheries, and the record of human response is clear. The two most important shocks during the last quarter of the 20th century were the expansion of the fishery in 1977–1981 following the declaration of the 200-mile zone of exclusive fisheries jurisdiction, and the collapse of the northern cod stock in 1992. Society's responses in both cases provide illustrative examples of what a society should not do.

The first of these periods was supposed to be one of rebuilding, of the slow development of a Newfoundland-based fishery to replace the distant water fleets that were being displaced. However, for a number of reasons, not the least of which was overarching optimism, the capacity of the fishery was allowed almost unrestricted expansion. This, combined with other factors, led to pressure on the stocks and, at least in one interpretation, the northern cod stock was never able to fully recover from the excessive distant water fishing of the late 1960s. The expansion ended in 1981 with the bankruptcy, or near bankruptcy, of the major Newfoundland fishing firms when international fish markets shrank in response to a worldwide economic recession. When the expansion started, there were only 13,000 fishermen. Suitably deployed, these fishermen would have been more than sufficient to handle a gradual increase in harvests. Instead, at the maximum, there were more than 30,000 fishermen. Similar comments could be made about capital (vessels, large and small, and fish processing plants), that needed modernization but not expansion. With a gradual and rational expansion, the future history of the Newfoundland fishery might have been very different from what it was.

The second of these periods resulted in several years when the government, using economic incentives, attempted to seduce unwilling fishermen into leaving the industry. Instead, fishermen, believing that the fish would return and that the government would support them until that time, essentially refused. The cost to government in income maintenance was high. With generous buyouts, and only very limited income maintenance payments, the government could have reduced the human population dependent on the fishery with less pain and expense than actually occurred.

Were there to be another major shock to the fishery, either beneficial or detrimental, how would the society react? It is not clear. If the lessons of the past were learned, and the political ambience permitted the lessons to be applied, then the necessary adjustments, regardless of whether the changes are positive or negative, could be made without being fraught with the short- and long-term problems encountered in the past (744).

5.4. North Pacific/Bering Sea

While numerous species of fish are caught in the Bering Sea, the dominant species is walleye pollock, a semi-demersal fish that was first subject to a directed fishery in 1964. The eastern Bering Sea (United States) catch since 1987 has averaged 1.2 million metric tons. While the western Bering Sea (Russia) catch peaked at 1,327,000 metric tons in 1988, by 2000 it had fallen to 393,180 metric tons (749–750).

More than in the other sections of this chapter, the authors bring oceanographic detail to bear on analyzing the effects of climate change on fish stocks. Climate change regimes are determined by four physical processes: lunar tidal cycles; variations in solar radiation; changes in the North Pacific circulation; and the Aleutian Low atmospheric pressure pattern. Just as the North Atlantic Current warms the northeastern Atlantic, the western Bering Sea is warmed by the influx of Pacific waters (753). Decadal scale changes in the atmospheric climate are transmitted to the eastern Bering Sea and to the biota through wind stress and annual variations in sea ice extent. These mechanisms alter the timing and abundance of primary (phytoplankton) and secondary (zooplankton) production by altering salinity, upwelling, nutrient supply, and vertical mixing (754). When sea ice retreats in March or later, phytoplankton blooms occur in cold water. Zooplankton are temperature sensitive. Therefore, when the bloom occurs in cold water, production of zooplankton is limited with detrimental effects on species further up the food chain. Alternatively, early ice retreat results in a warm water phytoplankton bloom in late spring, resulting in successful production of zooplankton which presumably results in improved recruitment higher up the food chain.

Consistent with what we have seen before, when waters are cold, there will be an expansion of the capelin range. With warmer temperatures and reduced ice cover, the range of capelin will contract. Warm conditions improve survival chances in young pollock by increasing zooplankton (copepod) abundance and reducing predation by cold water species. El Niño events in the 1990s warmed the eastern Bering Sea, yielding strong year-classes of pollock. During the same period, however, as a result of reduced inflow of Pacific water, there were no good pollock year-classes in the western Bering Sea (755–756).

Alaska salmon stocks experience multi-year periods of high abundance, and of low abundance, in response to water temperatures that are themselves determined in part by the Pacific Decadal Oscillation. During warm periods, the salmon do well, probably as a result of improved feeding conditions.

The three commercial species of crab in the Bering Sea show periodic patterns of abundance. Anomalous cold bottom water is deleterious to Tanner crab reproduction while northeast winds that promote upwelling shifts larvae to fine sediments which, when settled, promote survival. Red king crab demonstrates a decadal recruitment cycle that shows the stocks to be negatively correlated with a deepening Aleutian Low and warmer water temperatures (757).

Despite the authors' attempts to explain the reaction of fish and shellfish species to past climate change, they are not willing to project future reactions. They state that they cannot predict with any certainty the effects of future increases in sea surface temperature on commercial fish and shellfish species since to do so would require knowledge of storm activity and frequency, wind direction and intensity, water stratification, changes in currents, sea level pressure (the location and intensity of the Aleutian Low) and precipitation (757).

The population of walleye pollock fell during the 1990s. ‘‘Conventional wisdom assumes’’ that this was not the result of overfishing, but rather a reaction to environmental conditions (759).

The Bering Sea fisheries, largely a post-World War II phenomenon, have experienced at least two major dislocations. First, with the extension of United States jurisdiction, the Japanese and Soviet fleets were displaced with considerable hardship that is not further defined in the chapter. Second, the American fishing industry, aided by federal subsidies, grew rapidly. In addition, during the growth phase, there was a successful major shift in species, from a fishery dominated by crab to one dominated by pollock. The assumption made in the chapter is that with switches between warmer and cooler temperatures, stock assessment techniques would be sensitive enough to detect the effects of the changes on the stocks and that quotas would be modified to prevent overfishing. For species with short life spans, volatility might make this procedure more difficult, but ‘‘high natural variability is considered by managers’’. For species with very long life spans, very conservative quotas would be enforced. Stock crashes, such as the Bristol Bay red king crab stock which was extensively fished in the 1970s and then crashed, are generally in this chapter credited to environmental conditions and not to overfishing. This excessively optimistic view of the sensitivity and effectiveness of fisheries management seems Panglossian to me. And nothing is said about adjustments in the western Bering Sea, the domain of the old Soviet Union, where the dislocations of the past fifteen years must have been enormous (766–768).

6. Conclusions

The clearest conclusion is that the world's climate has always been changing. The changes often follow millennia-long trends of warming or cooling, but those long trends conceal a range of heterogeneous effects: dramatic differences from one part of the globe to another and among relatively narrow subareas (as different climatic changes in different regions of the Arctic); and shorter-term trends in a contrary direction within the overall trend. Thus, for example, there have been warming spells within a general long-term cooling period. Until a 150 years ago, or thereabouts, the north was cooling in what has been termed ‘‘The Little Ice Age’’. Then a warming trend started which has continued to this day. But the warming has not been smooth. The start of the 20th century was cool. Then the north started warming in the 1920s and, depending on location, the warming continued to, or through, the 1960s. A cooling period followed until the mid-1990s, when warming resumed.

To what extent has mankind influenced climate change, either now or in the past? The ACIA *Implementation Plan* of September 2000 noted that ‘‘there is no consensus of scientific opinion on whether these changes are due to anthropogenic influences or to natural variation’’ [2, at 3]. The *Plan* went on to state that regardless of the cause, it is necessary to synthesize and assess scientific knowledge of these changes and their effects. That is what the ACIA has done. There is very little evidence presented in the *ACIA* to warrant the claim that human activity is largely responsible for the current change.[7] When the issue is raised, and I have cited a number of examples, it is usually to comment that the role of anthropogenic influences is unknown, or uncertain. One of the strongest statements in the *ACIA* on this topic appears in chapter 6 (on the cryosphere), where it is noted that one of the five ACIA models demonstrates that the decrease in Arctic sea ice "is highly unlikely to have occurred as a result of natural variability (190)." However, the chapter continues with the comment that this conclusion "is based on the assumption that the natural variability of sea ice can be reliably inferred from climate model simulations (191)," clearly raising the question of whether that assumption is valid.

While there is little evidence, if any, in the *ACIA* to support the anthropogenic interpretation of current climate change, there is a background belief that this interpretation is correct. The synthesis document released in November 2004 refers to ice core and other evidence supporting the view that rising global temperatures in the past have been associated with rising levels of atmospheric carbon dioxide. Noting that since the start of the industrial revolution the global average temperature has risen by 0.6 °C and the carbon dioxide concentration has increased by 35%, the authors state, with reference to an IPCC report, that "there is an international scientific consensus that most of the warming observed over the past 50 years is attributable to human activities" [3, at 2].

Except for this one reference, the authors and editors of the ACIA documents are more cautious: a particular phenomenon *may* be anthropogenic; a set of events *may* occur. The *ACIA* is clear in stating that it is not reporting on forecasts, but merely on the results of climate models that project what may happen given a possible scenario of future emissions. Nonetheless, it seems likely that atmospheric temperatures will continue to rise, but not monotonically, that sea ice cover on the Arctic will shrink, that permanent terrestrial ice will recede, that permafrost will thaw. These events will not happen uniformly, and may not happen at all in certain locations, but they will most likely occur throughout much of the Arctic. We will accept that the net effect of global warming is negative: indigenous peoples' way of life will be impossible to maintain; certain mammals are in danger of extinction; sea level increases will flood low-lying areas; increased ultraviolet radiation will increase the occurrence of human cancers, etc. There are as well positive aspects to climate change in form of improved transportation, increased fish habitat, increased nutrients in the sea, increased domain for agriculture, etc. But it is probably not much of a stretch to conclude that the net effect is negative.

Running throughout the *ACIA* is the recognition of great uncertainty associated with all the conclusions. There is uncertainty about whether specific events are anthropogenic or "natural". With respect to fisheries, there is recognition that there is an overemphasis on projected temperature changes. But this limitation was enforced by the difficulty in projecting such other variables as upwelling changes and water layer mixing. Of greater importance, perhaps, is the uncertainty associated with changes in the key ocean currents, such as the North Atlantic Drift. There is further uncertainty over first causes, to what extent are the changes in variables of interest caused by major surface pressure shifts, e.g., the North Atlantic Oscillation. There is further uncertainty about what causes these pressure changes, and whether they can be predicted. The effects of climate change on fisheries are enmeshed in all of this uncertainty.

Nonetheless, the impressions left from Chapter 13 are that: (a) modest warming will, in general, benefit northern fisheries; and (b) that the quality of the human response to whatever changes occur will depend both on the employment of effective fishery management techniques and on the ability of the societies to make the necessary political decisions.

Is policy intervention, as in the Kyoto Protocol, warranted? Since climate change may be anthropogenic, and the increase in ultra-violet radiation is in part anthropogenic, a conservative position would be that human intervention would be prudent. Perhaps the proposals of the "anemic" policy statement referred to earlier: to adopt climate change mitigation strategies to limit greenhouse gas emissions; to promote and develop appropriate energy sources; to adapt as best as possible to climate change; to advance research; and to continue to monitor the situation—all pretty vague—are all that our present state of knowledge warrants. Certainly, the results of the December 2005 United Nations Climate Change Conference in Montreal support the view that such vague statements of intent are all that can be accomplished in the present political climate [9,10].

References

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[7] With respect to "substantial late winter and early spring reductions in arctic total column ozone", it is accepted with little doubt that the changes are at least in part anthropogenic (152, 157, 167). Ozone depletion results in increased UV radiation reaching the earth's surface and in combination with other factors can cause change in the Arctic ecosystem (154). Regarding climate change, however, ozone depletion processes are seen as a result, not a cause, of climate change (170). We have already seen that the indirect effects of increased UV radiation on fish could be substantial, that the effects remain unquantifiable, but that a modeling exercise showed only minimal effects on Atlantic cod.

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