The Potential Consequences of Climate Variability and Change

ALASKA

A Report of the Alaska Regional Assessment Group

For the U.S. Global Change Research Program

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PREPARING FOR A CHANGING CLIMATE

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Preface

Our assessment of the impacts of climate change in Alaska and the Bering Sea region started in 1995 and has now spanned a period of almost five years, with workshops taking place each year. The present report is a summary of the findings from all of these workshops. In 1995 our first workshop was on "Preparing for an Uncertain Future: Impacts of Short- and Long-Term Climate Change on Alaska." In 1996, the International Arctic Science Committee (IASC) provided funds for an impact assessment on the Bering Sea under an IASC project called BESIS (Bering Sea Impact Assessment). A proposal to the Office of Polar Programs, National Science Foundation was also funded and allowed us to conduct our second workshop in September 1996. The 1997 workshop received funding from the Department of Interior and was recognized by the U.S. Global Change Research Program (USGCRP) as the national workshop for the Alaska region. A fourth impacts assessment workshop under the USGCRP took place in Fairbanks, Alaska, in October 1998 with Department of Interior funding. With NOAA and IASC funds we also organized an international workshop in Tromsø, Norway, in April 1999, to begin a pan-Arctic assessment of the impacts of climate change.

Many people contributed to these workshops and we cannot list them all here. The names of the workshop leaders can be found in the appendix; the names of all participants are in the various publications that resulted from the workshops and which are listed below. These publications formed the basis of the present report.

Preparing for an Uncertain Future: Impacts of Short- and Long-Term Climate Change in Alaska. Eds. Anderson, P., and G. Weller. Proceedings of a Workshop in September 1995, Center for Global Change and Arctic System Research, University of Alaska Fairbanks, 43 pages.

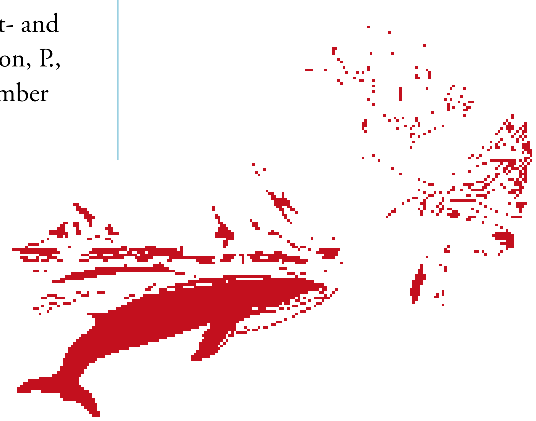
The Impacts of Global Climate Change in the Bering Sea Region. An Assessment Conducted by the International Arctic Science Committee under its Bering Sea Impacts Study (BESIS). Results of a Workshop at Girdwood, Alaska, September 1996. Center for Global Change and Arctic System Research, University of Alaska Fairbanks, 40 pages.

Implications of Global Change in Alaska and the Bering Sea Region. Proceedings of a Workshop at the University of Alaska Fairbanks on 3–6 June 1997. Eds. Weller, G. and P. Anderson, Center for Global Change and Arctic System Research, University of Alaska Fairbanks, 152 pages plus appendices.

Assessing the Consequences of Climate Change for Alaska and the Bering Sea Region. Proceedings of a Workshop at the University of Alaska Fairbanks, 29–30 October 1998. Center for Global Change and Arctic System Research, University of Alaska Fairbanks (in press).

Impacts of Global Climate Change in the Arctic Regions. Report from a Workshop on the Impacts of Global Change, 25–26 April 1999, Tromsø, Norway. Eds. Weller, G., and M. Lange. Published for International Arctic Science Committee by Center for Global Change and Arctic System Research, University of Alaska Fairbanks, 59 pages.

Measurements throughout this publication are given in medieval units (feet, miles, °F, etc.), followed by scientific metric units in brackets.



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Jack Ahgoot and Raymond Paneak ice fishing, Chandlar Lake, 1947

Executive Summary

Alaska is vulnerable to climate change. Climate trends over the last three decades have shown considerable warming. This has already led to major impacts on the environment and the economy. If present climate trends continue these

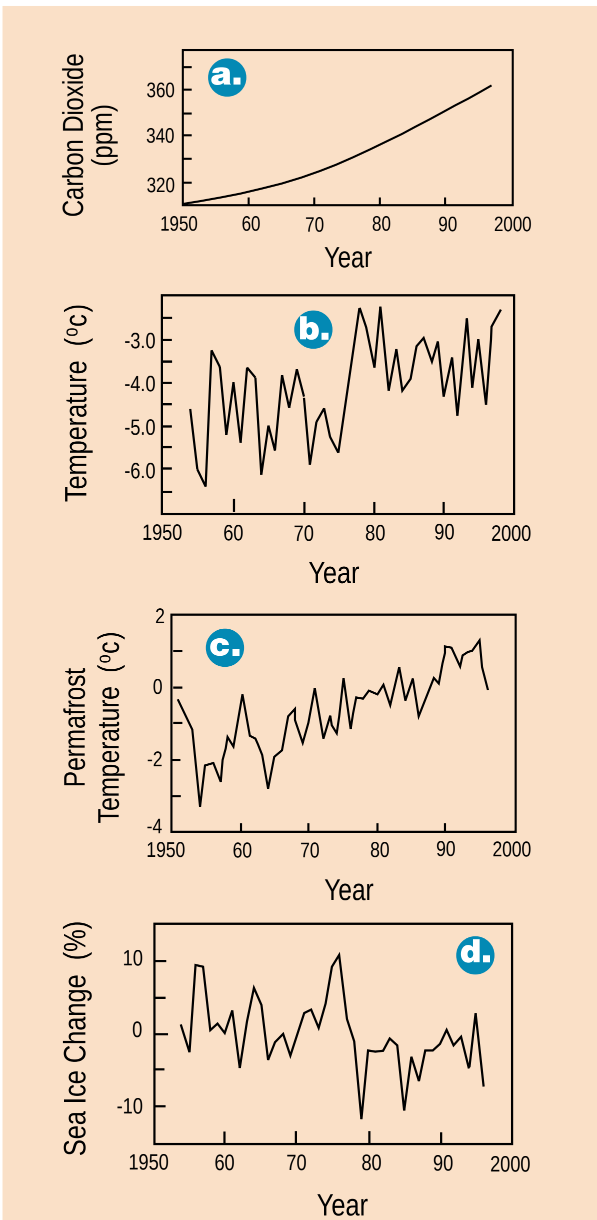


Fig. 1. Climate and climate-related trends in Alaska. a) CO_2 at Barrow, Alaska (smoothed), b) annual mean temperature composite from Anchorage, Fairbanks, Nome and Barrow, c) permafrost temperatures at Fairbanks, d) change in sea ice extent (%) in the Bering Sea.

impacts will be exacerbated and will hit the state's strongly natural resource-dependent economy hard. In Alaska there are few cities and many rural communities. Predominant economic activities include oil production along the Arctic coast (20% of total U.S. production), fishing in the Bering Sea and off the south coast, forestry in the southeast, agriculture and forestry in the interior, and a growing tourism industry. Subsistence livelihoods in Native communities throughout the state depend on fish, marine mammals and other wildlife, and play a very important social and cultural role.

Alaska's ecosystems are also threatened. They range from cool spruce-hemlock forest in the southeast and south-central coastal regions to boreal spruce forest in the interior and south-central region. Further north, tundra meadows and barrens dominate. Large areas of land are set aside in national parks, wilderness areas, and nature preserves. Small areas of land are in agriculture, with rather larger areas used for pasture and reindeer grazing. The marine ecosystems of the Bering Sea and Gulf of Alaska are among the most productive in the world and are highly susceptible to climate change.

Observed Climate Trends

Alaska's enormous size encompasses extreme climatic differences. The southern coastal margin is climatically similar to the Pacific Northwest, although cooler and with longer winters. North of the Alaska Range, the climate is continental, with moderate summers, very cold winters, and annual precipitation of 8–16 in (20–40 cm). North of the Brooks Range, an arctic semi-arid climate prevails, with less than 8 in (20 cm) of annual precipitation and snow on the ground for nine months of the year. There are widespread areas of permafrost and large glaciated areas throughout the state, and extensive sea ice along the western and northern coasts.

Alaska has experienced the largest regional warming of any state in the U.S., with a rise in average temperature of about 5°F (3°C) since the 1960s and 8°F (4.5°C) in winter. Records from some regions show a warming of nearly 3–4°F (1.5–2°C) quite suddenly in the late 1970s (Fig. 1). There has been extensive melting of glaciers, thawing of permafrost and reduction of sea-ice. The Alaskan regional warming is part of a larger warming trend throughout the Arctic. The large observed warming has been accompanied by increases in precipitation of roughly 30% between 1968 and 1990. Alaska is also strongly affected by El Niño and the interdecadal Arctic Oscillation, bringing warmer and wetter winters to coastal Alaska in their warm phases, and cooler, drier winters in their cool phases.

Scenario of a Future Climate

Climate projections suggest a continuation of the strong warming trend of recent decades, with the largest changes coming during winter months. In the models used in this assessment, warming of approximately 3–5.5° F (1.5–3°C) is projected by 2030 with 9–18° F (5–10°C) warming by 2100. The models also show Alaska getting wetter, with larger increases in northern and western Alaska and smaller increases or possibly decreases in the southeast. The reduction or loss of snow and ice has the effect of increasing the warming trends as reflective snow and ice surfaces are replaced with darker land and water surfaces that absorb more solar radiation. As a result, one of the two models analyzed in this study projects near-total melting of arctic sea ice by 2100. Large winter warming in Alaska will likely accelerate already evident trends of a shorter snow season, retreat and thinning of sea ice, thawing of permafrost, and accelerated melting of glaciers.

A Key Issue: The Melting of Snow, Ice and Permafrost

Alaska has undergone a marked reduction in extent and duration of snow cover, shorter seasons of river and lake ice, melting of mountain glaciers, retreat and thinning of sea ice, retreat of permafrost and increased depth of its active layer. The thawing that Alaska has already experienced has brought major ecological and socioeconomic impacts, which appear likely to be emblematic of further changes under projections of continued greenhouse-induced warming. Thawing and northward movement of the permafrost line over the past several decades has required costly road replacement, increased maintenance costs for pipelines and other infrastructure, changed forests to bogs and grasslands, and increased slope instabilities. Reduced sea-ice along Alaska's coasts has allowed increased coastal erosion and increased vulnerability to storm surges, but has also the potential of benefiting shipping and offshore petroleum exploration.

Forests and Agriculture

Warmer temperatures have brought some northward expansion of boreal forest, as well as significant increases in fire frequency and intensity, unprecedented insect outbreaks, and a 20% increase in growing-degree days, the latter having benefited both agriculture and forestry. Both the expansion of forests and their increased vulnerability to fire and pest disruption are expected to increase. One projection shows a 200% increase in the total area burned per decade, leading to a deciduous forest–dominated landscape on the Seward Peninsula, presently dominated by tundra vegetation.

Marine Ecosystems and Fisheries

Recent observations of climate-related changes in the Bering Sea showed abnormal conditions during 1997–1999. The changes observed include extreme die-off of seabirds, rare algal blooms, abnormally warm water temperatures, and very low numbers of returning salmon. While some of the changes observed in the 1997 and 1998 summers, such as warmer than usual ocean temperatures and altered currents and atmospheric conditions, might have been caused by El Niño, the area has been undergoing change on a much longer time scale going back several decades. Over that period one species of sea lion, for example, has declined by between 50% and 80%. Northern fur seal pups on the Pribilof Islands—the major Bering Sea breeding grounds—have declined by half between the 1950s and the 1980s. In parts of the Gulf of Alaska, harbor seal numbers are as much as 90% below what they were in the 1970s. There have been significant declines in the populations of some seabird species, including common murres, thick-billed murres, and red- and black-legged kittiwakes. Also, the number of returning salmon was far below expected levels, the fish were smaller than average and their traditional migratory patterns seemed to have been altered. Further impacts of climate change on Alaska's fisheries can be expected as the climate continues to warm.

Subsistence Livelihoods

Subsistence livelihoods are already being threatened by multiple climate-related factors, including reduced or displaced populations of marine mammals, seabirds and other wildlife, and reduction and thinning of sea-ice, making hunting more difficult and dangerous. Diverse forms of subsistence livelihoods that sustain Native communities depend on fish, marine mammals, and other wildlife, and include trapping, fishing and reindeer herding. They play a social and cultural role vastly greater than their contribution to monetary incomes.

The National Impact Assessment Process

A national assessment on the potential consequences of climate variability and change over time spans of 20–30 and 100 years began in 1997. The assessment is focused on both vulnerabilities and opportunities for the U.S., but recognizes that many of the issues of interest within the Nation have international aspects as well. A National Synthesis Report will draw on the results of 20 regional assessments that have investigated potential consequences of climate variability and change in different parts of the country. Alaska is one of these regions. The conclusions drawn from this national assessment are part of the U.S. contributions to the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report.

Goals of the Regional Impact Assessment

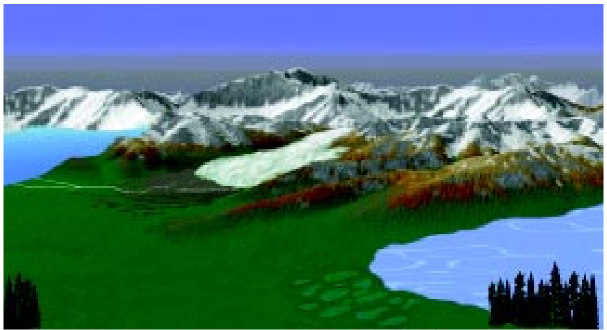
Regional assessments of impacts due to global climate change have become a high priority on the international research agenda. The International Geosphere-Biosphere Programme provides a good rationale for this regional emphasis (IGBP, 1991): "First, the research needed to

I. Introduction

develop a global perspective demands that regional differences in characteristics such as biogeography and climate be taken into consideration. Second, the goal of a practical predictive capability for global environmental change makes it necessary that this capacity be developed for distinct subcontinental regions. Global change predictions will be of greatest value to decision makers on a regional basis, and if scientists from throughout the region are involved from the start in the processes through which they are generated."

The Alaska regional impact assessment has been guided by the questions posed by the national assessment, as follows:

- What are the current environmental stresses and issues that will form a backdrop for potential additional impacts of climate change?
- How might climate variability and change exacerbate or ameliorate existing problems?
- What are the priority research and information needs that can better prepare policy makers to reach wise decisions related to climate variability and change?



Computer-generated composite of Alaskan landscape features

- What coping options exist that can build resilience to current environmental stresses, and also possibly lessen the impacts of climate change?

Description of the Region

The Alaska region, which includes the Bering Sea, is the largest of all the regions considered under a National Assessment Synthesis conducted for the entire United States. It spans about 60 degrees of longitude and 20 degrees of latitude. Alaska is sharply divided by mountain ranges into coastal and interior regions. With a longer coastline than all other 49 states combined, there are pronounced differences between the coastal regions themselves and the interior. Alaska's climate ranges from a mild and wet maritime climate in the south to the extreme cold polar desert climate in the north. The state contains the fourth largest glaciated area in the world and Alaska has more than 40 percent of the nation's surface-water resources (Lamke, 1986) (Fig. 2). Approximately 170 million acres of Alaska's 367 million acres are covered by wetlands; this is more than the total wetland area in the other 49 states (Dahl, 1990). Other natural resources include large numbers of wildlife, the nation's largest fishery in the Bering Sea, substantial petroleum resources, gold and other minerals, and the nation's largest areas set aside in parks, reserves and wildlife refuges. Alaska has a large Native population, which still practices traditional subsistence activities.

Alaska's Economy

Along the arctic coast Alaska's oil fields produce 20 percent of domestic petroleum needs. In southeast Alaska and along the Bering Sea coast, fisheries predominate in economic activities and the Alaskan fisheries are the largest in the nation. The fisheries resources of the Bering Sea are also exploited by many other nations. Timber harvesting occurs mostly in coastal areas in southeast Alaska. Mining for gold and other metals exists throughout the state. Some agriculture and forestry takes place in the interior. While vast expanses of boreal forest cover the interior, relatively little of it produces enough wood volume to support a commercial forest industry. Tourism is an important economic activity and the tourism industry covers all areas of the state. Diverse forms of subsistence livelihood practiced primarily in Native communities throughout the state depend on fish, marine mammals, and wildlife—including partly commercial reindeer herding—and play a social and cultural role vastly greater than their contribution to monetary incomes.

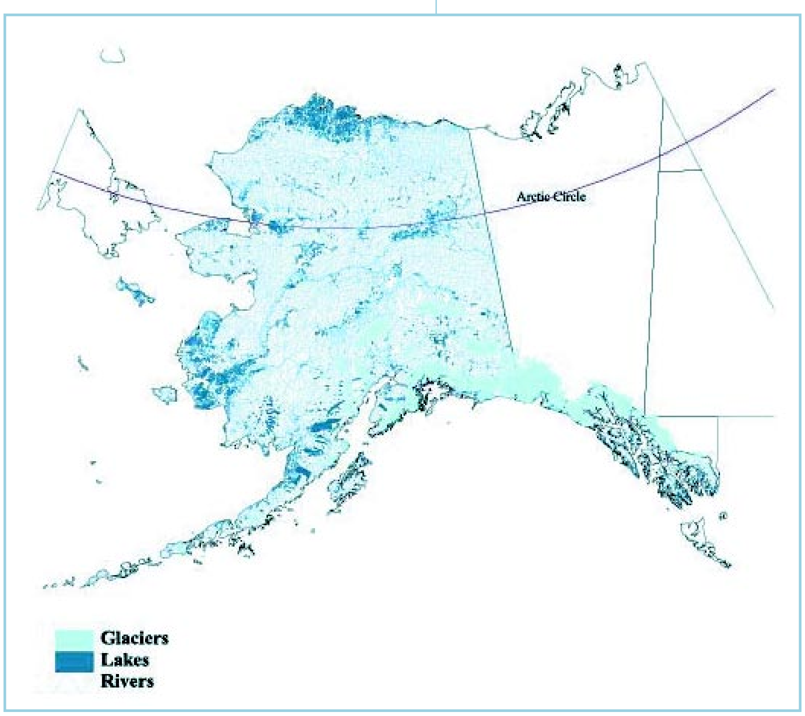


Fig. 2. Rivers, lakes and glaciers of Alaska (Domaratz, Michael A., Cheryl A. Hallam, Warren E. Schmidt, and Hugh W. Calkins. U.S. Geological Survey Circular 895, Digital Line Graphs from 1:2,000,000-Scale Maps, USGS Digital Cartographic Data Standards, 1982.)

The percent of total income contributed by various sectors in Alaska in 1995 is shown in

Table 1. These percentages have not changed much since 1995 (Goldsmith, 1997; percentages rounded off).

Table 1. Percent of total income from various sectors in Alaska for 1995	
Oil (taxes, production):	35%
Federal civilian:	28%
Federal military:	10%
Seafood:	7%
Permanent fund:	6%
Tourism:	5%
Misc. Income:	<5%
Timber:	2%
Mining:	2%
Agriculture:	0.1%

Alaska's Ecosystems

Alaskan ecosystem types (Fig. 3) correspond to climatic regimes that range from maritime wet and cool climates in the south to a cold continental climate in the interior and an extreme arctic cold and arid climate along the arctic coast. This has produced rainforest in the southeast and south-central coastal regions, shifting to boreal forest in the south-central region and through the interior, and arctic tundra in the Alaskan Peninsula and Aleutians, the west coast and Seward Peninsula, and north of the Brooks Range. A small quantity of land (about 30,000 acres or 12,000 hectares) is in agricultural production in the Tanana and Matanuska valleys and on the Kenai Peninsula. Larger areas are used for pasture (185,000 acres or 75,000 hectares) and reindeer grazing (about 12 million acres or 5 million hectares, mostly on the Seward Peninsula). Large tracts of land, about 60% of the surface area of the state, are set aside in national parks, wilderness areas and nature preserves. The marine ecosystems of the Bering Sea and Gulf of Alaska are among the most productive in the world and are highly susceptible to climate change.

Alaska's Climate

Alaska has very large climatic differences among its various regions because it spans 20 degrees of latitude and about 60 degrees of longitude. The range of climatic conditions rivals that of the 48 contiguous states as a whole. In the southern coastal margin, including the panhandle and Aleutians, an extreme maritime climate predominates, with heavy precipitation—up to 100 in (250 cm) per year—that leads to the formation of large glaciers. The interior has the most continental climate with yearly precipitation values of 8–16 in (20–40 cm) and normal January temperatures around –13°F (–25°C) in January and 59°F (15°C) in July. The region north of the Brooks Range is semi-arid with precipitation of less than 8 in (20 cm) per year and a mean July temperature of about 39°F (4°C). Winters are long with snow on the ground for about nine months. Because of the low annual mean temperatures throughout most of the state there are widespread areas of permafrost (Fig. 4), perpetually frozen ground, and extensive sea ice along Alaska's western and northern coasts.

Historical Climate Trends

Alaska, like other regions, has seen major climatic changes in the past that have led to great changes of the environment (Fig. 5). In

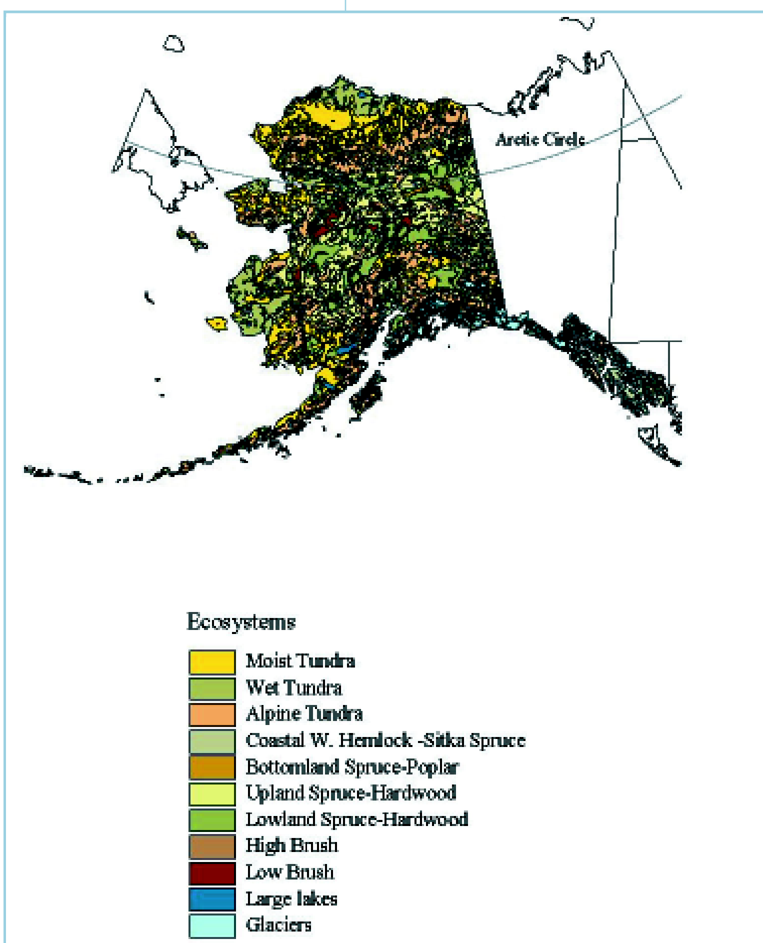


Fig. 3. Ecosystems of Alaska (Joint Federal-State Land Use Planning Commission for Alaska, 1973)

the 20th century there has been a warming to 1940, followed by a cooling, and a strong warming since the 1960s. Warming has been up to 1.5°F (1°C) per decade over the last three decades in the annual mean, with the largest warming occurring in the interior and arctic regions. In winter the increase has been even bigger, up to 3°F (2°C) per decade (Chapman and Walsh, 1993). Some Alaskan records show that a very large warming, of about 3°F (2°C), occurred suddenly around 1977 and has persisted since then. Similar warming is occurring throughout the circumpolar arctic region, and has been accompanied by extensive melting of glaciers and thawing of permafrost (Osterkamp, 1994), and reduction of sea ice extent and thickness (Chapman and Walsh, 1993; Wadhams, 1990; see also Chapter III). The climate has also become wetter over the century, but the trends are smaller and more spatially mixed. Alaska experienced a 30% increase over the region west of 141 degrees (i.e., all of Alaska except the panhandle) between 1968 and 1990.

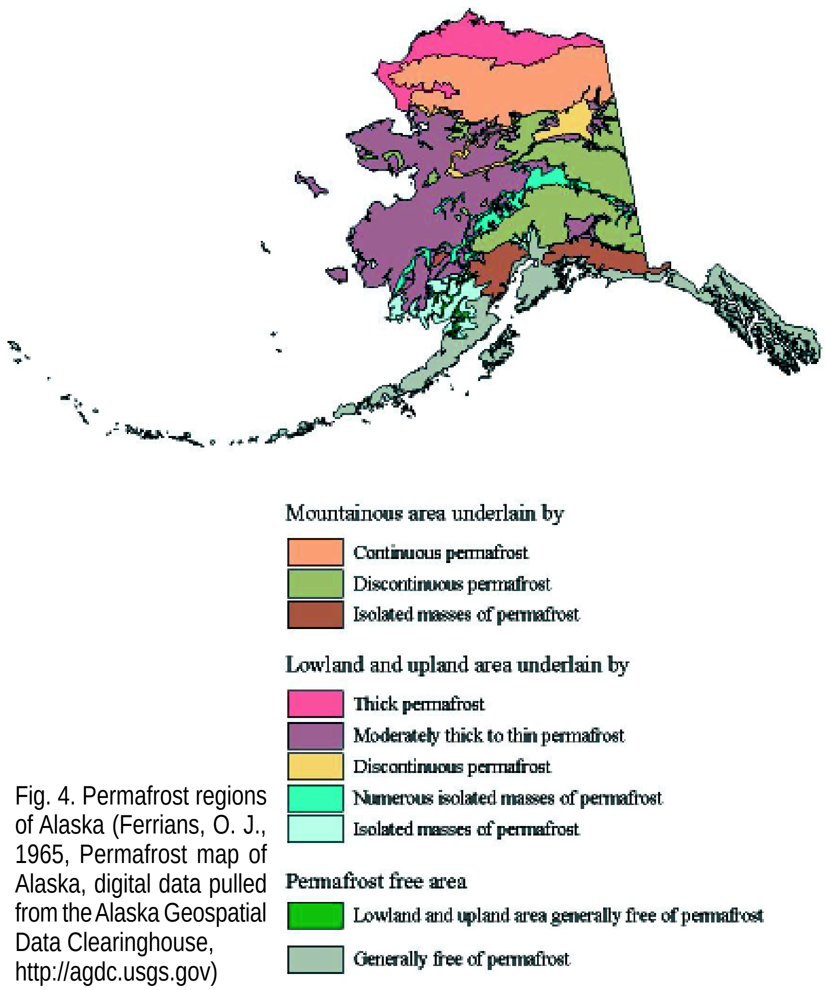


Fig. 4. Permafrost regions of Alaska (Ferrians, O. J., 1965, Permafrost map of Alaska, digital data pulled from the Alaska Geospatial Data Clearinghouse, http://agdc.usgs.gov)

In addition to long-term warming trends, the climate has shown strong multi-year cycles, which are now known to be coupled to large-scale climate oscillations: the 2- to 5-year El Niño/ Southern Oscillation (ENSO) in the Pacific, and the interdecadal (approx. 15-year) Arctic Oscillation (AO) of which the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) are part. Although the AO is less well known than ENSO, it now appears that its effect on climate and resources is even more important. Like ENSO, the AO is a pattern of oscillation in the climate that includes changes in ocean and atmosphere temperatures, winds, and precipitation. These oscillations lead to complex effects on marine ecosystems and forests. The effect of the AO on salmon stocks is particularly

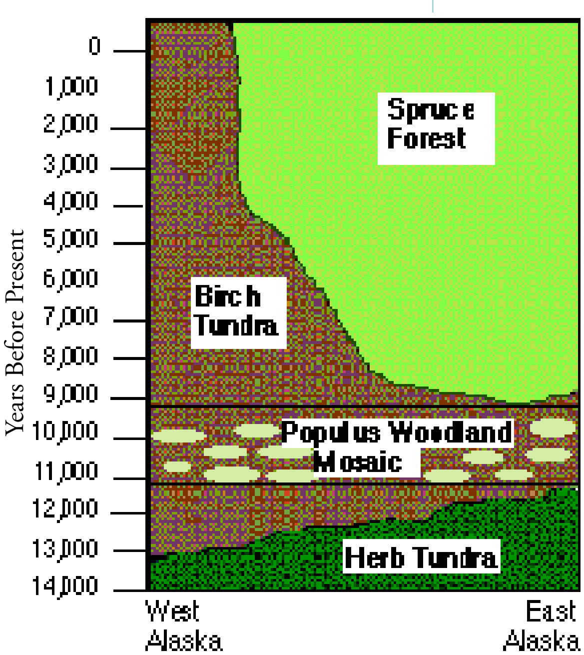


Fig. 5. Simplified scheme of vegetation development in Alaska from the last glacial period to the present. The horizontal axis represents an east-west transect across the state at the approximate latitude of Fairbanks.

striking. The origin and mechanism of these changes are not known, but may reflect combined effects of changes in streamflow, and the nutrient content, temperature, and vertical stability of coastal waters. Thompson and Wallace (1998) have analyzed the Arctic Oscillation and its associated components, the PDO and NAO. The climate of the northern hemisphere is clearly affected by the AO, but the combination of the AO and ENSO, which also influences climate, cannot explain the observed climate trends. Nor can solar variability. Overpeck et al. (1997) have shown that the difference is due to greenhouse warming which is already being observed in the Arctic.

Table 2. Annual mean temperature increases in Alaska as modeled by two GCMs, compared with three-decade observed trends extrapolated linearly to the years 2030 and 2100. The range in values shows differences among the various regions of Alaska.

	Year 2030	Year 2100
Canadian Model	3–6° F (1.5–3.5° C)	9–18° F (5–10° C)
Hadley Model	3–4.5° F (1.5–2.5° C)	7–12° F (4–6.5° C)
Extrapolated Observed Trends	2–4.5° F (1–2.5° C)	5.5–14.5° F (3–8° C)

Future Climates

Because of the large scale of climate variations within Alaska, General Circulation Model (GCM) predictions for different regions also vary somewhat (Tao et al., 1996). Two GCMs were used to project future climates in Alaska, the Canadian Climate Model and the United Kingdom Hadley Center Model. In Alaska, the strong projected trends toward a warmer, wetter climate broadly continue the trends observed in recent decades. In the Canadian and Hadley models, projected warming is smallest in the south and southeast, largest in the northwest, and is strongest in winter. The Canadian model projects the largest warming trends: annual-average temperature in the southeast increases 2.7°F (1.5°C) by 2030 and 9°F (5°C) by 2100, in the northwest 6.3°F (3.5°C) by 2030 and more than 18°F (10°C) by 2100. The strong warming in this model is accompanied by near-total summer melting of arctic sea ice by 2100. In the Hadley model, annual-average warming ranges from 2.7–4.5°F (1.5–2.5°C) by 2030, and 7.2–11.7°F (4.0–6.5°C) by 2100 with only slight loss of sea ice.

Comparing these model-projected changes to the 5°F (3°C) temperature change already observed over the past few decades, they range from half as much again to a doubling by 2030, and a doubling to a tripling of recent changes by 2100. Table 2 summarizes the two model projections for Alaska for years 2030 and 2100 and compares them to three-decade (1966–1995) observed trends (Fig. 6, Chapman and Walsh, 1993, updated) extrapolated

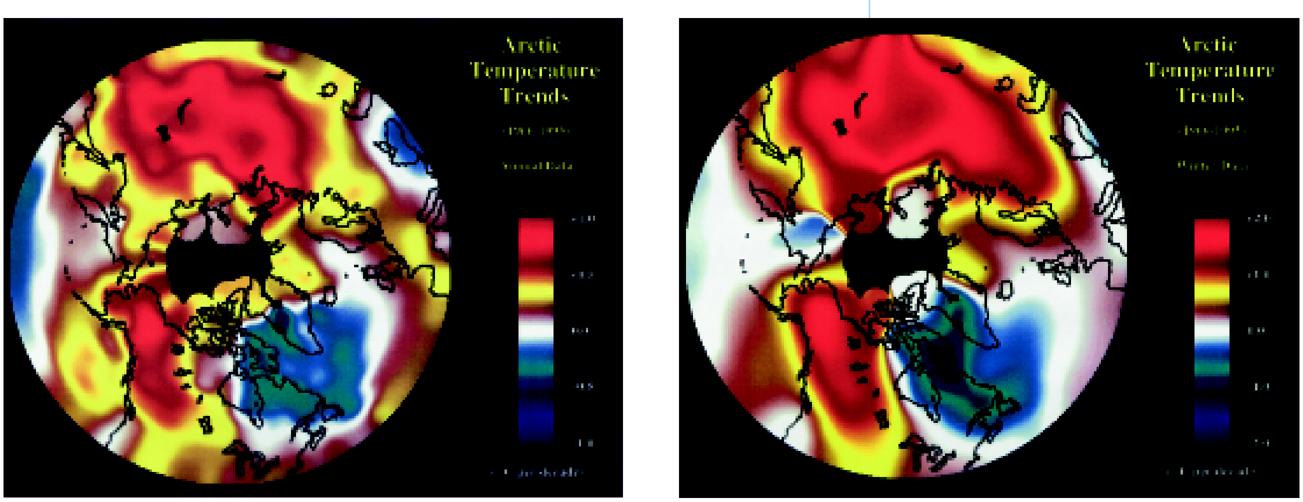


Fig. 6. Observed temperature trends in the Arctic from meteorological stations for the period 1966–1995. Annual mean—left; winter—right. (Chapman and Walsh, 1993, updated)

linearly to the years 2030 and 2100. What this shows is that the projected model trends are not very different from those actually observed in Alaska at present. There is a range of values since there are considerable differences among the various regions of Alaska, with the southeast and interior of Alaska experiencing the greatest warming and the northwest the least.

As a consequence of these changes there will be widespread thawing of permafrost (Fig. 7), accelerated glacier melting, a shorter snow season, thinner and less sea ice and a gradual movement of the boreal forests upslope and northward (BESIS, 1997; 1998; 1999).

Both models project that the Aleutian low-pressure system will grow deeper and may shift slightly to the south, increasing hydrological activity in the region. Under these conditions, Alaska will continue to grow wetter, with annual precipitation increases of 20–25% in the north and northwest, ranging to very little change in the southeast. In term of projected seasonal and spatial distribution of precipitation changes, both the Hadley and Canadian models project that winters are wetter in the east and drier in the west, while summers are drier in southeast Alaska and wetter elsewhere. Winter soil moisture changes with precipitation, but in summer, increased evaporation from the warmed climate exceeds any projected increases in precipitation, so soils dry everywhere in all the models.

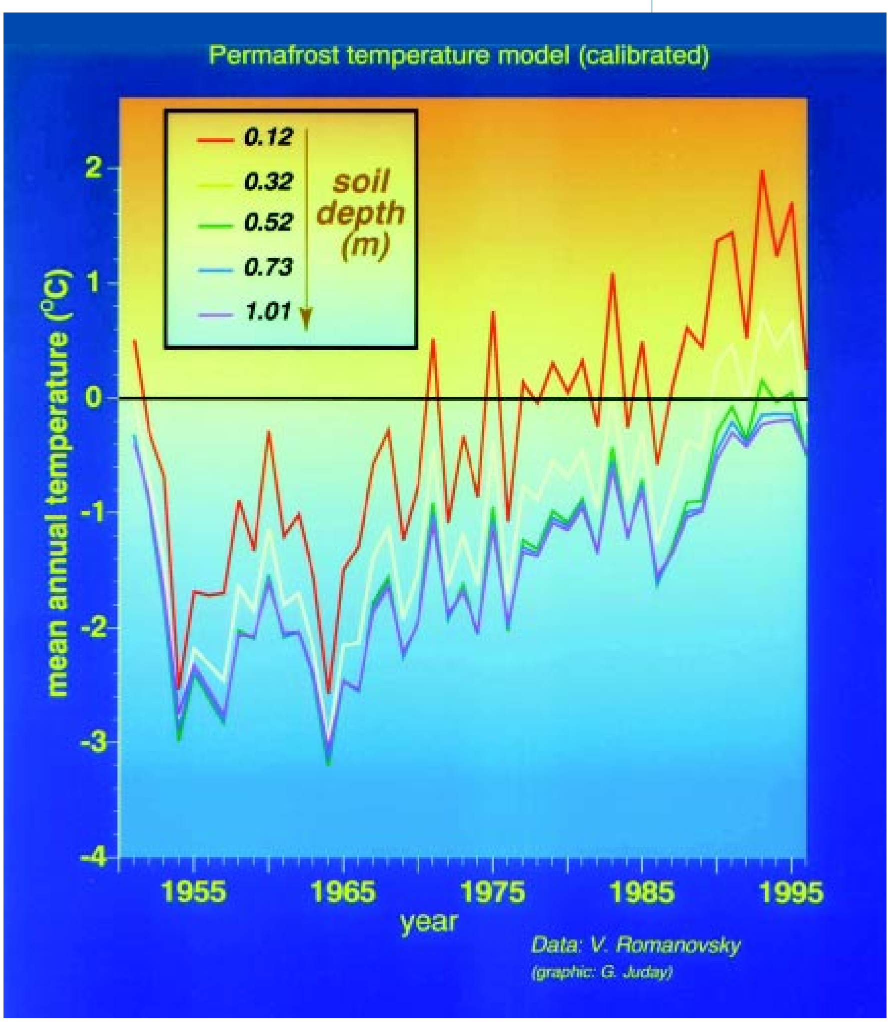
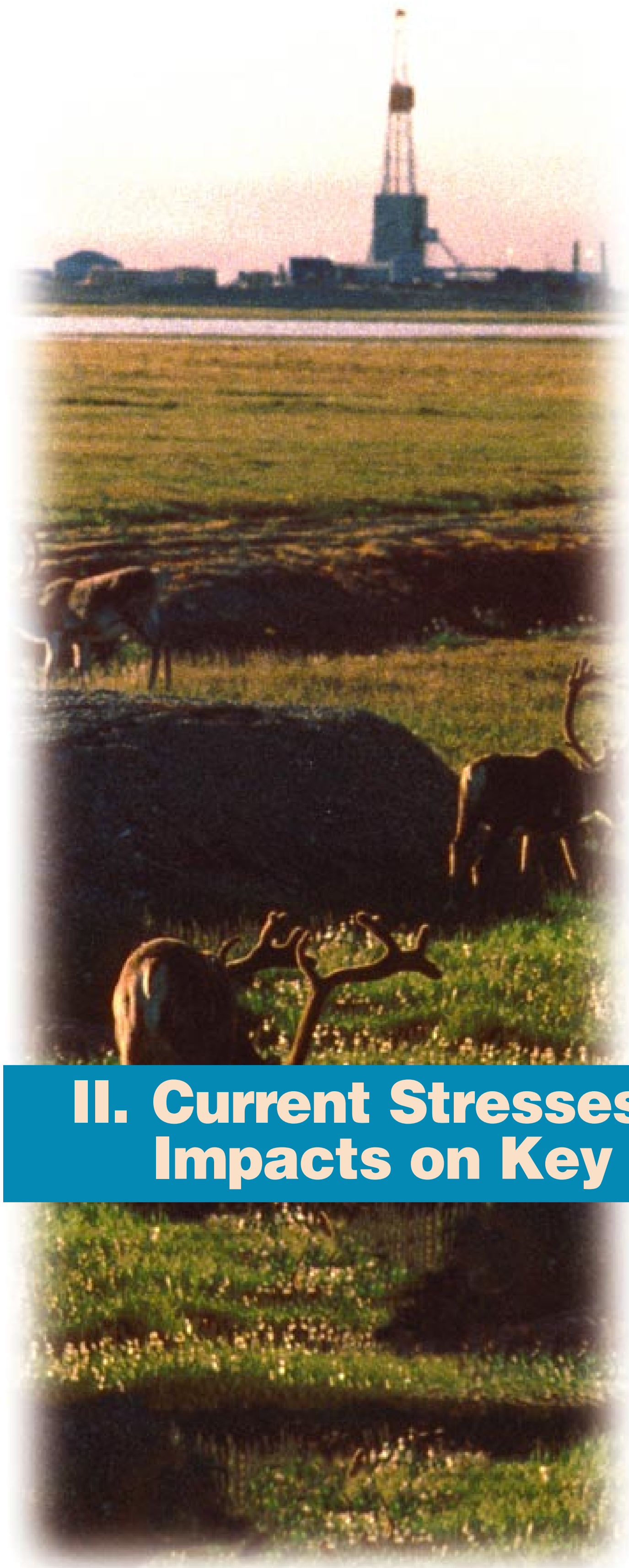


Fig. 7. Change in permafrost temperatures at various depths in Fairbanks, Alaska

II. Current Stresses and Future Climate Impacts on Key Economic Sectors



Fisheries

The fisheries in the Alaska region are among the most productive in the world. For example, over 28 percent of recent world total landings of fish, mollusks, and crustaceans have been harvested from the North Pacific Ocean and the Bering Sea. Walleye pollock (*Theragra chalco–gramma*) landings alone exceeded 4.8 million metric tons in 1991, and accounted for approximately 5 percent of the combined world landings of fish, mollusks, and crustaceans. The productivity of these and other arctic fisheries is controlled by the interplay of biological and oceanographic processes. Changes in the velocity and direction of ocean currents affect the availability of nutrients and the disposition of larval and juvenile organisms, thereby influencing recruitment, growth, and mortality.

The effects of climate variation on some arctic fish populations are fairly well known in terms of empirical relationships but generally poorly known in terms of mechanisms. Data on commercially exploited species in the Bering Sea date back to the mid-1960s for some groundfish species and to the early part of this century for some stocks of Pacific salmon, Pacific halibut, and Pacific herring. The survival and growth of salmon depend on the influence of environmental factors in freshwater and oceanic life-stages. Elevated stream temperature, stream flow rates, and air temperatures have been identified as potentially beneficial factors (Rogers, 1984).

It has also been long known that salmonid populations show responses to changes in climatic conditions (Pearcy, 1984). The effect of warming has been positive for most stocks; some of the highest salmon catches on record in Alaska have occurred in the last decade. While there has still been interannual variability, catches and populations in this later period have been above average at the least. Positive correlations between salmon returns and positive air and sea surface temperature anomalies, reduced Bering Sea ice cover, and negative Southern Oscillation Index anomalies have been reported by Quinn and Marshall (1989), among others. It is likely, however, that salmon have a rather narrow range of tolerance and that the warming of the mixed layer is progressing to the point where the stocks are in danger.

Many groundfish stocks have also shown a positive response during this period (NRC, 1996). Conversely, some stocks have had a negative response. King crab stocks in the eastern Bering Sea and Kodiak declined during the 1980s, and this decline is thought to be due to a combination of factors including environmental effects, overfishing, natural mortality, and changes in reproductive parameters.

Less well understood are the effects of climate change on the spatial distributions of fish populations. While declines and increases in fish populations are often accompanied by contractions and expansions in range, this need not be the case. For Pacific salmon, it is well known from high seas studies that there are threshold temperature ranges that affect distribution. As a consequence, it is not well understood how climate change might affect the behavior of harvesters reacting to changes in fish behavior.

Factors other than climate change affect fisheries, including changes in fish prices, changes in technology for fish harvesting and utilization, changes in fisheries management and changes in societal needs and preferences. All of these make it difficult to fully assess the impacts of climate change on arctic fisheries. Nevertheless, the following impacts have been observed in recent years (BESIS, 1997; 1998; 1999). The signs following the bullet statements are: beneficial +; detrimental -.

- Significant correlations have been observed between abundance and/or harvests of various fish species. For example, major increases in catches of some Alaskan salmon have occurred in recent years (+).

- On the other hand, salmon stocks in Western Alaska, the Pacific Northwest and Canada have decreased, illustrating their narrow range of temperature tolerance (-).

Other impacts likely to occur if climate warming continues include:

- Climate change is likely to reduce the abundance of some species while increasing the abundance of others, affecting commercial harvests (+ and -).
- It is reasonable to assume that climate change could halve or double average harvests of any given species; some fisheries may disappear, other new ones may develop. This could increase or decrease local economies by hundreds of million dollars annually (+ and -).

Forestry

Tree growth in the boreal forest depends critically on both temperature and precipitation (Fig. 8).

Much of the risk to the boreal forest from climate change associated with global warming involves decreases in effective moisture sufficient for forest growth, tree mortality from insect outbreaks, probability of an increase of large fires, and changes caused by thawing of permafrost. The effects of a projected warming would depend critically on accompanying changes in precipitation.

One of the characteristic features of the boreal forest is that insect outbreaks are a dominant disturbance factor and that outbreaks can result in tree death over vast areas (Juday, 1996; Fleming and Volney, 1995). The probability of an increase in large fires in the boreal forest is also substantial, largely because observations in Alaska have shown that the overall area burned is well correlated with the average summer temperature. The total area burned in North America has increased substantially in recent decades (Fig. 9, from Kasischke and Stocks, 1999). The new landscape produced by burning probably would support a significantly lower proportion of conifers and instead there are likely to be large areas of relatively pure hardwood stands that would be relatively fire-resistant.

Changes to the boreal forest that would be caused by thawing of permafrost are potentially so extensive and so profound that it is difficult to summarize them. The major pathways of change would involve an unstable transition when surface subsidence from the melting of the ground ice content would alter ground contours and collect and reroute water. Once the thawing had taken place the site productivity should increase substantially, but the vegetation community that would develop would probably not be similar to that which grew on permafrost. The disappearance of an impervious frozen layer would allow precipitation to infiltrate the ground much more effectively compared to the tendency of permafrost to shed rain immediately. The hydrology of streams and rivers would be quite different.

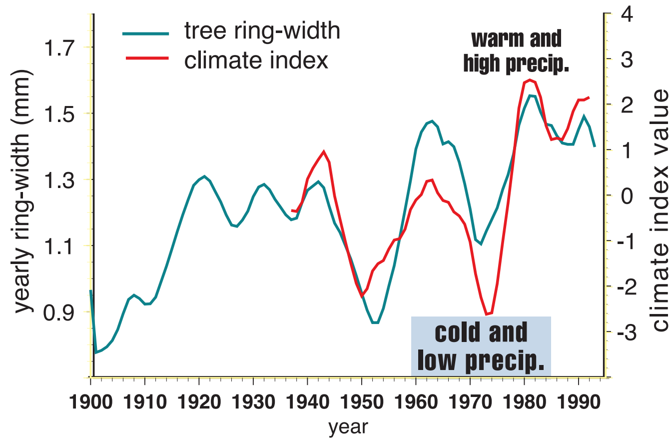


Fig. 8. Tree ring-width as a function of a climate index (temperature and precipitation), showing the favorable growing conditions during warm and high precipitation periods. (Juday, 1999)

The following impacts have been observed in Alaska in recent years (BESIS, 1997; 1998; 1999):

- The warmer and drier climate in Southeast Alaska has caused forest problems such as increased fire frequency and insect outbreaks which have reduced economic forest yields (-).
- Insect (spruce bark beetle) outbreaks in Alaska have recently become the most widespread infestations observed to date (-).
- Forest fires in a fairly newly established vacation community near Anchorage, Alaska destroyed 454 structures in 1996 at a cost of about $80 million (-).
- A warmer climate has lengthened the growing season and growing degree days by 20% for agriculture and forestry in Alaska, with the potential of producing higher yields (+).
- Boreal forests are expanding north at the rate of 60 miles (100 km) for each 2°F (1°C) increase, thus increasing potential yields in the long term (+).

Other impacts likely to occur if climate warming continues include:

- New settlements of vacation homes in northern forest areas increase the risk of wildfire damage and associated costs (-).
- By far the most important effect of climate change is the risk of catastrophic wildfire in settled areas (-).
- One projection (Rupp et al., 1999) shows a 200% increase in the total area burned per decade, leading to a deciduous forest-dominated landscape on the Seward Peninsula, presently dominated by tundra vegetation (+ and -).
- Changes in temperature and precipitation will affect coastal forest hydrology and salmon spawning streams important to subsistence, commercial and sport fisheries (-).

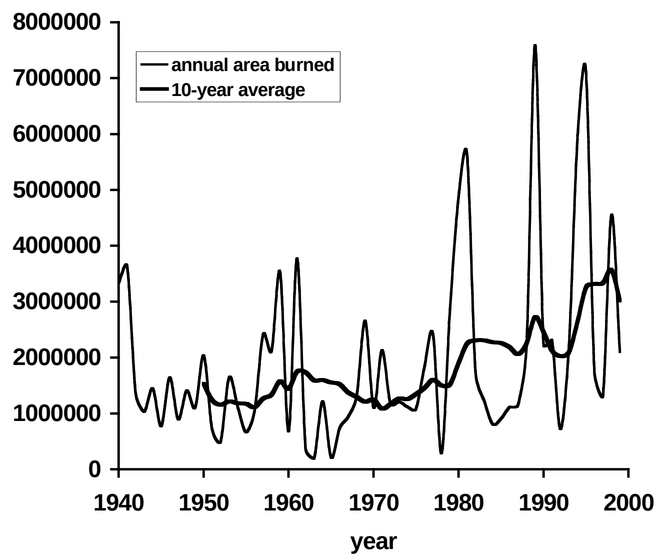


Fig. 9. Total area of boreal forest burned in North America. This plot contains a 10-year running average as well as the annual area burned for the time period 1950 to 1999 (Kasischke and Stocks, 1999).

- Hydrologic changes in forested watersheds include warmer stream temperatures and lower summer flow from low elevation streams, higher flow from higher elevation streams (+ and -).
- There are likely to be changes in the range of vertebrate animals and changes in productivity of aquatic ecosystems in forestlands (+ and -).
- Increased damage is likely to occur through windthrow and blowdown in coastal forests (-).
- Other long-term effects might include: general treeline advance in elevation and latitude; colonization of formerly glaciated lands; transition of tree species and ecotypes (+ and -).

Agriculture

Alaska is involved in the production of a diverse array of agricultural products and enterprises, ranging from animals for sport and pleasure to crops and animals for food, clothing and shelter. The agricultural production includes:

- Grass fields for feed and pastures
- Grains for animal feed and food
- Potatoes
- Vegetables
- Dairy animals
- Cattle
- Furred animals
- Dogs
- Land reclamation
- Greenhouse products
- Exotic animal breeds (buffalo, elk, muskoxen, llamas, and yak)

Forestry and reindeer herding can also be considered to be part of agricultural production but both are discussed in greater detail elsewhere. The most important climatic factor for agriculture in Alaska is precipitation. Another important factor, particularly in reference to climate change, is permafrost.

i) Negative Impacts of Climate Change on Agricultural Production

As the temperature rises, the permafrost interface with unfrozen ground/seasonal frost will most likely recede. Regions that now contain soils with intermittent permafrost may become permafrost free. This could affect the fragile water balance in areas where precipitation is low. If the temperature rise is extreme, desertification could occur. There is already increasing erosion and loss of organic materials in the entire circumpolar region. Drying of the soil will cause this to increase. Revegetation programs are needed now and this need would increase accordingly.

There are three areas of production that could be severely affected if temperatures should rise. In traditional field agriculture it may be possible to avoid massive damages by irrigation, controlled environments, revegetation programs and conservation-oriented soil management. In forestry (see section above), problems will be intense and will include loss of soil moisture, severe insect attacks, increased fires, as well as a negative CO_2 balance which will feed back on the global climate. In reindeer herding, short-term damages will most likely be negligible. Long-term damages, however, will result from changes in vegetation and degradation of pasture quality (Weller and Lange, 1999).

ii) Positive Effects of Climate Change on Agricultural Production

As the climate changes and temperatures rise, agricultural endeavors could benefit. There is a potential for new crops and animals in the circumpolar north. Temperature increases along with adequate moisture will mean higher productivity per unit. In short, the circumpolar north's agriculture could become important in world trade in more than just niche crops and livestock. As temperatures rise globally and if desertification occurs in more temperate zones, the economic frontier for production could move north and the risks of production there will be lowered. Land areas appropriate for both crop and animal production exist in Alaska. An important factor in this movement is the supply of water. This has not been a problem in Alaska to date. Water supply has global implications, however, particularly for traditional agriculture (Weller and Lange, 1999).

Reindeer Husbandry

Five potential challenges to the health of reindeer husbandry are related to global climate change: 1) ice-coating of winter forage; 2) poor quality forage in warm and dry summers; 3) caribou range expansion into reindeer areas; 4) tundra fires; and 5) forest expansion into tundra. Four of these trends (1, 2, 4, and 5) are likely to become serious problems following a continuous warming of Alaska's climate. This may well present new challenges to the Native reindeer industry.

The role of recent climate change in a drastic decline of Russia's domestic reindeer stock, which dropped from 2.3 million to about 1.6 million between 1991 and 1997, is still unknown but the impact of climate/weather fluctuations cannot be ignored. During the long arctic winter, reindeer depend on access to range that is rich in lichens. The lichens provide carbohydrates almost exclusively as a source of energy to maintain body temperature in winter. Reindeer can effectively paw through snow to reach the lichens. If warmer than normal temperatures produce freezing rain, the resulting ice cover makes the lichens unavailable and this often causes reindeer to starve to death. Such an event occurred on the Chukchi Peninsula in northeastern Siberia in the fall of 1996, leading to the death of thousands of domestic reindeer.

Subsistence Livelihoods

The harvest of fish and game for direct consumption is critical to indigenous communities throughout the Arctic. Subsistence activities meet nutritional needs, sustain important cultural values, and reinforce social networks of cooperation and sharing. In many indigenous communities, participation in commercial fishing, trapping and reindeer herding also contributes significantly to cash incomes.

Climate change is likely to have significant impacts on key marine and terrestrial species availability for subsistence purposes. At a minimum, salmon, herring, walrus, seals, whales, caribou, moose and various species of waterfowl are likely to undergo shifts in range and abundance. This will entail local adjustments in harvest strategies and allocations of labor and capital (such as boats, snow machines, weapons).

Changes in diet, nutritional health, and exposure to air, water, and food-borne contaminants can also be expected. Adjustments in the balance between the "two economies" of rural areas (subsistence and wage) will occur. This suite of changes will be complex and largely indirect because of the mediating influences of market trends, the regulatory environment, and the pace and direction of rural development.

The following impacts on the subsistence lifestyles in Native villages and communities in Alaska, which depend heavily on fishing and hunting, have been observed in recent years. Most of the impacts listed below come from comprehensive interviews in Alaskan Native communities, for example by Gibson and Schullinger (1998).

- A warmer climate with milder winters and less (or no) shore-fast ice and snow has impeded access to offshore and tundra food resources (-).
- Recent decreases in anadromous fish stocks, which make up 60% of wildlife resources used by subsistence users, have directly affected the latter's dietary and economic well-being (-).
- The availability of marine mammals for subsistence is also lower, due to shifts in oceanographic and sea-ice conditions. While whale catches are normal, walrus harvests are low. Marine mammals are an important food source in many coastal communities (-).

Whitefish seine netting, Kobuk River

- Increases in the frequency and ferocity of storm surges have triggered increased coastal erosion and threatened several villages in the Bering Sea; this has led to plans for relocation of some villages at great expense (-).
- These storm surges have also altered the protection of coastal habitats by barrier islands and spits which are highly vulnerable to erosion and wave destruction (-).
- A warmer climate has also thawed traditional ice cellars in several northern villages in Alaska, making them useless for the storage of meat (-).
- Human health problems may have increased due to new diseases moving north (-).

Other impacts likely to occur in the future include:

- A decrease in the area of pack ice has important implications on primary productivity and the entire food chain (-).
- For example, walrus and bearded seals require sea ice strong enough to support their weight but over water shallow enough so that they can reach the bottom to feed. Changes in ice conditions may adversely affect these species (-).
- Changes in atmospheric and oceanic circulation may bring contaminants from military and industrial installations closer into the food chain and human consumption (-).
- As the boreal forest intrudes further north at the expense of tundra and shrub communities, there will be changes in habitats and the distribution and density of a number of wildlife species on land (+ and -).

Tourism

As the climate changes, the landscape changes with it (e.g., glaciers may disappear, new ecosystems may be created, wildlife will increase or decrease, etc.) and this in turn increases or decreases the attractiveness of the region to tourism. A different but likely impact in Alaska on the environment is due to tourism itself. Tourism is projected to increase steadily in the Arctic, and this will affect the land and its uses. Noise from tourist activities, trampling of vegetation and other impacts are likely to be experienced. In other areas of the world, for example Antarctica, tourism and scientific activities in remote areas constitute the biggest impacts on the environment. The same may apply to remote locations in Alaska, which have so far not experienced much tourist activity. Tourism of course also

has other impacts, for example on the economy of frequently visited regions. Ecotourism is on the rise and tourists may enhance the migration and establishment of invasive dominant species. Finally, tourism may generate both public and political awareness of changes in Alaska.

Transportation, Energy and Infrastructure

Alaska is the supplier and source for a large fraction of the non-renewable resources for the rest of the world. Alaska, as well as Siberia and Northwest Canada, contain large reserves of liquid and gas petroleum and also vast coal resources. Only a portion of these resources have been discovered, explored or exploited so far. The predicted effects of climate change on the production, storage and transportation of petroleum, gas and coal, on mining, and on transportation have important implications, both negative and positive, for the economy of the northern hemisphere.

Energy production by means of hydroelectric systems, fossil fuel, and other less-standard techniques, and impacts on the infrastructure of power generation, and on transportation will be affected by changes in the seasonal temperatures, precipitation, wind and solar radiation, and by glacial melt, permafrost thawing, river flow, and snow accumulation. Climate effects on the river systems, port facilities, and hindrances or improvements in ocean transportation (e.g., reduction in sea ice thickness and extent) will have vital impacts on regional energy needs, as well as on transportation of materials both into and out of the Arctic.

Examples of likely impacts on infrastructure and the geophysical cause for these impacts, the availability of any remedial action and the time frame of predictions most useful to put remediation into effect, the decisionmakers and stakeholders involved in this, and the recommended remedial action are shown in Table 3, based on experience in Alaska from 1992 to the present.

The following impacts on infrastructure have been observed in recent years (BESIS 1997; 1998; 1999):

- Failure of buildings has occurred due to a change in the properties of permafrost that is warming (-). For examples see Chapter IV.
- Accelerated permafrost thawing has also led to costly increases in road damage and road maintenance in Alaska (up to $3 million to replace 1 mile [1.6 km] of road system) (-).
- Increased slope instability, landslides and erosion have occurred in thawing permafrost terrain in the Mackenzie Basin, threatening roads and bridges, and causing local floods (-).
- The disappearance of permafrost reduces construction problems in the long run; in some areas permafrost boundaries have moved north by tens of miles in the last century (+).
- Reductions in sea ice extent and thickness have allowed easier access to villages and industrial installations in some regions of the Arctic (e.g., Bering Sea) (+).

Other impacts likely to occur if climate warming continues include:

- The mechanical properties of permafrost will decrease further with warming, resulting in possible failure of pilings for buildings and pipelines, and of roadbeds (-).

Table 3. Examples showing infrastructure affected by climate change and extreme weather events, whether remediation exists, the stakeholders involved, and remediation efforts, based on experience in Alaska from 1992 to present (modified from Weller and Lange, 1999).

Infrastructure (geophysical cause)	Time Frame of Prediction	Does Remediation Exist?	Decisionmaker/ Stakeholder	Remediation Efforts
Roads & airports (permafrost)	Long term	Yes and No	State and Federal agencies, Community	Plan ahead or fix it later
Housing & construction (permafrost)	Long term	Yes	Owner, Contractor, Community, Government	Fix it before
All Infrastructure (extreme weather events)	None	Yes and No	State, Federal, Private sector, Community	Engineer it correctly or fix it later
Pipelines (permafrost)	Long term	Yes	Private sector, Government	Engineer it correctly
Hydro power (ice, hydrologic cycle, extreme weather)	Long term	Yes	State, Private, Federal energy regulatory committee	First inspections required, Plan ahead
Non-hydro power	Long term but less critical	Generally	State, Private	Less affected, remediation less important
Power lines (ice, extreme weather, permafrost)	Long and short term	Yes	State, Private	Plan ahead, Fix at once
Barge ocean traffic (ocean ice, storm surges)	Long term and less of problem	—	Private	No problem, so no remediation needed
Barge river traffic (ice, freezing temperatures)	Seasonal	No	Private, Community	Adjust schedules
Ice roads (early thaw, permafrost, lack of snow)	Immediate	No	Private, Community, Governmental regulators	Adjust schedules

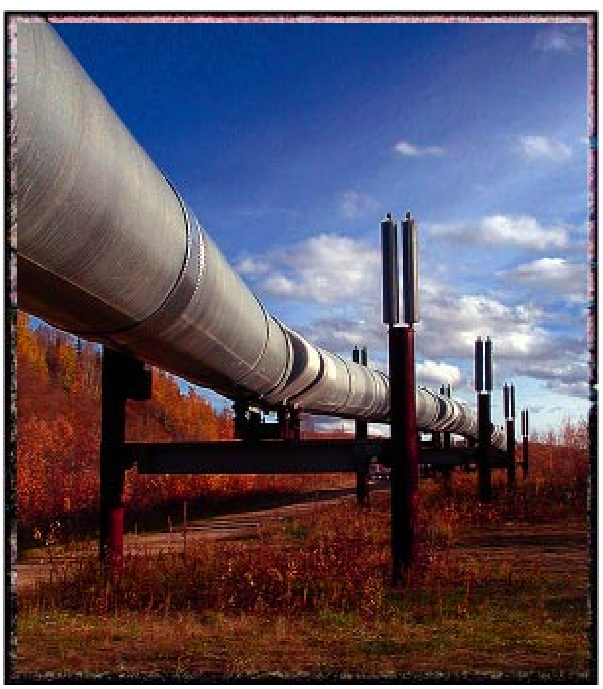
• Ice and snow roads, frequently used by the oil industry to reduce environmental damage to the tundra, may not be thick enough or last long enough in the future. (-).

• Power outages due to more severe winter snow storms could lead to threats to human life and safety, as well as increased repair costs (-).

• Ship and barge traffic on rivers and in the ocean will benefit from a longer ice-free season and thinner ice (+).

• Higher temperatures will lead to cost savings in power generation in remote arctic towns and villages (+).

Permafrost problems deserve some special attention. There is great concern that the impact of global warming on permafrost and reduction of permafrost bearing capacity can exceed the safety factor that is incorporated in the design of existing structures. This has become a particularly serious problem in northern Russia (see also Chapter IV).



An exposed section of the trans-Alaskan pipeline on thaw-unstable permafrost ground near Fairbanks. The pipe is insulated and jacketed and rests on supports equipped with cooling fins.

III. Cross-Cutting Issues and Challenges of Future Climate Change

The Thawing of Alaska

The property of water to change phase at 32°F (0°C) is probably the most important factor in the observed and expected climate impacts in Alaska where the environment and practically all human activities are so strongly dominated by snow and ice. Much of Alaska's environment is close to the melting point of ice (e.g., Fairbanks has a mean annual temperature of about 28°F or –2°C) and a relatively small warming of the climate can cause major environmental changes and feedbacks. One of these is the positive feedback through the effect of climate on snow cover. Warmer temperatures decrease the area of snow cover, darkening the surface and in doing so increasing the absorption of solar radiation to further increase the air temperature.

Many components of the cryosphere (snow and ice regions of Earth) are sensitive to changes in atmospheric temperature because of their thermal proximity to melting. The projected warming of the climate will reduce the area and volume of the cryosphere. This reduction will have significant impacts on related ecosystems, associated people and their livelihoods. There will also be striking changes in the landscapes of many high mountain ranges and of lands at northern high latitudes. These changes may be exacerbated where they are accompanied by growing numbers of people and increased economic activities (IPCC, 1996).

Observations over the last few decades already confirm dramatic melting of snow and ice in the Arctic, including Alaska, due to a warmer climate.

Sea Ice:

There have been substantial reductions in both ice extent and thickness in the Arctic in recent decades:

- A recent study using passive microwave data from satellites through 1996 has shown arctic sea ice extent decreasing by 2.9% (± 0.2%) per decade (Cavalieri et al., 1997).
- Sea-ice extent in the Bering Sea has been reduced by about 5% over the last 40 years, with the steepest decrease occurring in the late 1970s (BESIS, 1997).

- Sea ice thickness, a sensitive indicator of climate change, has decreased by more than 4 ft (about 1.3 m), from 10 ft (3.1 m) to 6 ft (1.8 m), in most of the deep water portion of the Arctic Ocean between the 1960/1970s and the 1990s, based on submarine sonar records (Rothrock et al., 1999).
- The sea ice thickness decrease is greatest in the central and eastern Arctic and less in the Beaufort and Chukchi seas (Rothrock et al., 1999).

Glaciers and Ice Sheets:

- Glaciers in the arctic and subarctic regions have generally receded, with typical ice-thickness decreases of 33 ft (10 m) over the last 40 years, but some glaciers have thickened in their upper regions (BESIS, 1997). A warming of 2°F (1°C), if sustained, appears to reduce glacier lengths by about 15%.
- The mass balance of Greenland is still uncertain, but there appears to have been a tendency towards increased melt area between 1979–1991 that ended abruptly in 1992, possibly due to the effects of the Mt. Pinatubo eruption (Abdalati and Steffen, 1997).
- Balances have been positive for European glaciers in Scandinavia and Iceland due to increased winter precipitation (Serreze et al., 1999).
- Over the period 1961–1990, small melting glaciers worldwide have contributed about 0.29 in (7.36 mm) to sea level rise, with the Arctic Islands contributing 0.05 in (1.36 mm), Alaska 0.02 in (0.54 mm), and Asia 0.13 in (3.34 mm) (Serreze et al., 1999).

Seasonal Snow Cover:

- Cyclone and anticyclone frequency has increased over the Arctic between 1952–1989 (Everett et al., 1998; section 3.2).
- Annual snowfall has increased in the same period over Northern Canada (north of 55°N) by about 20% and by about 11% over Alaska (Everett et al., 1998; section 3.2).
- While there is more snow in winter, satellite records indicate that since 1972 northern hemisphere annual snow cover on both continents has decreased by about 10%, largely due to spring and summer deficits since the 1980s (Serreze et al., 1999).
- There has also been a decrease in snow depth in Canada since 1964, especially during spring, while winter depths have declined in some areas over European Russia since the turn of the century but have increased in others (Serreze et al., 1999).

Permafrost:

- Borehole measurements in continuous permafrost have shown warming of up to 3.5–7°F (2–4°C) in northern Alaska over the last century (Lachenbruch and Marshall, 1986).
- Discontinuous permafrost throughout Alaska has warmed, and some of it is currently thawing from the top and bottom (Osterkamp, 1994; Osterkamp and Romanovsky, 1999).
- Near-surface permafrost also became warmer by 1°F (0.6–0.7°C) in Siberia during the period 1970–1990; this warming may in part be due to a deeper snow cover in winter (Pavlov, 1994).

River and Lake Ice:

- River and lake ice formation in Alaska occurs later in fall and breakup occurs earlier in spring, leading to shorter ice-covered periods. The annual break-up of the Tanana River ice in interior Alaska has been recorded since the 1920s and shows most break-up dates to occur in April in the 1990s compared with most of them occurring in May in the 1920s (Nenana Ice Classic, 1999).

Additional changes, as projected by the IPCC assessment (IPCC, 1996; Everett et al., 1998), will include further pronounced reductions in seasonal snow, permafrost, and glacier and periglacial features with a corresponding shift in landscape processes. Increases in the thickness of the active layer of permafrost and the disappearance of most of the ice-rich discontinuous permafrost over a century-long time span will occur (Fig. 10). The IPCC report also predicts the disappearance of up to a quarter of the presently existing mountain glacier mass and less ice on rivers and lakes. Freeze-up dates will be delayed, and break-up will begin earlier. The river-ice season could be shortened by up to a month. There is likely to be substantially less sea ice in the polar oceans.

As a further result of these changes in the cryosphere, the following additional impacts are expected: Widespread loss of discontinuous permafrost will trigger erosion or subsidence of ice-rich landscapes, change hydrologic processes, and release carbon dioxide (CO_2) and methane (CH_4) to the atmosphere. Cryospheric change will reduce slope stability and increase the incidence of erosion and landslides to threaten structures, pipelines, and communication links. Engineering and agricultural practices will need to adjust to changes in snow, ice and permafrost distributions. Thawing of permafrost could lead to disruption of petroleum production and distribution systems in the tundra unless mitigation techniques are adopted. On the other hand, improved opportunities for water transport, tourism and trade are expected from a reduction in sea, river and lake ice. Reduced sea ice may aid new exploration and production of oil in the Arctic Basin. These will have important implications for the people and economies of the Arctic. Table 4 shows some of the

Table 4. Projected impacts due to a 5.5° F (3° C) warming of permafrost (modified from Weller and Lange, 1999)

FEATURE/ PARAMETER	CONTINUOUS PERMAFROST TERRAIN			DISCONTINUOUS PERMAFROST TERRAIN		
	Low	Moderate	High	Low	Moderate	High
Thaw Lakes	X					X
Coastal Processes		X				X
Eolian Activity	X			?	← X	
Vegetation		X →	X	X	→ X	
Active Layer Thickness	X					X
Permafrost Thawing	X					X
Thaw Settlement	X					X
Slope Instability		X				X
Erosion		X				X
Solifluction		X				X
Engineering Impacts		X				X

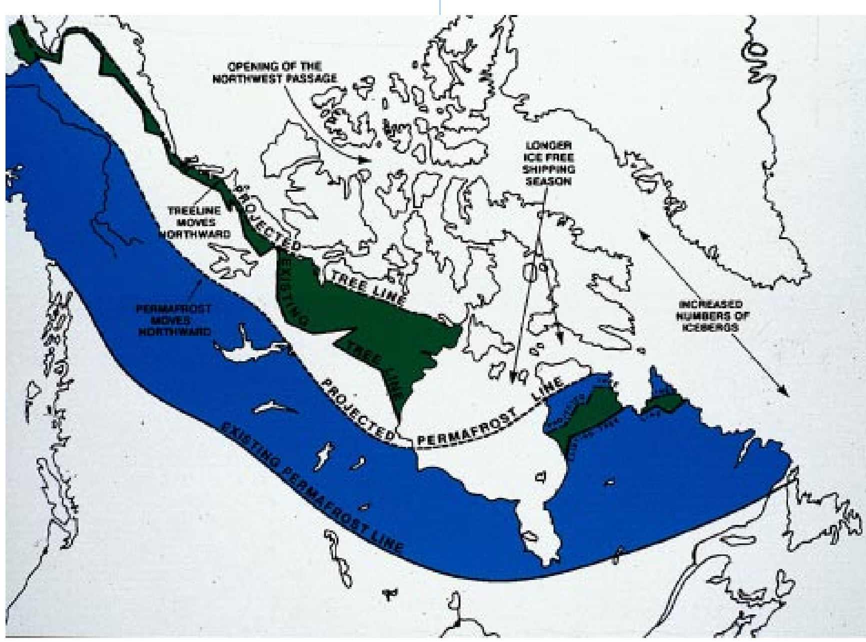


Fig. 10. Projected Northward movement of the permafrost boundary and tree-line after a doubling of atmospheric CO_2 (from Environment Canada, 1989, extrapolated into Alaska).

expected impacts (BESIS, 1997) if permafrost warms by 5.5°F (3°C). Not all of these changes are necessarily detrimental.

Water Availability

The liquid phase of water is also important in the northern environment. Alaska contains more than 40 percent of the nation's surface-water resources, much of which are undeveloped. Seasonal stream-flow variations result from precipitation and temperature fluctuations; ranges in basin elevations; and the effects of the natural storage and release from snowpack, glaciers, and lakes. For Alaskan streams, low-flow occurs during the winter when most rivers are ice-covered. Many interior and arctic rivers and lakes freeze solid, making them an unreliable water source during winter months. High-flow periods generally occur in the fall and spring, and are associated with rainfall and snowmelt, respectively. Flooding due to ice jamming during the spring break-up can cause extensive damage. Glacial rivers have a sustained period of relatively stable summer flow due to the contribution of the glacial meltwater. Permafrost also has a profound effect on the occurrence and availability of ground water in all but the south coastal regions of Alaska. Permafrost forms a virtually impermeable layer that restricts recharge, discharge, and movement of ground water; functions as a confining layer; and decreases the volume in which water can be stored.

All of the above parameters will be affected by a continuing trend towards a warmer climate, and this in turn will affect the entire hydrological regime of Alaska. The likely future impacts are difficult to assess, however, since big rivers flowing into the Arctic have watersheds that extend well south and into quite different climatic regimes. The Mackenzie Basin studies have projected that there will be a seven percent reduction of streamflow as a result of the expected climate warming (MBIS, 1997). River levels and flow would be lower during the fall and winter and would be lower than the extremely low levels observed in 1995

Fig. 11. Severe erosion occurs along much of the coast of the Arctic underlain by permafrost.

(MBIS, 1997). This is because the expected increase in precipitation would be offset by increased evaporation (MBIS, 1997). Similar effects can be expected in Alaska. Changes in the extent of permafrost will affect the rate of infiltration, the moisture content of the active layer, the depth to water, and landforms through thermokarst development.

Coastal Environmental Changes

The coast of Alaska, which exceeds in length the coastlines of the other 49 states, presents special problems (Fig. 11). Tidal amplitudes along the Western coast of Alaska (the Yukon-Kuskokwim delta) can be as large as 15 ft (5 m) between seasonal high and low tides. Large tidal amplitude produces high hydrological energy along the coast and well into large rivers in the area. High hydrological energy associated with much of the coastline of the Y-K delta is associated with high rates of erosion of exposed peats along much of this coastline. This is exacerbated by storm surges (see next paragraph). Aerial photography shows disappearance of up to 1,500 ft (500 m) of coastline in some locations, primarily exposed points, between 1950 and 1984. South of Hooper Bay, 150 ft (50 m) disappeared between 1988 and 1993 (BESIS, 1998). Erosion is also rapid on large former tributaries of the Yukon River. At some points as much as 30 ft (10 m) of river bank have disappeared in a single growing season. Erosion has forced movement of the village of Newtok in the central Y-K delta, and the relocation of other villages including Kivalina and Shishmaref on the Bering Sea coast is being considered. The cost of relocating Kivalina, quoted in the Anchorage Daily News of Nov. 2, 1997 by Orson Smith, Corps of Engineers manager for the Kivalina project, may be up to $50 million.

On the western and northern coast of Alaska sea ice is another problem. Sea ice is present along the Bering Sea coast for half of the year and along the Chukchi and Beaufort Sea coasts in the north for up to 10 months or longer in most years. The presence of ice not only affects the weather and climate of the region, but also restricts all human activities, from fishing to offshore oil exploration. Recent observations have shown a five percent reduction in sea ice extent in the Bering Sea over the last three decades, and the lowest ever sea ice extent has been observed in the Beaufort Sea in the fall of 1998 (BESIS, 1998). With less ice, storm surges have become more severe because the larger open water areas can generate bigger waves. Adding to the resulting erosion is the thawing of permafrost in coastal cliffs. This has led to unprecedented coastal retreat rates that pose serious problems in Native villages along the coast. As the climate continues to warm, these impacts, both positive and negative, can only become more pronounced.

The Gulf of Alaska is ringed by extensive glacier systems, which constitute the fourth-largest glaciated region on Earth (after Antarctica, Greenland and the Canadian islands) and have been identified as major contributors to sea level rise over the last century (see Chapter II). These glaciers are produced by frequent intense storm systems generated by the Aleutian Low, which dump huge snow loads (up to 30 ft or 10 m water equivalent per year), on the coastal mountains. The runoff from these glaciers (over half a million cubic feet per second) produces the Alaskan coastal current with its low-salinity waters that flow westward along the coast and through the passes of the Aleutian Islands into the Bering Sea (Royer, 1981; 1982). Any warming of the climate will intensify this coastal current through increased glacier melting and will in turn affect the weather, climate, fisheries and biota along the entire southern coastline of Alaska.

Impacts on Ecosystems

Ocean ecosystems and fisheries are highly vulnerable to changes in sea temperature and sea ice conditions (NRC, 1996; Brander, 1996; Knapp, 1999). Recent observations of climate-related changes in the Bering Sea showed abnormal conditions during the last two summers. The changes observed include extreme die-off of seabirds, rare algal blooms, abnormally warm water temperatures, and very low numbers of salmon. While some of the changes observed in the 1997 and 1998 summers—warmer than usual ocean temperatures, and altered currents and atmospheric conditions—are quite unusual, the area has

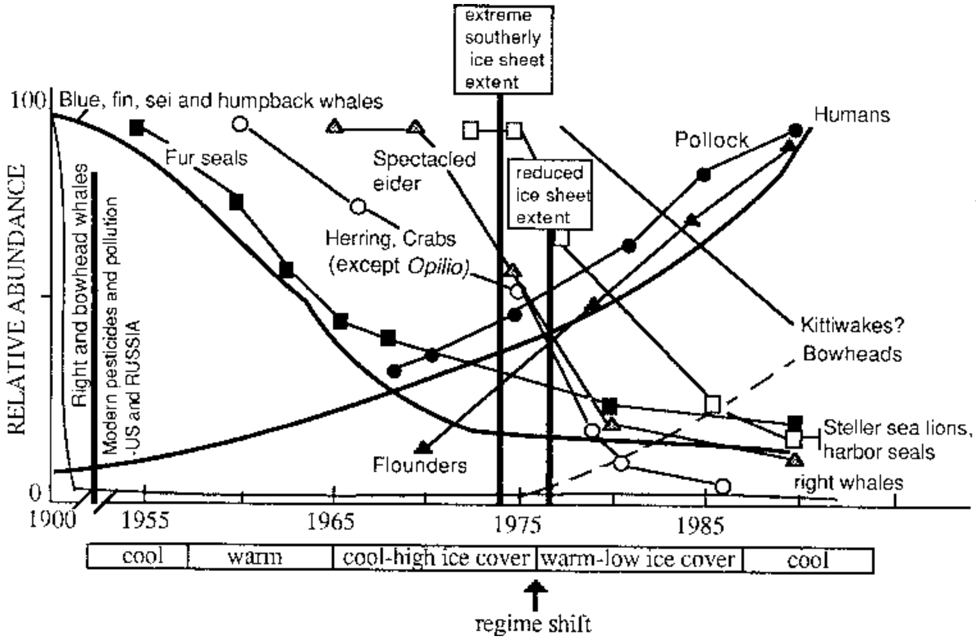


Fig. 12. Schematic temporal change in relative abundance of marine mammals, seabirds, fish, and shellfish in the Bering Sea (from NRC, 1996). Lower bar indicative of changes in sea-surface temperature. Reprinted with permission from the Bering Sea Ecosystem. Copyright 1996 by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D.C.

been undergoing change on a much longer time scale going back several decades (NRC, 1996; NOAA, 1999; see also Fig. 12).

Over that period the western population of Steller sea lions has declined by between 50% and 80%. Northern fur seal pups on the Pribilof Islands—the major Bering Sea breeding grounds—have declined by half between the 1950s and the 1980s. In parts of the Gulf of Alaska harbor seal numbers are as much as 90% below what they were in the 1970s. There have been significant declines in the populations of some seabird species, including common murres, thick-billed murres, and red- and black-legged kittiwakes (BESIS, 1999). There have also been big variations in the abundance of some fish and shellfish species over the past 30 years. Some have registered large increases (NOAA, 1999).

One of the most striking changes observed involved the appearance in 1997 of large areas of milky, aquamarine water over most of the continental shelf. This was caused by changes in water temperature and atmospheric pressure, which led to a massive bloom of coccolithophores, a type of non-toxic, microscopic marine plant (Fig. 13). The coccolithophores replaced the normal summer plankton and had profound but not well understood effects on the food chain.

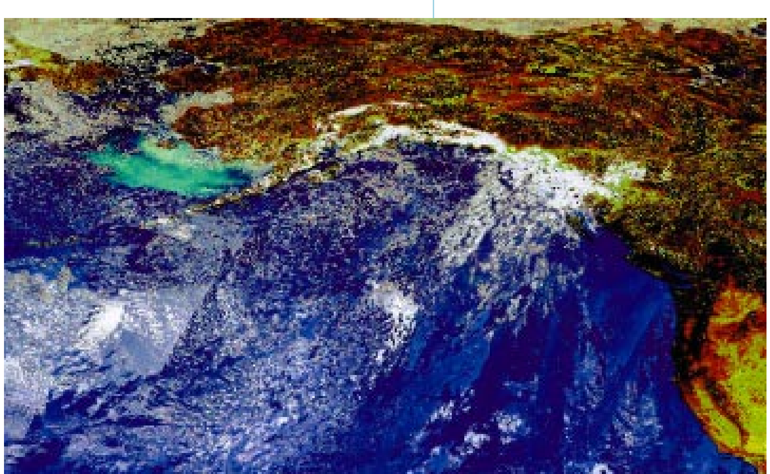


Fig. 13. SeaWifs Composite Image of cocco-lithophore bloom, shown in turquoise, in September 1997 (NOAA Pacific Marine Environmental Laboratory)

Blooms of this sort have never been seen in the Bering Sea for extended periods, and despite different atmospheric conditions in 1998, the bloom returned. Other changes recorded included unprecedented mortality in one seabird species, the short-tailed shearwater, and unsuccessful reproduction rates for another, the kittiwake. The number of returning salmon was far below expected levels, the fish were smaller than average, and their traditional migratory patterns seemed to have been altered. There was also an unusual sighting of Pacific white-sided dolphins in one area, and northern right whales have been seen in the Bering Sea Shelf/Bristol Bay area during recent summers for the first time.

Components of the Alaska marine ecosystem appear to react to many different environmental variables in the atmosphere and the ocean, but overall, climate-driven variability in the Bering Sea ecosystem is significant. It appears that climate has caused relatively rapid shifts in the organization of this marine ecosystem, most recently in the late 1970s, and that changes over periods of decades may have larger effects than those over yearly periods (NRC, 1996). The recent observations of climate-related changes in the Bering Sea showed abnormal conditions during the 1997 and 1998 summers. These impacts may be amplified if the climate continues to warm.

Unlike marine ecosystems, where impacts may be observable on very short time scales, changes in terrestrial ecosystems may take much more time. Ecological models predict major shifts in vegetation, with forests expanding into tundra regions, and coastal forests shifting from conifers to mixed broadleaf and conifers, but these changes occur on time scales of hundreds of years as shown. On the Seward Peninsula in Alaska this slow transition from tundra to forest is illustrated in Fig. 14 (Rupp et al., 1999).

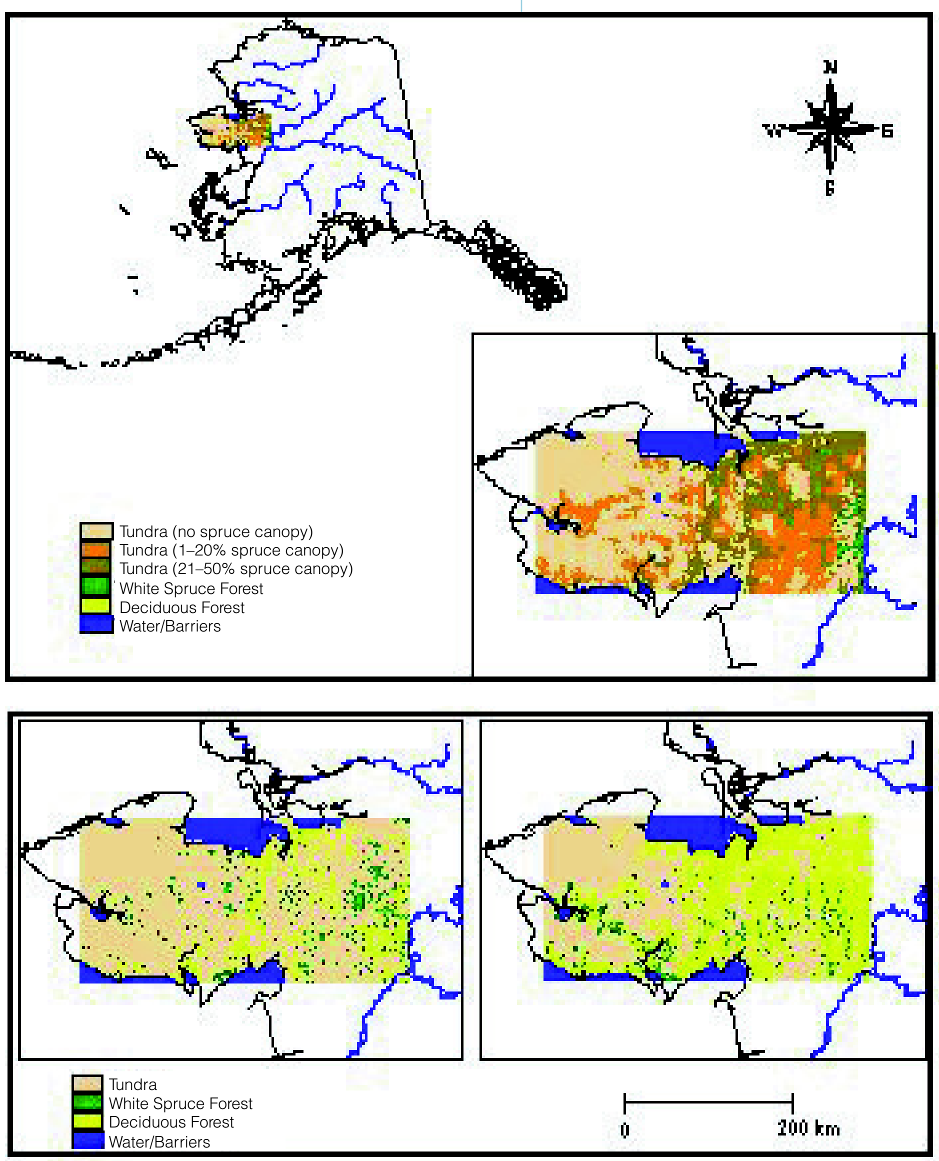


Fig. 14. Vegetation changes on the Seward Peninsula, Alaska, at present and after 100 and 200 years, following an intantaneous temperature rise of 7°F (4°C). Rupp et al., 1999

Other effects already observable on land include thawing permafrost beginning to modify landscapes by changing forests to grasslands and bogs and increasing slope instabilities. The tundra, in previous decades a sink for carbon dioxide, has now become a source (Oechel et al., 1993). Continued warming and thawing of permafrost would extend and magnify these effects.

Social Impacts on Native Communities

There is no universal model of “Native response” to climate change, as northern communities are not all the same. They have highly diversified subsistence-based economies and they do not respond to environmental trends in the same standard way as do vegetation, permafrost, and sea ice. Social, economic, and political differences may obscure local responses. Also, Native (indigenous) people are only a part of the arctic resident population. As such, they are preoccupied with the various issues, political and economic, that are of critical importance in their respective areas. For many indigenous people, climate change may not be a top priority. In many northern areas debates about the ongoing (or forthcoming) climate trends may look like a "luxury," compared to the acute social and economic problems they face on a daily level. Scientists have to be aware that they may well be indoctrinating Native residents with their anxieties about climate change and other related topics (Weller and Lange, 1999).

In trying to assess scientific versus "Native" perspectives on climate change, a key issue is the meaning of "uncertainty" and the differences in understanding "uncertainty" and in living with it between scientists and Native communities. Under the scientific approach, the key strategy is to identify the "uncertainty" (in this case future climate change), target it aggressively, evaluate potential causes and damages, and to turn it into "certainty," that is, into a model or into an analyzed and stratified phenomenon, at the least. Most of the scientific projects related to the study of climate change are organized in this way. The Native perspective, however, is to live with the uncertainty and to try to cope with it. While scientists often view "change" as a short-term and rapid phenomenon, Native residents can live with it long-term because they see it as existential. These differences are to be acknowledged in any attempt at building a model of human response and at collecting data on climate change among the Native residents.

The operational framework for assessing the social consequences of climate change include the following parameters:

- Sensitivity—predisposition to be affected by an internal impact; in this regard every community is sensitive to climate change.
- Adaptability—potential to react in a way to mitigate negative change; here various communities differ in the strategies and effectiveness of their adaptability. Traditionally, Native communities have a high degree of adaptability, and they share a highly valuable pool of strategies for adapting to arctic environmental change.
- Vulnerability—beyond one's ability to adapt. In general, modernization increases the communities' vulnerability as it makes people more dependent on modern life-support networks and technologies, including electricity, sewage, heating, construction on permafrost, etc., which are highly vulnerable to climate change.

There are many examples of successful Native adaptations to climate change across the arctic region, both in pre-history and in modern times. Factors that enhanced Native adaptability and decreased vulnerabilities to climate change include:


Loading dogsled with butchered caribou, Anaktuvuk Pass, 1950

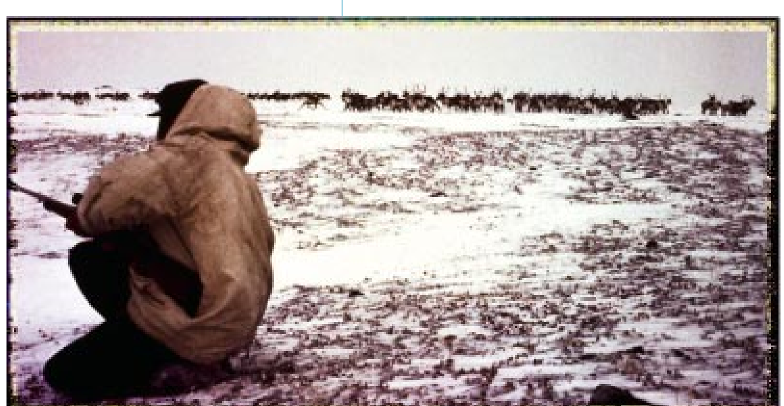
- “Being on the land.” This facilitates advance warning and opens local strategies in using alternate resources in case of any environmental change.
- Maintaining a diverse economy (usually a combination of hunting, both marine and land game, fishing, herding and trapping).
- “Always being ready.” A product of high mobility and existential attitude to climate change.
- Relying on long-term observations and generationally transmitted local knowledge about numerous components of the ecosystem.

Modern factors constraining adaptability and increasing vulnerability of arctic Native communities to climate change include:

- Current strong dependence on village and urban lifestyle and related employment.
- Continuing population growth and high concentration of people in modern residential communities that are often built in areas of low (or no) ecological sustainability.
- Dependence on outside inputs and infrastructure and the risk of its shortfall and even failure (as is now happening in the Russian Arctic).
- Rigid or non-responsive bureaucratic and governmental forms now in control of Native life via economic and welfare policies, hunting regulations, and restraints on mobility.
- Openness to outside messages, agendas and anxieties (e.g., environmental quality, contamination, game regulation regimes).

Native communities remain very sensitive to environmental trends. However, as modernization progresses, their pattern of response to climate change is shifting from a Sensitivity = Adaptability to a Sensitivity = Vulnerability model (Weller and Lange, 1999).

Nunamiut hunter and caribou in winter.



Vulnerability and Cost of Climate-Related Impacts

Permafrost thawing has probably had the greatest economic impact in Alaska so far and may present the greatest vulnerability in the future. In Siberia, Russian engineers are very concerned about the safety of apartment buildings and pipelines in permafrost terrain. Many of these have already failed (Fig. 15). Hundreds of these structures may become unsafe within 30 years if present climate trends continue since the piles on which the buildings rest are thawing out (Khrustalev, 1999; Weller and Lange, 1999). Roads, building, airfields and pipelines are under threat in the entire discontinuous permafrost zone of the Arctic.

Cole (1999) estimated that it has cost on average about $35M/year in recent years for road repairs in permafrost terrain in Alaska, severe storm damage to electric transmission lines, and effects of thawing on ice winter roads. Some of these costs are related to a change in climate, others to extreme weather events. Other costs of climate-related impacts are difficult to assess at present since there are many non-climate parameters that also play a role. This is particularly true for the Alaskan fisheries. Some fisheries have done very well recently, others have crashed. Future climate changes could halve or double average harvests, resulting in hundreds of millions dollars gains or losses annually (Knapp, 1999). Table 5 shows the sensitivities (high, medium, low, or none) of economic sectors in Alaska to various agents of change (modified from Weller and Lange, 1999). The resulting economic impacts can be either positive or negative, depending on the direction of change. More on whether they are likely to be positive or negative in the future can be found elsewhere in this report.

IV. Planning for the 21st Century

Coping and Adaptation Strategies

Responsible institutions in Alaska are not generally aware of the problems resulting from climate change that will be witnessed in the future. This awareness is important as there are some coping and adaptation strategies that can be applied now. They include:

- Long-term forecasting and planning. The greater the extent to which one can anticipate the longer-term effects due to climate change, the better one can adjust to changes. This is true whether the impacts are in fisheries, forestry or other economic activities. Even though long-term forecasts may be highly uncertain, they may still be valuable.

- Changes in management and political institutions. How management and political institutions are designed will affect the nature and scale of economic and social disruptions caused by climate change. For example, political agreement over fisheries allocations should recognize that significant future changes in harvest levels are not only possible but also likely.
- Public expenditures to reduce public risk. In Alaska, engineers continue business as usual by building roads, houses and other infrastructure on permafrost and repairing the damage later at great cost. Through planning and by using modern and initially more expensive techniques it may be possible to avoid these continuing repair costs in future years.
- Incentives to reduce public cost and risks. An aggressive strategy to reduce the cost of climate-related impacts such as forest fires would be a set of policies that puts the cost on the individuals who settle in risky areas, rather than on society. Also, since most areas now at risk from damaging forest fires in Alaska have only recently been settled, infrastructure for economic development could only be provided in areas that are already densely settled, thus reducing the fire risk.
- Native strategies. While scientists often view change as a short-term and rapid phenomenon, Native residents can live with long-term uncertainties and generally can cope with change. There are many examples of successful Native adaptations to climate change across the arctic region, both in pre-history and in modern times. Factors that enhance Native adaptability and decrease vulnerabilities to climate change include maintaining a diverse economy, use of alternate natural resources, high mobility, customary sharing of subsistence resources, and relying on local environmental knowledge.

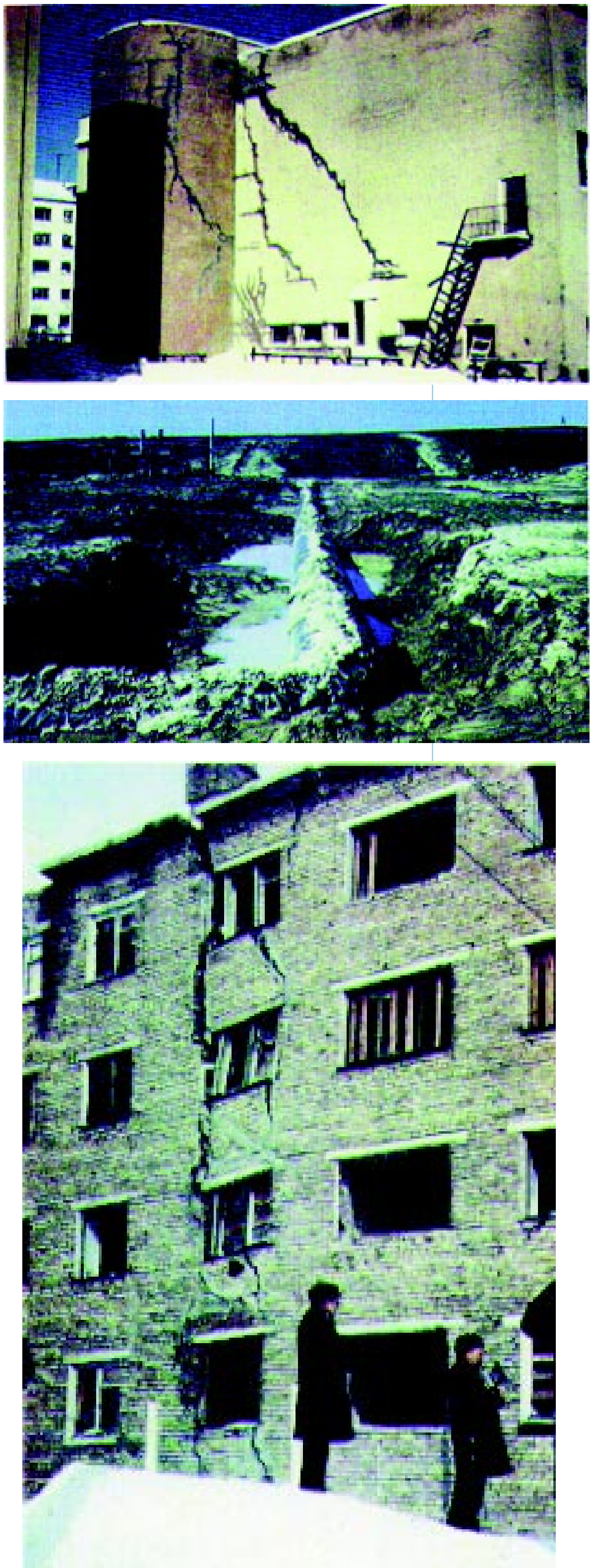


Fig. 15. Typical examples of the effects of permafrost thawing on buildings and pipelines in Siberia. Photos by S. Yu. Parmuzin.

Information and Research Needs

Impact assessments provide an excellent means of interdisciplinary analysis and synthesis of change; this is the underlying philosophy of the ongoing regional impacts assessments of the U.S. Global Change Research Program. Key questions that need to be answered are:

1. What are the likely regional impacts of global change (Alaska and the Bering Sea region in our case)?
2. What are the available data bases to assess these impacts?
3. What are the gaps in information needed to conduct the impacts assessment?
4. What else is needed to adequately conduct the impacts assessment?

A crucial unknown concerning impacts of future climate change in Alaska concerns how multi-year climate oscillations like the AO and ENSO will behave in a greenhouse-warmed world. Climate model scenarios do not reproduce well the patterns of interannual and interdecadal variability that have been observed. If these patterns continue to behave as they have in this century, then the changes projected from climate models must be modified by these observed patterns of variability. But whether these cycles will behave as they have in a greenhouse-warmed world, or will show coupled changes, is a critical unknown.

Impacts due to projected climate changes have already been shown to affect most components of the physical environment, particularly snow and ice. For example,

Table 5. Magnitudes (High, Medium, Low, or None shown as a blank) of the impact of climate change on various economic sectors.

AGENTS OF CHANGE	**Cash Market**								**Non-Cash Market Activity Sectors**	
	Infrastructure Sectors		**Resource Use Sectors**							
	Petroleum	Transportation	Mining	Fisheries	Forestry	Agriculture	Aquaculture	Tourism	Subsistence	Recreation
PHYSICAL										
Climate										
air temperature					HIGH	HIGH		MEDIUM		MEDIUM
precipitation		LOW			HIGH	HIGH		LOW		MEDIUM
Soils										
permafrost	HIGH	HIGH	LOW		HIGH	MEDIUM				
Marine										
sea level	LOW	HIGH		LOW					MEDIUM	
sea ice	MEDIUM	HIGH	LOW	HIGH				LOW	HIGH	
currents				HIGH			LOW		MEDIUM	
sea temperature				HIGH			MEDIUM			
Fresh Water										
water temperature		LOW		HIGH			LOW			LOW
hydrology		LOW		HIGH	MEDIUM	HIGH	MEDIUM	LOW	LOW	MEDIUM
BIOLOGICAL										
Plant Life										
productivity				HIGH	HIGH	LOW			HIGH	
distribution				HIGH	LOW					
mortality				HIGH	HIGH			LOW	HIGH	MEDIUM
recruitment				HIGH	HIGH				MEDIUM	
Animals										
productivity				HIGH	HIGH	MEDIUM		MEDIUM	HIGH	HIGH
distribution	LOW			HIGH	HIGH			LOW	MEDIUM	LOW
mortality				MEDIUM	MEDIUM				HIGH	HIGH
recruitment				HIGH	HIGH				HIGH	MEDIUM
migration	LOW			HIGH	HIGH			LOW	HIGH	LOW
CHEMICAL										
Ozone	LOW	LOW			LOW	LOW	LOW		LOW	
CO_2	LOW	LOW			HIGH	MEDIUM				
CH_4	LOW				HIGH	LOW				

reductions in sea ice extent in the Arctic have been observed, associated with climatic warming, and permafrost on land is thawing rapidly, leading to coastal and inland areas becoming free of permafrost. While the biological components of the arctic ecosystem appear to react to many different environmental variables in the atmosphere and the ocean, climate-driven variability is significant. It appears that climate has caused relatively rapid shifts in the organization of the marine ecosystem, and that changes over periods of decades may have larger effects than those over yearly periods. Less data are available to assess the impacts of climate change on economic activities, and future projections are difficult due to the many additional complex factors that also affect regional economic performance.

Many problems remain in adequately assessing impacts. Data sources are sparse, particularly data on the ocean, and analysis and synthesis efforts need to bring the diverse data and information sets together. For example, standardized GIS data formats are needed to allow a synthesis of information from different regions. Additional field work is also needed in some areas despite the fact that there are many existing and planned research projects in the region. Future workshops must lead to iterative improvements of the entire impacts assessment process.

Conclusion

Our five workshops were attended by a total of about 400 people. The affiliations of the attendees in the first four workshops are listed below. From the beginning we involved people from other countries bordering Alaska (Russia and Canada) or with economic or research interests in the Bering Sea (Japan and China). The fifth workshop, unlike the others, was an international affair that attempted an assessment of global change impacts for the entire Arctic, including Alaska. Attendees of that workshop are not included in the percentages below.

Affiliation	Attendance (%)
Academia	37
Government	28
Industry/Private	18
NGO’s	5
Foreign Institutions	12
Total	100

As the workshops progressed from year to year, participation by stakeholder groups beyond academia and government was expanded, including members of the fishery and forestry industry in Alaska, the big international petroleum companies, power and energy producers in Alaska, consultants and private individuals. It also increasingly included representatives of the Alaska Native community. This trend can be seen clearly in the numbers presented in the appendix.

We have attempted to make the information from our workshops available to the general public, to schools, stakeholders, and decision makers in easily understood forms by printing brochures and posters, and through talks in various Alaskan communities. While there is a long way to go to get our message across, we believe that we have made a useful start. We plan to have additional workshops to refine our assessments and to let the people of Alaska know what future climate change might mean to the State and its inhabitants.

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Partners and Participants

About 400 people participated in our five workshops to date. It would take too much space to list them all, but a summary of each is provided below:

1. 1995 Workshop (Fairbanks, Alaska):

Co-Chairs:

John Shively, Commissioner, Alaska Dept. of Natural Resources

Juan Roederer, Professor Emeritus, University of Alaska Fairbanks

Working Group Chairs:

Gunter Weller, University of Alaska Fairbanks (Climate)

Scott Armbruster, University of Alaska Fairbanks (Ecosystems)

Keith Criddle, University of Alaska Fairbanks (Economy)

Jerry McBeath, University of Alaska Fairbanks (Policy)

Attendance:

Academia	28
Government	8
Industry/Private	7
NGOs	2
Foreign Institutions	4
Total:	49

2. 1996 Workshop (Girdwood, Alaska):

Co-Chairs:

Vera Alexander, University of Alaska Fairbanks

Douglas Siegel-Causey, National Science Foundation

Working Group Chairs:

Gunter Weller, University of Alaska Fairbanks (Cryosphere)

C. Peter McRoy, University of Alaska Fairbanks (Marine Ecosystem)

Vera Alexander, University of Alaska Fairbanks (Fisheries)

Aron Crowell, Smithsonian Institution (Natives/ Subsistence)

Attendance:

Academia	16
Government	7
Industry/Private	5
NGOs	1
Foreign Institutions	16
Total:	45

3. 1997 Workshop (Fairbanks, Alaska):

Co-Chairs:

Gunter Weller, University of Alaska Fairbanks

Patricia Anderson, University of Alaska Fairbanks

Working Group Chairs:

Keith Criddle, University of Alaska Fairbanks (Fisheries)

James Sedinger, University of Alaska Fairbanks (Coastal Zone)

Glenn Juday, University of Alaska Fairbanks (Land Ecosystem)

Merritt Helfferich, Consultant, Fairbanks (Resources)

Thomas Osterkamp, University of Alaska Fairbanks (Infrastructure)

Attendance:

Academia	42
Government	38
Industry/Private	18
NGOs	6
Foreign Institutions	9
Total:	113

4. 1998 Workshop (Fairbanks, Alaska):

Co-Chairs:

Gunter Weller, University of Alaska Fairbanks

Patricia Anderson, University of Alaska Fairbanks

Bronwen Wang, U.S. Geological Survey

Working Group Chairs:

Gunnar Knapp, University of Alaska Anchorage (Fisheries)

Matthew Berman, University of Alaska Anchorage (Forestry)

Don Callaway, National Park Service (Subsistence)

Henry Cole, Consultant, Fairbanks (Transportation and Energy)

Rosa Meehan, U.S. Fish and Wildlife Service (Wildlife)

Attendance:

Academia	15
Government	24
Industry/Private	20
NGOs	3
Foreign Institutions	3
Total:	65

5. 1999 Workshop (Tromsø, Norway):

Co-Chairs:

Gunter Weller, University of Alaska Fairbanks

Manfred Lange, University of Münster, Germany

Working Group Chairs:

Terry Callaghan, Sheffield Uni., UK, and Abisko Research Station (Biological impacts)

Stewart Cohen, Environment Canada, Vancouver, Canada (Physical impacts)

Henry Cole, Fairbanks, USA (Transportation, energy, and infrastructure)

Glenn Juday, University of Alaska Fairbanks, USA (Economics)

Hans Kolbein-Dahle, County Government of Tromsø, Norway (Agriculture)

Harald Loeng, Inst. for Marine Research, Bergen, Norway (Ocean climate, fisheries)

Ulf Molau, Göteborg University, Sweden (Terrestrial ecosystems)

Piers Vitebski, Scott Polar Research Institute, UK (Social impacts)

Attendance:

Representatives from 18 countries conducting research in the Arctic

Total attendance: 110

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