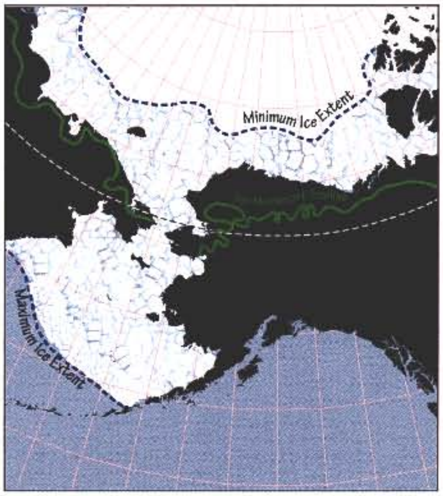

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Implications of Global Change in Alaska and the Bering Sea Region

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"It is the first, and in a way the most important task of science to enable us to predict future experience, so that we may direct our present activities accordingly."

Heinrich Hertz, 1894

FOREWORD

In a 1992 address to the American Association for the Advancement of Science, Dael Wolfle, distinguished scholar and senior science advisor, talked about the issue of prediction in science. He said that a major goal of science is to obtain a sufficiently robust understanding of a set of phenomena so that one can make accurate predictions of events that have not yet occurred. This was also the purpose of the discussions at the workshop reported in these proceedings. The topic was global change and the likely regional impacts in Alaska and the Bering Sea region expected as a consequence of global change.

While considerable uncertainties still exist about the exact nature of these impacts, there can no longer be any doubt that major changes in the climate have occurred in recent decades in the region, with visible and measurable consequences following the climate changes. Even greater impacts are likely in the future; some of them will be positive while others will be detrimental to human activities. Our purpose in organizing the workshop was to bring scientists and stakeholders, the people affected by change, together to discuss the future, based on what we know and what we can predict with some confidence, and to begin a dialog about possible mitigation or adaptation measures.

The process of getting the stakeholders and scientists together to discuss the relevant issues was an important product in itself. This and the published proceedings can be the basis of successive improvements in future workshops. It is clear that a definitive assessment of climate impacts is not possible immediately but will need annual updates as new information becomes available and is considered. Since the regional impacts assessments have become a high priority in many countries, including the United States where the U.S. Global Change Research Program (USGCRP) is taking the lead, such future workshops will undoubtedly occur. This workshop was part of a series of USGCRP regional climate change workshops being held in 1997 and 1998 as a first step in a U.S. national asssessment of the consequences of climate change.

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Summary of Main Implications of Global Change in the Region

From the onset of the industrial revolution, human activities have increased production of "greenhouse" gases, principally CO_2, methane, chlorofluorocarbons (CFCs), nitrous oxide, and water vapor. These gases occur naturally in the atmosphere, trapping heat which would otherwise escape from the Earth. In the elevated concentrations due to human activities, however, they exacerbate warming. We refer to this as the "greenhouse effect."

Computer models have predicted a global warming of about 2-3°C (5°F) when the carbon dioxide content of the atmosphere doubles (expected within 80-100 years at the present rate). In the high northern latitudes, including Alaska, the warming is projected to be twice as much, i.e., about 4-6°C (10°F).

This has led to concern about the possible environmental and socioeconomic impacts due to this climate change. Sixteen-thousand scientists around the world, including the majority of living Nobel Prize winners in the sciences, have joined together to sound the alarm about this projected global warming. This unprecedented response provides testimony to the growing level of concern within the international scientific community.

Private sector industries with long-term financial horizons or climate dependent activities such as banking, insurance, and agriculture firms and the several island states are also expressing increasing concern about both the market and non-market impacts. The seriousness of the potential long-term impacts is reflected in recent statements of interest in their mitigation from energy firm top executives.

Assessments of the likely impacts of global change are most relevant at a regional level where the stakeholders, the individuals and groups who are directly affected, can address issues, uncertainties, market and non-market impacts, and other problems of particular concern to them and can participate in decisions on mitigation and adaptation to the occurring and expected changes. The present assessment deals with the implications of climate change in Alaska and the Bering Sea region.

One of the first questions usually asked is: How real are these changes and how sure can one ever be that they will have the expected impacts? Here are some facts to explain what is known.

FACT: The carbon dioxide content of the atmosphere has increased by about 20 percent since the beginning of the industrial revolution, following the same upward trend as the world population (i.e., more people = more pollution).

FACT: This increase is a man-made effect and is primarily due to the burning of fossil fuels such as oil, gas, coal, and wood, and the large-scale deforestation in the Amazon and elsewhere.

FACT: Carbon dioxide and other so-called greenhouse gases (e.g. methane, nitrous oxide, CFCs) produce climate warming through the greenhouse effect. This result follows from basic physics.

FACT: Observations from meteorological stations in Alaska, NW Canada, and Siberia indicate that the annual mean temperature in these areas has become warmer by up to 1°C per decade over the last 30 years or so. *This exceeds the rate of change predicted for the greenhouse effect,* but is not necessarily due to the greenhouse effect alone.

FACT: Other indicators support this dramatic change. Permafrost is thawing throughout Alaska and Siberia, sea ice extent in the Bering Sea has shrunk by about 5 percent over the last 30 years, and glaciers are melting.

IMPACTS: Among the numerous implications of climate change in the Alaska and Bering Sea region are the following, indicating whether they have positive (+) or negative (-) impacts on human activities .

I. Socioeconomic impacts that have occurred over the last decade:

- Major increases in catches of Alaskan salmon have occurred in recent years, due to the increase of El Niño conditions since the mid-1970s (+)
- The same conditions have unfavorably affected Pacific Northwest and Canadian salmon stocks due to increased smolt predation and adverse streamflow (-)
- Accelerated permafrost thawing has led to costly increases in road damage and road maintenance, up to $3 million to replace 1 mile of road system (-)
- Permafrost thawing has also caused major landscape changes from forest to bogs, grasslands, and wetland ecosystems, affecting land use (-)
- Increased slope instability, landslides, and erosion have occurred in thawing permafrost terrain, threatening roads and bridges and causing local floods (-)
- The disappearance of permafrost reduces construction problems; in some areas permafrost boundaries have moved north by 80 miles in the last century (+)
- The warmer and drier climate has caused forest problems such as increased fire frequency and insect outbreaks which have reduced economic forest yields (-)
- A warmer climate has lengthened the growing season and growing degree days by 20% for agriculture and forestry, with the potential of producing higher yields (+)
- Boreal forests are expanding north at the rate of 60 miles for each 2°F temperature increase, thus increasing potential yields (+)
- With less sea ice in the Bering Sea, increased storm surge frequency and severity have caused increased coastal erosion and inundation and threats to structures (-)
- Subsistence lifestyles have been adversely affected, for example through changes in sea ice conditions making hunting on the ice more dangerous (-)
- The availability of marine mammals for subsistence is lower, due to changes in oceanographic and sea ice conditions (-)
- A warmer climate has also thawed traditional ice cellars in several northern villages, making them useless (-)
- Human health problems have increased due to new diseases moving north (-)
- The extended length of the summer season has been accompanied by an expansion of summer tourism (+)

II. Possible additional future consequences of climate change:

Fisheries

- Change in catches by location, volume, and species, and in markets (- and +)
- Seafood and fish industry (harvesters and processors) financial stresses caused by the need for relocation (-)
- Local loss of fishing industry jobs due to relocation of support services (-)
- Eventual worldwide financial losses as global fisheries decline (-), perhaps benefiting Alaskan fisheries (+)

Oil and Gas

- Cost of maintaining structures (pipelines etc.) in thawing permafrost terrain (-)
- Improved construction after the melting of permafrost (+)
- Economic benefits resulting from extended surface mining (+)
- Improved offshore exploration and production with less sea ice (+)
- Increased threats from higher sea levels and erosion to coastal installations (-)

Agriculture, Forestry, and Wildlife

- Higher yields in agriculture and forestry due to longer growing season (+)
- Increased incidence of forest fires and losses to timber industry (-)
- Increased insect outbreaks and infestations, leading to economic losses (-)
- Losses/changes in wildlife and reindeer herding as ecosystems change (+ and -)
- Losses/changes in fish and marine mammals with decline in sea ice extent (-)
- Effects on tourism: longer season (+), but melting glaciers, smoke from forest fires (-)
- Flooding of coastal wetlands, affecting waterfowl and shorebird breeding (-)

Government

- Reduction in local income/need for higher subsidies in villages to keep standards of living, as subsistence resources decline (-)
- Greater investments needed to combat rising sea level, thawing of permafrost (-)
- Possible need for greater investment in health services (new diseases) (-)
- Reconstruction costs of government infrastructure (-)
- Increased costs of forest fire control (-)

Subsistence and Local Economy

- Increased village economy problems due to fewer subsistence resources (-)
- Possible greater availability of other subsistence resources (e.g. salmon) in some areas (+)
- Possible relocation of populations closer to new subsistence harvest sources (-)
- Change in energy pattern use due to climate change (+)
- Change in local transportation methods (+ and -)

Construction and Transportation

- Higher cost of maintaining roads, bridges, etc. in thawing permafrost terrain (-)
- Easier construction of buildings, roads, airports, etc. in permafrost-free terrain (+)
- Greater availability of freshwater resources, potable water (+)
- Improved shipping to villages and oil facilities due to less sea ice (+)

Global Economy

- Impacts on the insurance industry and the costs to the insured (-)
- Changes in world markets and resource prices (-)
- New, quicker, and therefore cheaper trans-Arctic shipping routes (+)
- Relocation/protection of port and coastal facilities due to sea level rise (-)

Non-Market Concerns

- Changes in quality and duration of human life (+ and -)
- Loss of cultural and historic assets, particularly in coastal areas (-)
- Surprises and new risks due to non-linear changes (+ and -)

1. Introduction

Climate change due to greenhouse warming is expected to have major impacts on the global environment and human activities. To assess its likely impacts an international group of experts, the Intergovernmental Panel on Climate Change (IPCC) has been created. The latest update of the their report *Climate Change 1995* (1996) includes a chapter (Chapter 7 of Working Group II) on climate change and its impacts on the polar regions. The report lists the degree of confidence in the following predictions, following a doubling of atmospheric CO_2:

- ♦ 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 extent of glaciers has often been used as an indicator of past global temperatures (High Confidence).
- ♦ 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 (High Confidence).
- ♦ There will be striking changes in the landscapes of many high mountain ranges and of lands at northern high latitudes (High Confidence). These changes may be exacerbated where they are accompanied by growing numbers of people and increased economic activities (Medium Confidence).

The chapter goes on to state that the following changes and associated impacts on the polar regions are likely:

- ♦ Pronounced reductions in seasonal snow, permafrost, glacial and periglacial features with a corresponding shift in landscape processes (High Confidence).
- ♦ 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 (High Confidence).
- ♦ Disappearance of up to a quarter of the presently existing mountain glacier mass (Medium Confidence).
- ♦ 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 (Medium Confidence).
- ♦ A large change in the extent and thickness of sea ice, not only from warming but also from changes in circulation patterns of both atmosphere and oceans. There is likely to be substantially less sea ice in the polar oceans (Medium Confidence).

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 (High Confidence).

- Cryospheric change will reduce slope stability and increase the incidence of natural hazards for people, structures, and communication links. Buildings, other structures, pipelines, and communication links will be threatened (High Confidence).
- Engineering and agricultural practices will need to adjust to changes in snow, ice, and permafrost distributions (High Confidence).
- Thawing of permafrost could lead to disruption of petroleum production and distribution systems in the tundra, unless mitigation techniques are adopted. Reduced sea ice may aid new exploration and production of oil in the Arctic Basin (High Confidence).
- Improved opportunities for water transport, tourism and trade are expected from a reduction in sea, river, and lake ice. These will have important implications for the people and economies of the Arctic (Medium Confidence).

Additional impacts occur on arctic biota and ecosystems, but these are not discussed in detail in the IPCC report. It is very likely, however, that reductions in snow and ice covers will adversely affect species which depend on these features for habitat, feeding, and reproduction. Snow cover changes on land affect both plants and animals, including large mammals such as moose, caribou, and muskoxen. The marine ecosystem, including ice algal communities, polar cod, ringed seals, walrus, and polar bears will be affected by changes in sea ice extent and characteristics.

These predictions apply in a very general sense to the high latitudes and are not region-specific. It is known, on the other hand, that the climate worldwide, including the Arctic, has changed in a very patchy manner, with warming occurring in most areas but cooling being present in some other smaller regions. This has led the U.S. Global Change Research Program, and indeed other nations' global change research, to adopt a regional approach to assessing the consequences of changes in climate and other global environmental conditions.

To examine the validity of the predictions above, a workshop on regional impacts of global change in Alaska and the Bering Sea region, defined roughly as the area between the Mackenzie River in Canada and the Lena River in Siberia, was held at the University of Alaska Fairbanks on 3-6 June 1997. The resulting proceedings represent the integration of information provided to the workshop participants in the form of technical background papers (prepared in advance by guest authors) along with the additional insights and information gained as a result of the workshop group discussions among scientists and stakeholders during the course of the workshop. The following chapters summarize current thinking about the consequences of climate change in nine critical sectors: forests, tundra, wildlife and reindeer, land use, marine biological resources, subsistence fisheries, coastal systems, permafrost, and non-renewable resources.

A key conclusion is that changes in historical climate patterns in the region over the last three decades have been substantial, of the magnitude expected from greenhouse warming. The resulting impacts observed are large and can only get even more pronounced if present climate trends continue.

2. Climate Trends and Scenarios[1]

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2.1 Long-term Global Climate Changes

Large changes in global climate have occurred in the past. As the Earth cooled gradually tens of millions of years ago, ice sheets began to form in the polar regions. There is evidence for initial glaciation in the Antarctic approximately 40 million years ago (during the Eocene), and in parts of the Arctic approximately 20 million years ago (during the Miocene). The first large-scale continental glaciation in the northern hemisphere occurred approximately 5 million years ago. For the last 3 million years, ice ages have occurred in roughly 100,000-year cycles[2]. We are presently experiencing a warm period between ice ages.

Analysis of cores[3] from the Greenland and Antarctic ice sheets indicates that global temperature was approximately 8°C lower during ice ages than it is today. The results of this change were obviously profound. The last ice age peaked approximately 20,000 years ago with an ice sheet several kilometers thick covering large parts of Northern Europe and North America. Sea level at that time was as much as 100 meters lower than it is today.

The ice-core records also show a remarkable correlation between temperature and the carbon dioxide (CO_2) content of the atmosphere[4]. While the relationship between these two parameters has yet to be fully explained, one appears to amplify the other.

The ice-core records also show dramatic short-term fluctuations in climate, which cannot be due to astronomical factors but have, as yet, no satisfactory explanation.

All of this evidence confirms that:

- ♦ climate is variable and probably chaotic in nature, although recent research suggest that there may be preferred patterns, such as El Niño-Southern Oscillations, which could be predictable,
- ♦ we do not fully understand the dynamics, and
- ♦ future changes will be difficult to predict.

A new man-made factor in the equation is air pollution on a global scale. From the onset of the industrial revolution, human activities have increased production of "greenhouse" gases, principally CO_2, methane, chlorofluorocarbons (CFCs), nitrous oxide, and water vapor. These gases occur naturally in the atmosphere, trapping heat which would otherwise escape from the Earth. In current concentrations, however, they exacerbate warming, especially over land in the polar regions and in winter. We refer to this as "the greenhouse effect."

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[1] Previously published in Anderson, P.A. and G. Weller (eds.) 1995. Preparing for an Uncertain Future: Impacts of Short- and Long-Term Climate Change on Alaska. Center for Global Change and Arctic System Research, University of Alaska Fairbanks, pp 5-11.

[2] The 100,000-year ice-age cycle is believed to be driven primarily by variations in the Earth's orbit around the sun (Milankovitch 1930).

[3] The temperature record is reconstructed primarily through analysis of oxygen-isotope ratios in the ice cores.

[4] Atmospheric CO_2 is determined through chemical analysis of air bubbles entrapped in the ice.

In addition to promoting warming, CFCs have catalyzed significant reductions in stratospheric ozone over the last several decades. Ozone in the upper atmosphere serves to filter incoming UV radiation. The reduction in the ozone layer has been documented annually over Antarctica and intermittently over the Arctic.

Contrary to the effect of greenhouse gases, particulate pollution (aerosols) such as sulfur dioxide (SO_2) block incoming solar radiation and, thereby, promote cooling.

Reduction of biomass in all environments will also have a long-term effect on climate. The greatest decrease in biomass has occurred in the Amazon, Southeast Asia, and the rain forests of Northwest North America, where forests continue to be cleared for agricultural use, logging, mining, and industrial development. Also, industrial pollution has reduced a fundamental component of plant biomass (phytoplankton) in the world's oceans.

2.2 Recent Global Climate Changes and Trends

Analysis of the entire global record indicates that, over the last 100 years, global climate has warmed approximately 0.5°C (Figure 2.1); the last few years have been the warmest on record. Figure 2.2a (Chapman and Walsh 1993) shows that temperatures in northern North America and Asia over the last 30 years are as much as 2.0°C/decade warmer in winter. Summer trends are much less pronounced (Figure 2.2b).

Models of greenhouse effect have predicted at least this much warming. Some researchers have argued that particulate pollutants (aerosols, which block incoming solar radiation) have depressed the warming effect in industrialized regions. Climate trends in the Arctic more clearly exhibit the amount of warming predicted by the models than do trends in industrialized latitudes.

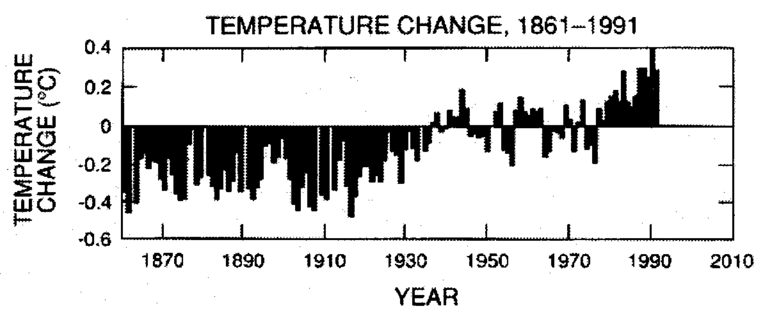
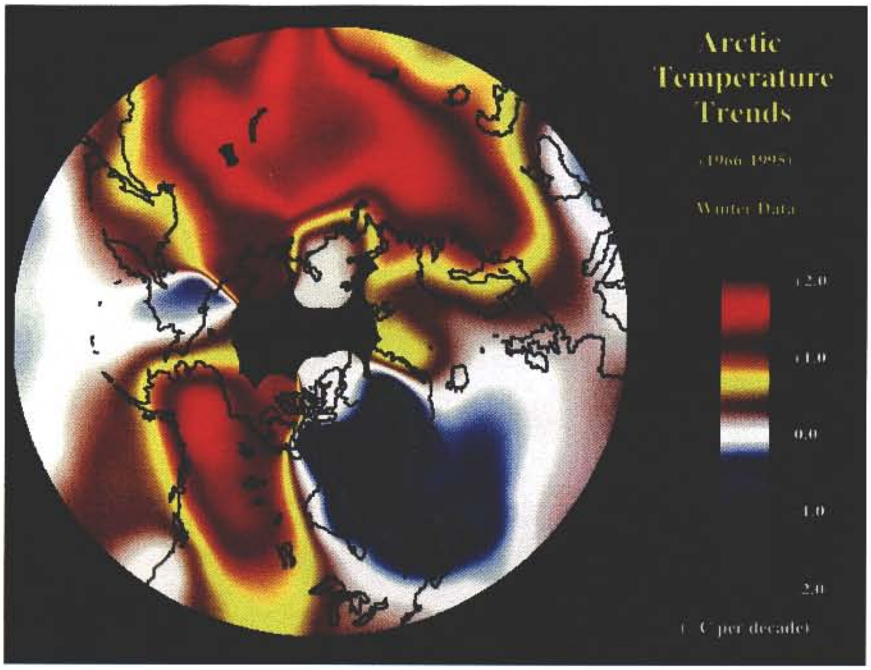


Figure 2.1. Global temperature increased from 1861-1991. 1990 and 1991 were two of the four warmest years since worldwide records began to be kept in the 19th century; 1990 and 1991 closed out the warmest decade on record.

As predicted by the models, temperature increases are greatest in winter and over high-latitude land masses, primarily because of the feedback effects of snow. Trends are less obvious in the Central Arctic Ocean, where data is more limited. While the observed changes vary by region and in some areas even include cooling (e.g., Soviet ice-station data), overall warming trends in the Arctic are clear.



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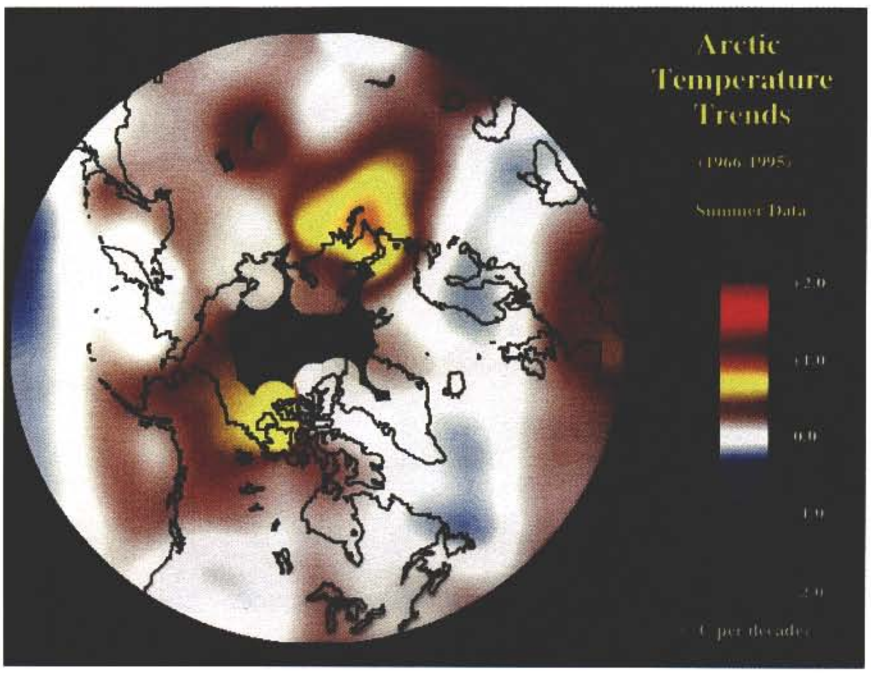

b

Figure 2.2. a. Observed trends of arctic winter mean temperatures from 1966-1995. Temperatures in northern North America are as much as 2°C/decade warmer in winter (Chapman and Walsh unpublished). b. The same analysis as in Figure 2.2a, but for summer. Summer trends are much less pronounced than winter trends.

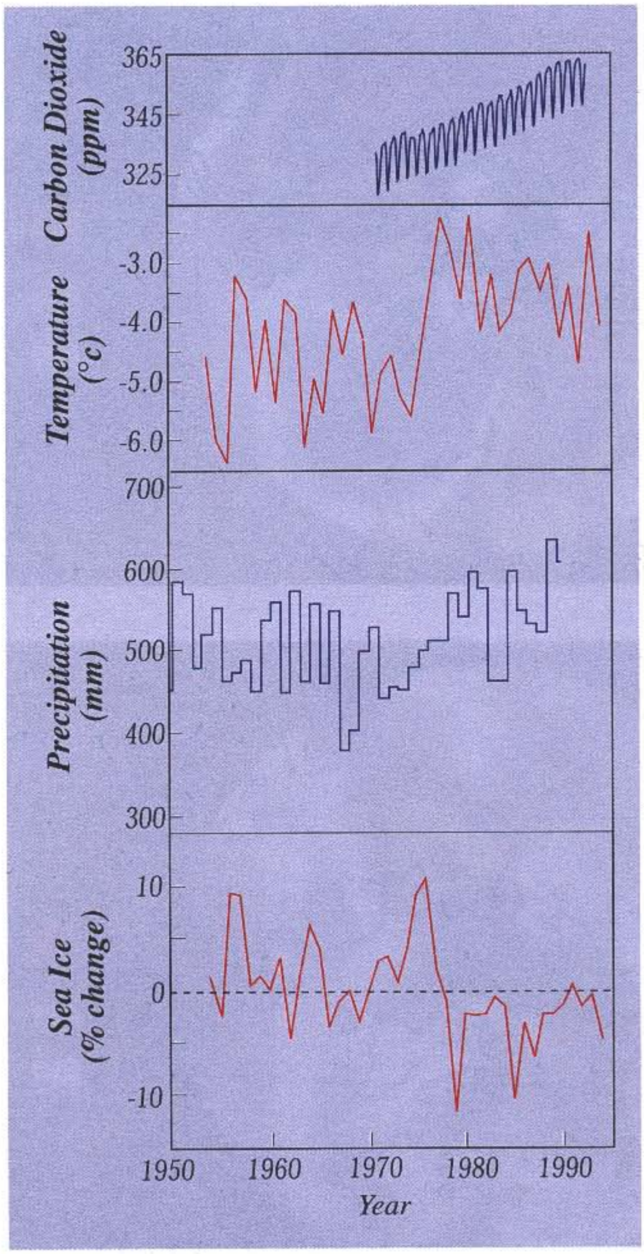

Figure 2.3. Climate-related observations in the Alaska region:
a) Atmospheric CO_2 concentrations at Barrow (Conway et al. 1994);
b) Combined annual air temperatures at Anchorage, Fairbanks, Nome and Barrow (Bowling pers. comm.); c) Precipitation in Alaska west of 141° (Groisman et al. 1994); d) Changes in sea-ice extent in the Bering Sea (Niebauer pers. comm.).

2.3 Observed Climate-related Trends in the Arctic

Climate-related trends based on direct measurements in Alaska and its surrounding oceans are shown in Figure 2.3. Carbon dioxide (CO_2) concentrations in the atmosphere have been measured at Barrow since 1971 (Conway et al. 1994); these show the same upward trend that is observed worldwide. Air temperatures for Anchorage, Fairbanks, Nome, and Barrow were analyzed by Bowling (pers. comm.) for the period 1954-1994. Considered together, they show a step increase of nearly 2°C around 1977; the warmer temperatures have persisted since then. Sea-ice extent shows a step decrease of about 5% in the Bering Sea in approximately 1977 (Niebauer pers. comm.); the lower extent has persisted since then. Precipitation in Alaska west of 141° (not including Southeast Alaska) has increased since 1970 (Groisman et al. 1994).

Other data sets for Alaska and the Arctic also indicate a warming trend. Permafrost temperatures measured in boreholes in northern Alaska are 2-4°C warmer than they were 50-100 years ago (Lachenbruch and Marshall 1986). Discontinuous permafrost has warmed considerably and is thawing in some locations (Osterkamp 1994). In Siberia, similar changes have occurred. Northern hemisphere snow extent has decreased during the past two decades (Robinson and Dewey 1990). Sea-ice thickness, a sensitive indicator of climate change, appears to have decreased between 1976 and 1987 (Wadhams 1990); however, the measurements made by upward-looking sonar on nuclear submarines are as yet too scattered to allow reliable conclusions to be drawn. Glaciers also continue to recede. Eight glaciers (7 in Alaska, the other in the state of Washington) showed on average a decrease in thickness of 10 m during the interval between the late 1950's and the mid-1990's, a time span of just under 40 years (Sapiano et al. 1997). All these observations are consistent with a warmer climate in the Arctic, as predicted by the computer models.

In short, Alaska has experienced considerable climatic warming since the 1950s; most of this warming occurred after 1976. Table 2.1 provides a summary, based on an analysis by Chapman and Walsh (1993).

Table 2.1. Observed Climate trends of land and ocean regions of Alaska, by season

	Air Temperatures (°C/decade) 1960-1990				
Climatic Zone	Spring	Summer	Fall	Winter	Year
Arctic (N. of the Brooks Range)	+0.7	+0.3	-0.2	+0.8	+0.4
Interior	+1.0	+0.2	0	+1.2	+0.6
Gulf of Alaska	+0.4	0	+0.1	+0.4	+0.2
Bering Sea	+0.2	+0.2	+0.3	+0.2	+0.2

2.4 Climate Scenarios for Alaska

Current climate models still have a number of deficiencies, including poor representation of cloud and aerosol effects on the climate system. Extrapolation over long time intervals also remains problematical. Nevertheless, the results of modeling agree well with observed trends of climate in Alaska, corroborating the credibility of the Alaskan models. On the basis of these models and observations, a climate scenario can be constructed for Alaska approximately 100 years from now, when the CO_2 content of the atmosphere is expected to have doubled. This is a hypothetical scenario, perhaps only one of a number that may be realistic.

Table 2.2 summarizes this climate scenario. There is general agreement between the modeling results and the extrapolated observations. Both show a warming trend in all of the four regions, particularly in winter, although in two cases, there are large differences in the magnitude of the projected warming.

Table 2.2. Climate Scenario for Alaska (four doubling of CO_2)

Climatic Zone	Termperature °C			Precipitation	
	Model[1]	Observation[2] (extrapolated)		Model[1]	Observation[3]
Arctic					
Summer	+3	+3	(+0.9)	Wetter	
Winter	+7	+7	(+2.4)	Wetter	
Interior					For Alaska west of 141°, precipitation has increased by 30% from 1968 to 1990
Summer	+4	+2	(+0.6)	Wetter	
Winter	+5	+11	(+3.6)	Wetter	
Gulf of Alaska					
Summer	+4	0	(0)	Wetter	
Winter	+5	+4	(+1.2)	Wetter	
Bering Sea					
Summer	+4	+2	(+0.6)	Wetter	
Winter	+7	+2	(+0.6)	Wetter	

[1] Based on GFDL GCM simulations by Manabe, et al. (1992)

[2] Based on three-decade trend analyses by Chapman and Walsh (1993) and linear extrapolation to 80-100 years (30-year actual trends in brackets)

[3] From DOE worldwide "Trends" based on analysis by Groisman, et al. (1994)

The next steps in improving regional climate scenarios are to use high resolution regional climate models. A meeting of minds between regional modelers and impacts researchers took place at the UK Meteorological Office in Bracknell, UK, in November 1996. It was sponsored by WCRP, EMaPS, and IASC and its goal was to identify the requirements of regional climate scenarios. Although coupled atmosphere-ice-ocean models exist now for the Arctic (e g., Lynch et al. 1995) which have much greater resolution than the general circulation models, their use was thought to be premature, considering all the uncertainties of the general circulation models in which the regional models would have to be nested.

Nevertheless, recent experience with observed changes in climate patterns in the Arctic as well as ongoing research to improve our understanding of the physical, natural, and human impacts of climate change scenarios like the one described provide a useful starting point for assessing the consequences of climate change for this region. The following chapters summarize current thinking about the consequences of climate change.

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3. FORESTS, CLIMATE STRESS, INSECTS, AND FIRE

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3.1 Introduction

Forests are one of the major renewable resources of Alaska. Alaska's forests provide habitat for wildlife (including many species important for subsistence), forest products and opportunities to expand forest products production, and the scenic backdrop for much of Alaska's tourism industry. Ecological processes in high latitude forests are a significant feedback to the world carbon cycle and a major potential source of additional greenhouse gases to the atmosphere.

There are two major types of forest in Alaska (1) the coastal temperate rainforest of southeast and southcentral Alaska and (2) the boreal forest or taiga of southcentral and interior Alaska (Figure 3.01). The boreal forest covers the larger area by far, about 46.2 million ha (114 million ac) versus 5 million ha (12.3 million ac) for the coastal forest (Labau and Van Hess 1990).

Worldwide, cool temperate rainforests are confined to narrow coastal strips in Chile, New Zealand, Australia, northwest Europe, and northwestern North America, including southeast and southcentral Alaska. They are not naturally abundant on the Earth, and a large proportion of the remaining unlogged share of this forest type is found in Alaska. Alaska contains 19% of world total of 26.6 million ha (65.7 million ac) of temperate rainforest, and 38% of the total unlogged area (11.6 million ha; Ecotrust et al. 1995).

The coastal forest of Alaska supports a significant forest products industry which is undergoing structural change. The two large pulp mills in southeast Alaska which were the major part of the industry closed operations in the last two years. However, strong markets exist for sawlogs from both southcentral and southeast Alaska. The majority of logs produced from privately owned land in the coastal region are exported, but Alaska-based sawmill operations are limited by the lack of available logs from the public lands, which cannot be exported. The new Tongass National Forest Land and Resource Management Plan will probably result in a timber harvest of less than half the level typical of the 1980s. Investment in new forms of value added forest products manufacture is likely for the new harvest level, but the long-term survival of the forest products industry depends directly on the availability of a predictable supply of suitable wood from public lands.

Two established industries depend on the coastal forest remaining in a relatively lightly disturbed or undisturbed condition. The fishing industry depends on the critical contribution the coastal forest makes to high quality salmon habitat, a important factor in one of the world's most productive fisheries. The coastal forest is also the scènic background for a vigorously expanding tourism industry, especially cruise ships and wilderness lodges. Alaska Native communities make use of the coastal forest across the spectrum of land uses, from protected wildlife habitat to industrial logging and many uses in between.

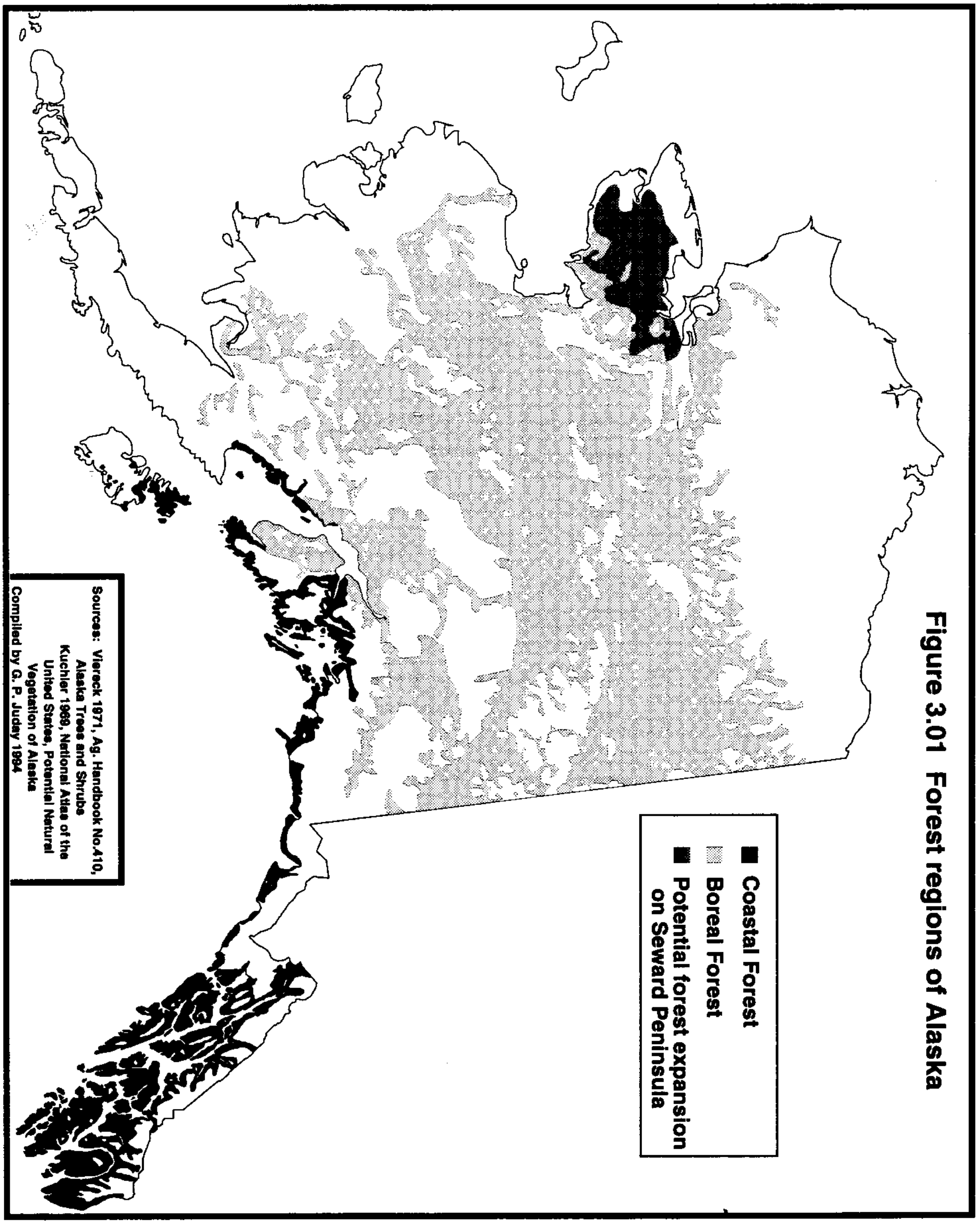


Figure 3.01 Forest regions of Alaska

The world boreal forest zone makes up about 17% of the Earth's land surface area (Bonan 1992) and increasingly is being used as a source for the world timber trade. Of all the major forest regions of the world, the boreal zone supports the lowest density of settled human populations. In much of the boreal forest native peoples still pursue traditional ways of life modified to various degrees by modern circumstances. The boreal forest is among the last of the Earth's forest regions to be widely exploited for industrial economies. Timber and mineral extraction are fairly recent land uses, but they have increased greatly in extent since the mid 20th century.

The most widespread form of active, programmed land use today in boreal Alaska is forest management, specifically fire management and wood products harvest. A small forest products industry operates in the Alaskan boreal region, concentrated on supplying local markets with rough lumber, house logs, fuelwood, and specialty products. The dominant large conifer, white spruce (*Picea glauca*), is significantly more valuable than the broadleaf trees. Export of higher value boreal white spruce increased significantly in response to a doubling or tripling of stumpage prices after major reductions of public timber harvest were implemented on public lands in the Pacific Northwest. Another small (in extent), but important and expanding land use in the Alaska boreal forest region is hard rock mining. Within one to a few decades most of the new large mines in the United States will be in Alaska, and many are either in the boreal region or serviced from it. Expansion of human settlements, both villages and urban centers, and the construction of transportation facilities are increasing in boreal Alaska, generating additional demands for forest management in specific areas.

Nearly all of the Alaska boreal forest still supports most of its native wildlife including free-ranging large predators. Alaska hosts a huge influx of migratory birds that depend on summer breeding grounds in its boreal forests. Many prime wilderness areas are attracting increasing numbers of visitors with attendant impacts. Large-scale fires are suppressed when human habitation or commercially valuable timber is threatened. A forest management response is needed for events such as extensive insect-caused tree mortality.

In Alaska, productive forest sites within the boreal zone are limited to permafrost-free locations with suitable soils, mainly along the larger rivers and on low elevation south slopes. Certain wetlands in the boreal region, especially those that experience non-acidic groundwater flow, are highly productive as well. Only about 12% of the Alaska boreal forest is sufficiently productive to meet the definition of commercial forest land (Labau and Van Hess 1990). However, the total productive Alaska boreal forest area of about 5.5 million ha (13.5 million ac) is greater than the productive forest land base of many states. With continued climate warming sufficient to thaw permafrost, the productive boreal forest area in Alaska would expand by a factor of 3 or 4 times. Currently productive sites within the Alaska boreal forest are scattered across diverse landscapes with a limited transportation system, so that access to them is a significant cost to any form of timber cutting or management.

The boreal forest is an important component of the Earth's climate system. The stored pools of carbon in boreal forest soils and trees represent a significant share of the total terrestrial carbon reservoir. The release of this carbon to the atmosphere as carbon dioxide or methane as the result of climate warming could be a major positive feedback loop in future climate warming.

Several features of climate, especially temperature, control many different forest responses (Figure 3.02). It could be said that a forest could experience several different kinds of warming. In considering the issue of current or potential global warming/global change effects on forests in Alaska it is important to be specific. Changes in any one of these characteristics of temperature variability could produce significant forest change while other features of temperature remained essentially unchanged. However, a considerable amount of ecological research on the forests of Alaska has been conducted in the last 3 decades, and some of the major pathways of climate-driven change are now understood. The forests of Alaska are a good place to study and observe climate change. The climate of the far north is naturally highly variable from year to year, as its residents know. The forests of Alaska are limited by several different features of the current climate and so they respond in different measurable ways to the climate changes as they happen. Recently a substantial amount of evidence has begun to accumulate that climate change in Alaska's forest regions has surpassed the range of background variability and is changing systematically in ways that are posing significant challenges to several Alaska forest resources.

Figure 3.02 Characteristics of temperature variability important in climate change effects on forests and other Alaska vegetation

Characteristic of temperature variability	Consequences to vegetation
Maximum daily	Various threshold values must be equaled or exceeded to trigger various plant development functions (e.g. seed production) throughout the growing season.
Minimum daily	Low levels retard plant development, even when daily means are otherwise suitable, can represent damaging or killing freezing conditions (e.g. insects in winter).
Mean monthly	Useful overall summary, especially for long-term trend analysis (e.g. tree-rings).
Growing degree days	Useful measure of cumulative heat accumulation, various thresholds associated with several different seasonal plant development functions.
Frost-free season	Represents consecutive number of days without lethal cold - in Alaska can be 0, -2, -4^{o}C or colder depending on the plant species or variety.

3.2 Past effects of climate change

Past Climate Change

Historically, coastal forests of Alaska have experienced and responded to variations in climate. These responses can provide insights into how coastal forests are likely to respond to future climate changes. During the current interglacial, regional vegetation patterns of southeast Alaska have changed several times in response to changing climate. Heusser (1952) described 5 major climatic periods and their associated vegetation for southeast Alaska over the past 8000 years. The period from 8000 to 6000 years B.P. was cool and moist; this period was characterized by dominance of shore pine (*Pinus contorta var. contorta*). From 6000 to 5000 years B.P. the climate became warmer and drier and Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) succession took place. Western hemlock predominance was achieved from 5000 to 2000 years B.P. when maximum warmth and dryness occurred. Mountain hemlock (*Tsuga mertensiana*) attained its maximum during this time. The warming and drying that occurred during this thermal maximum allowed forests to invade muskegs[1], and fires occurred (Heusser 1953) in a region that is now occupied by temperate rainforests.

From 2000 to 200 years B.P. the climate became cooler and wetter; a hemlock maximum occurred, and pine expanded its range. The later phase of this cool wet period, from about 1350 to 1840 A.D., is recognized across the northern hemisphere as the Little Ice Age. The final climatic period in southeast Alaska has been the warming and/or drying since the end of the Little Ice Age. Tree-ring reconstructions of some of the features of the climate of south coastal Alaska indicate the timing and the magnitude of warming since 1600 A.D. (Wiles et al. 1996).

Not all vegetation change that occurred in the coastal forest since the termination of the worldwide glacial period 12,000 B.P. was directly controlled by climate. Sitka spruce is still expanding its range westward in the Alaska coastal region (Veblen and Alaback 1996). Time and geographic barriers along the complex mountainous Alaska coast probably have prevented Sitka spruce from occupying all climatically suitable sites. The area of the coastal landscape covered by muskegs has declined by 40% since deglaciation because of forest expansion (Stephens et al. 1970).

In addition to the major periods of climate and vegetation change on the scale of thousands of years, decadal and century long climatic changes result in vegetation responses such as changes in vegetation abundance and limited changes in distribution (Bartlein 1988). For example, the cooler and wetter climate that occurred during the Little Ice Age allowed muskegs to expand at the expense of the surrounding forests (Heusser 1953).

Instrument-based climate records are available for a few locations in the Alaska coastal region starting in the early years of the 20th century (Juday 1984). Mean annual temperature at coastal stations shows a strong cycling trend with a period of about 19 years between peaks (Figure 3.03; Juday 1984, Royer 1993). In the mid 1970s temperatures in Alaska coastal stations increased abruptly to the highest level of the 20th century; even the low period in the temperature cycle that followed was markedly warmer than any similar period in the instrument-based record (Figures 3.04 and 3.05). Storm frequency and intensity increased at the same time as the recent rapid rise in temperature. The number of days with gale-force winds at coastal locations more than doubled in the late 1970s compared to the previous two decades (Figure 3.06).

[1]A muskeg is a relatively open wet peatland with a ground cover high in *Sphagnum* mosses and/or sedges (Stephens et al. 1970).

Figure 3.03 Smoothed mean annual temperature (MAT) at Valdez, Sitka and Juneau Downtown

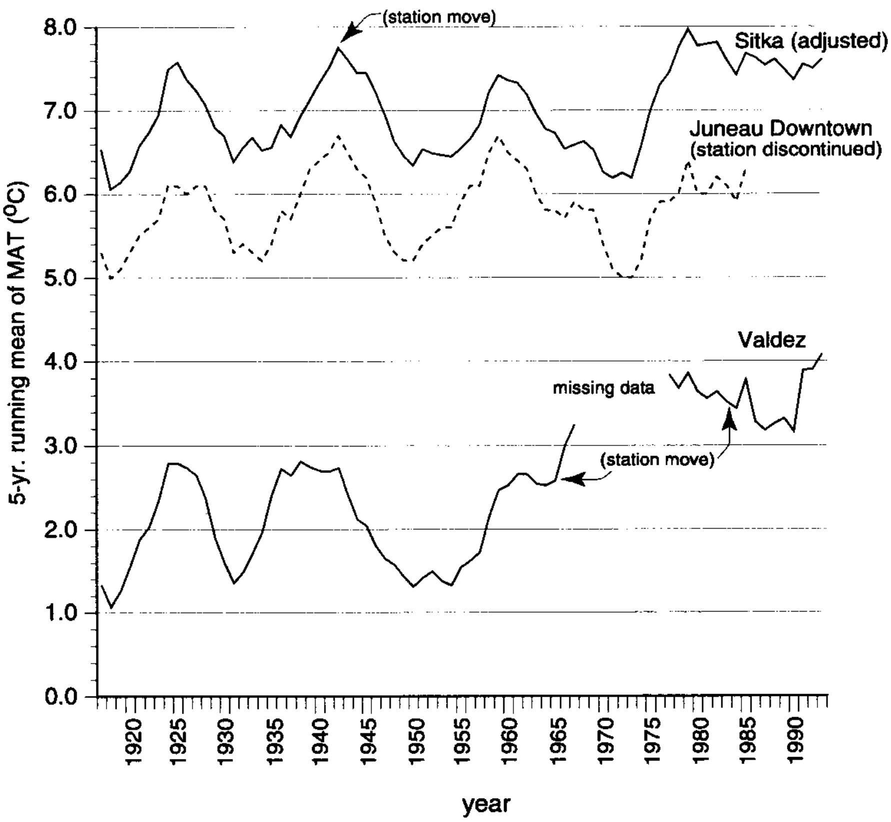


Figure 3.04 Smoothed mean annual temperature, Anchorage, 1918-1994

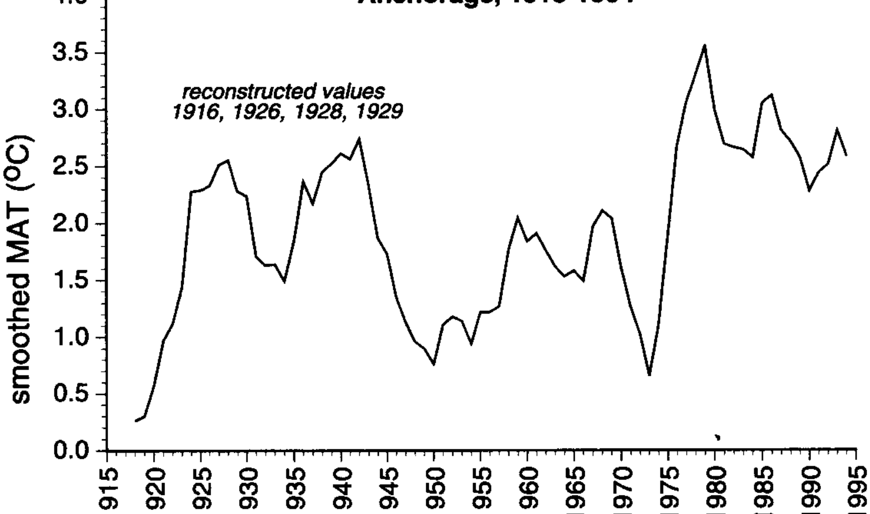


Figure 3.05 20th century mean annual temperature (MAT), unsmoothed, and 4.5° C warmer scenario at Anchorage

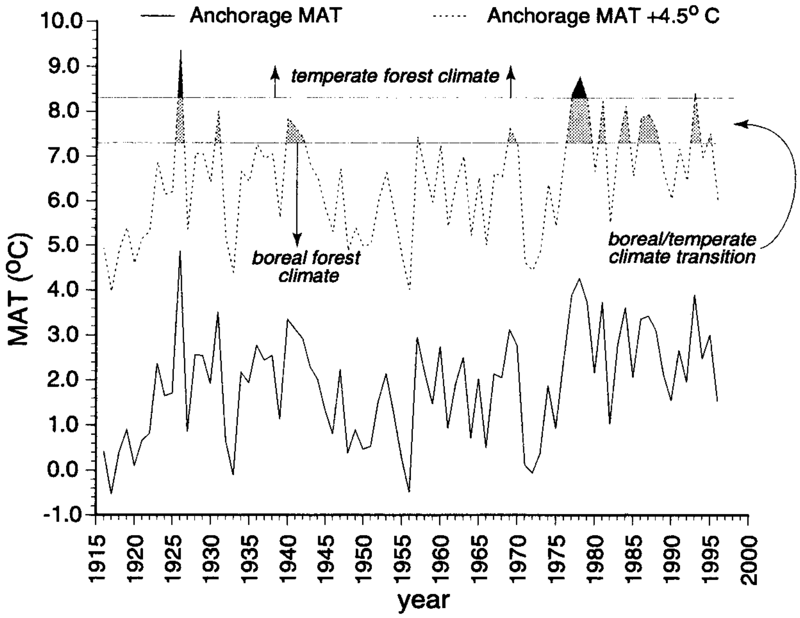
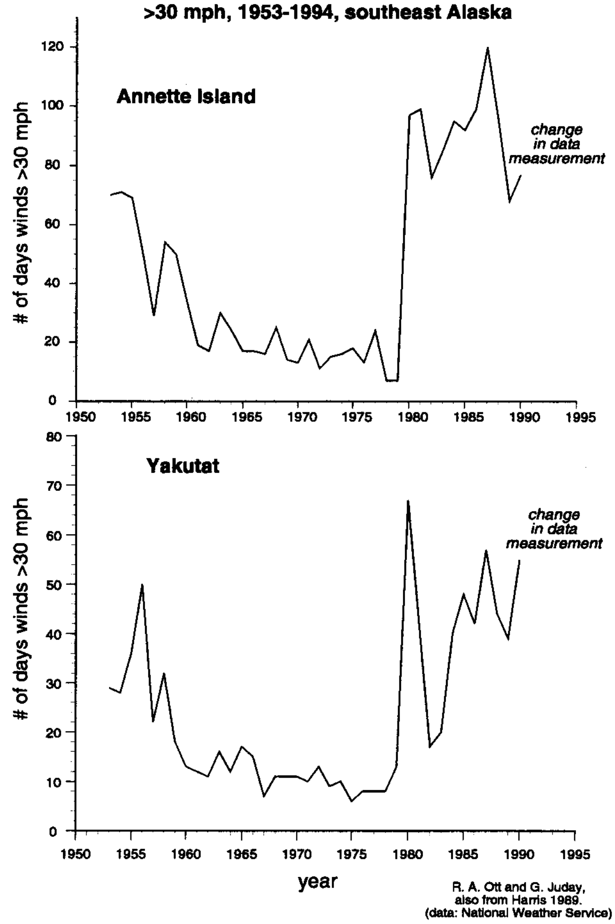


Figure 3.06 Number of days, by year, with fastest mile wind >30 mph, 1953-1994, southeast Alaska



The coastal forest of Alaska displays evidence of several responses to the warming of the past 20 years that are consistent with the anticipated effects of global change. In southeast Alaska, the frequency of snow avalanches at low and moderate elevations has declined since the late 1970s in response to climatic warming (more of the winter precipitation falling as rain and less as snow). The result is that mountain hemlock is currently colonizing alpine tundra in the region, and the shrub salmonberry (*Rubus spectabilis*) is invading meadows dominated by heather (*Cassiope*) or sedge (*Carex*; Veblen and Alaback 1996). A decline in the frequency of severe snow accumulation at low elevations in southeast Alaska has allowed Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) better access to critical winter forage plants. A series of winters with low snowfall is partly responsible for higher winter survival and increased overall population levels of deer. One result may be reduced tree regeneration of the Alaska yellow-cedar (*Chamaecyparis nootkatensis*), a preferred browse species of deer (Hennon 1992).

The boreal forest of western North America today is the product of many and often pronounced climatic fluctuations from its establishment, following the most recent glacial period. Throughout the last glacial period the climate of lowland central Alaska, central Yukon Territory, and far eastern Russia was too arid to permit the formation of ice sheets. These regions were never glaciated, but trees were unable to grow in the extremely cold and arid landscape. Following the end of full glacial conditions across interior Alaska about 14,000 years ago, an abrupt warming occurred, permitting the northward migration of trees in North America (Pielou 1991).

Balsam poplar (*Populus balsamifera*) was usually the first tree species to appear in interior Alaska following the late glacial warming. Balsam poplar appears to have expanded across the landscape from 10,000 to 8,000 B.P. from small populations that were already present. Other tree species migrated from newly established populations in Canada northwestward across interior Alaska as the glacial ice sheets retreated in Canada and the climate warmed. About 9,000 years ago in western Canada white spruce spread rapidly northward across 2,000 km of newly deglaciated land in only 1,000 years. This rapid movement of forest was caused by the transport of seeds on strong northward winds caused by clockwise atmospheric circulation around the remnant ice cap of northern Quebec and western Hudson Bay (Ritchie and MacDonald 1986). Spruce and most other elements of the boreal forest were generally established near their current limits in Alaska about 6,000 years ago (Ager 1983).

Studies of past climates using tree-rings have produced a reliable picture of temperature variation in interior and northern Alaska since the early 1500s. Alaska temperature trends are in general agreement with overall northern hemisphere high latitude temperature trends (D'Arrigo and Jacoby 1993, Jacoby and D'Arrigo 1989). Temperatures during the Little Ice Age were distinctly cooler than during the 20th century in interior Alaska. The tree-ring reconstructions show the full effects of the Little Ice Age in the earliest portions of the record (from at least the 1500s to 1700), a partial warming in the early 1700s, an abrupt return to cold from about 1800 to 1840, and a steady warming since 1840 interrupted only by a minor cooling from the mid 1940s to the mid 70s.

Tree-ring reconstructions of climate are based on a substantial period of overlap with modern instrument-based climate data. The climate record from the University Experiment Station beginning in 1906, combined with the Fairbanks Airport (mid-1948 onward) provide representative data for most of the 20th century in central interior Alaska (Juday 1984).

Significant climate warming, and drying in certain localities, has been observed in interior Alaska over the last 20 years. For example, the mean daily maximum temperature in the warm season at Fairbanks has been rising sharply (over 3°C per century) since 1949 (Figure 3.07). Perhaps equally significant, the number of days with the warmest extreme of temperatures, 26°C (80°F) or warmer, has increased substantially from just over a week in the early 1950s to nearly 3 weeks in the 1990s (Figure 3.08). The extremes of warm temperatures in the boreal forest are associated with moisture stress to trees and with rapid maturation of insects and their population buildups.

Figure 3.07 Mean daily maximum temperature (°C) at Fairbanks (1949-1996), 1 April to 30 September

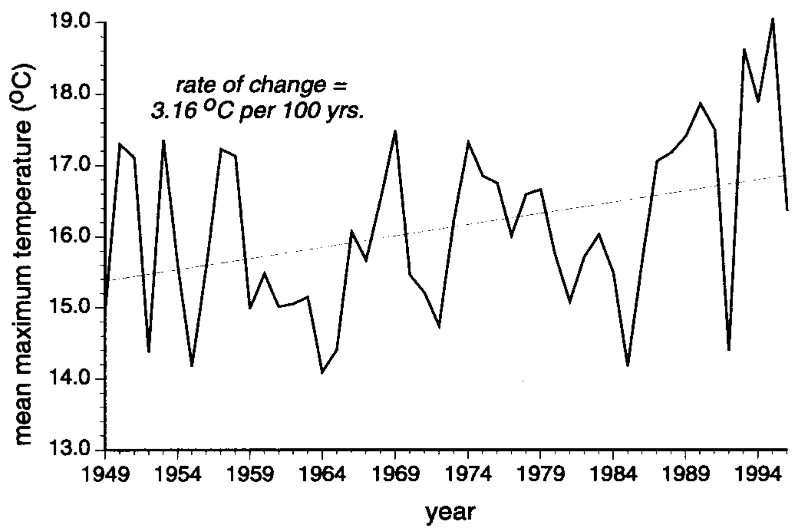
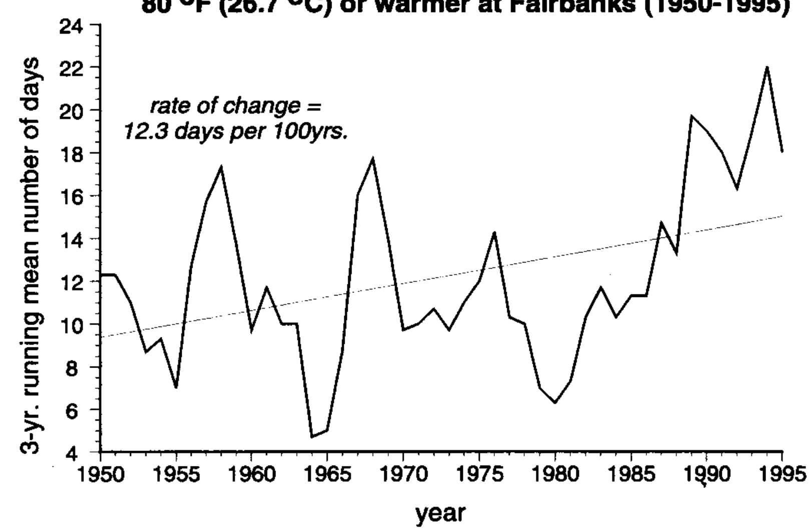


Figure 3.08 Smoothed number of days with maximum temperature 80 °F (26.7 °C) or warmer at Fairbanks (1950-1995)



The warming in interior Alaska has been effective in pushing back the date at which spring and early summer events begin. The earlier start to spring is reflected in the date at which ice breaks up on the Tanana River (Figure 3.09). The trend toward earlier breakup dates is particularly strong in the last 10 years; 3 of the 4 earliest breakup dates in the 81-year record are in the 1990s (Figure 3.09). Warm early spring and summer weather is apparently a necessary trigger factor in the production of the infrequent abundant white spruce cone and seed crops (Alden 1985, Zasada et al. 1992). Until recently the occurrence of a high number of days with warm temperatures in the early summer would be followed predictably the following year by a white spruce cone crop, unless a crop was already being produced in the trigger year. In the last decade or more, greater numbers of warm days than ever have occurred, but crops are not being formed.

Figure 3.09 Breakup date and time on the Tanana River 1917-1997

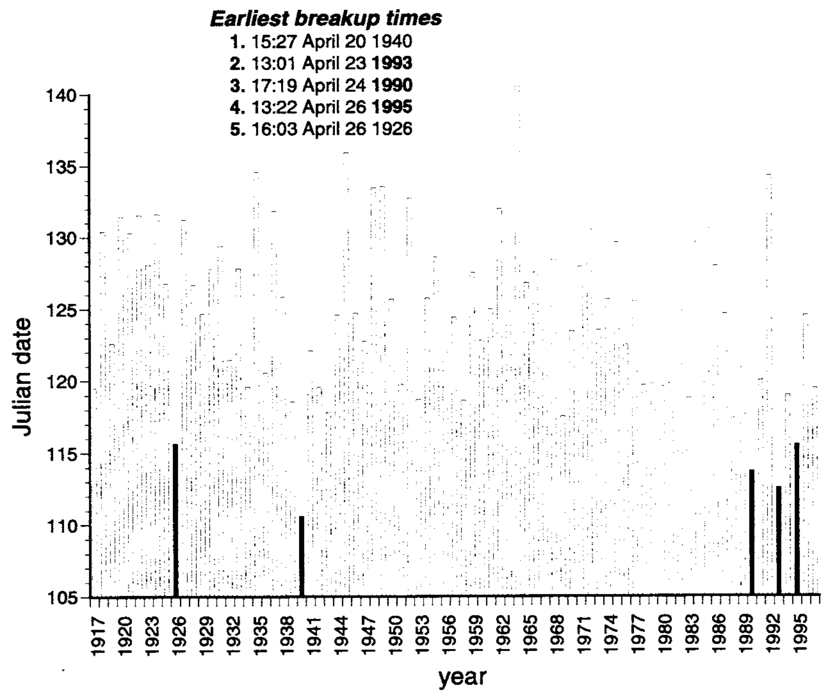


Figure 3.10 illustrates how the recent Alaskan warming could be translated into longer growing seasons that begin earlier and terminate later in the year. A standard measure of growing season warmth is growing degree days[2]. A comparison of growing degree days from the most recent 24 years (1973-96) of the Fairbanks Airport climate data compared to the first 24 years (1949-72) shows the expected pattern of warmer and extended growing seasons (Figure 3.11). The average annual total of growing degree days is 10% greater in the most recent half of the Fairbanks record than in the first half (Figure 3.11). Myneni et al. (1997) claim that an increase in growing season length between 1981 and 1991 is detectable from satellite data in the northern hemisphere, concentrated in the area between 45° and 70° N.

[2]Growing degree days are calculated as the mean of the high and low temperature for the date minus a threshold value such as 0°C (32°F).

Figure 3.10 Effect of recent Alaska climate warming on length of growing season and timing of "shoulder" seasons

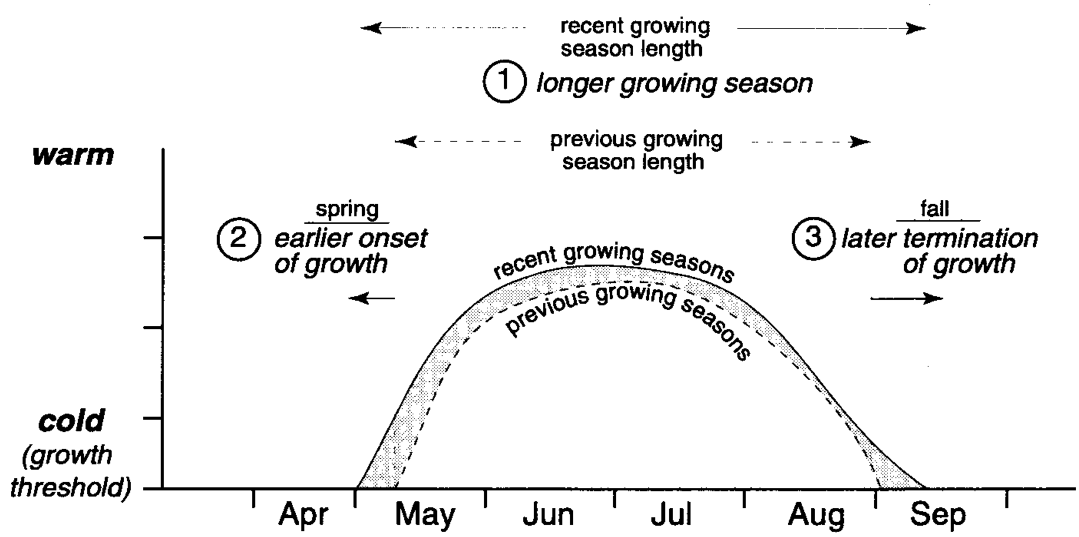
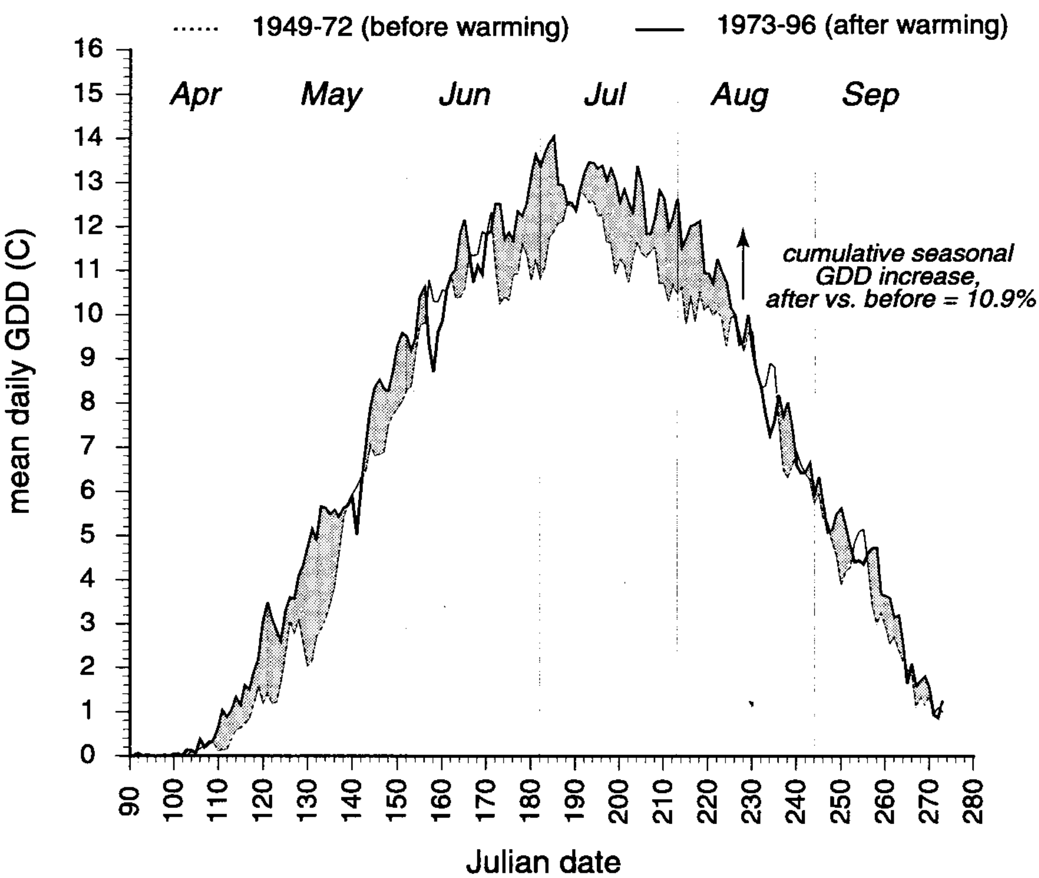
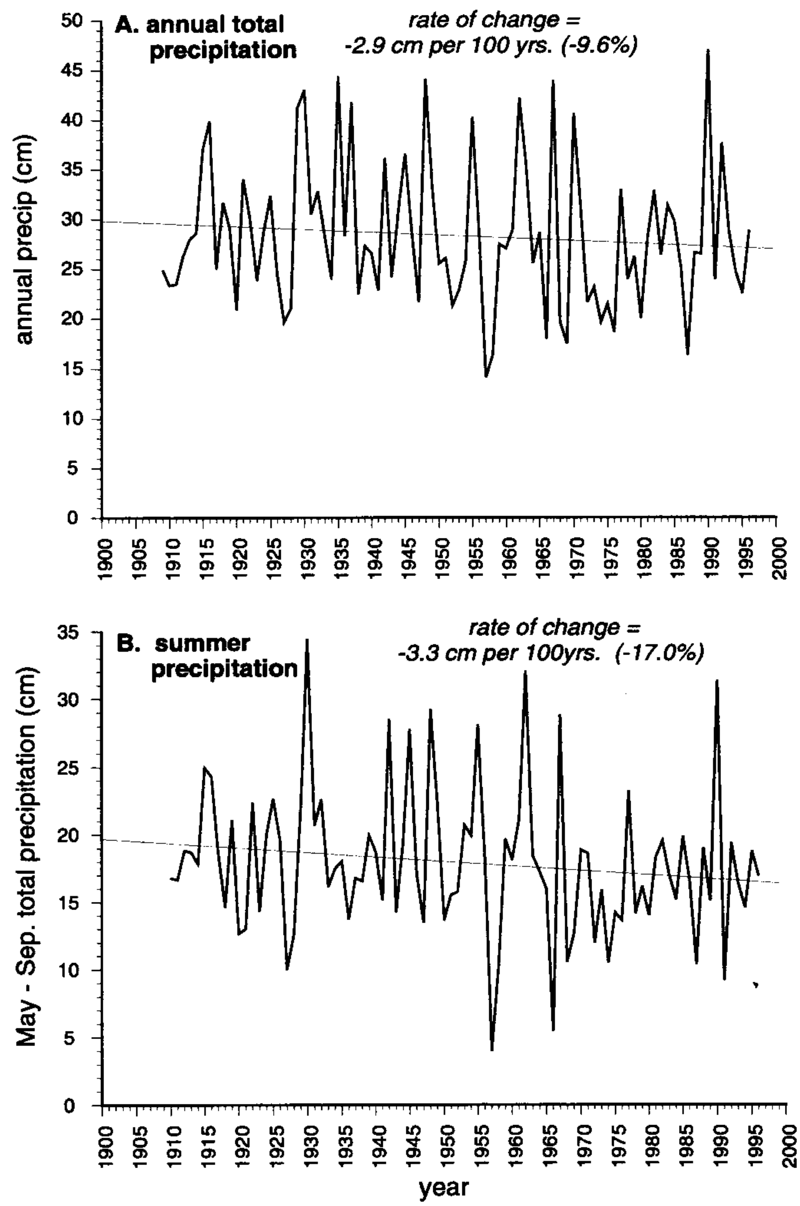


Figure 3.11 Growing season change in mean daily growing degree days (GDD) (4.4° threshold) at Fairbanks before and after climatic warming



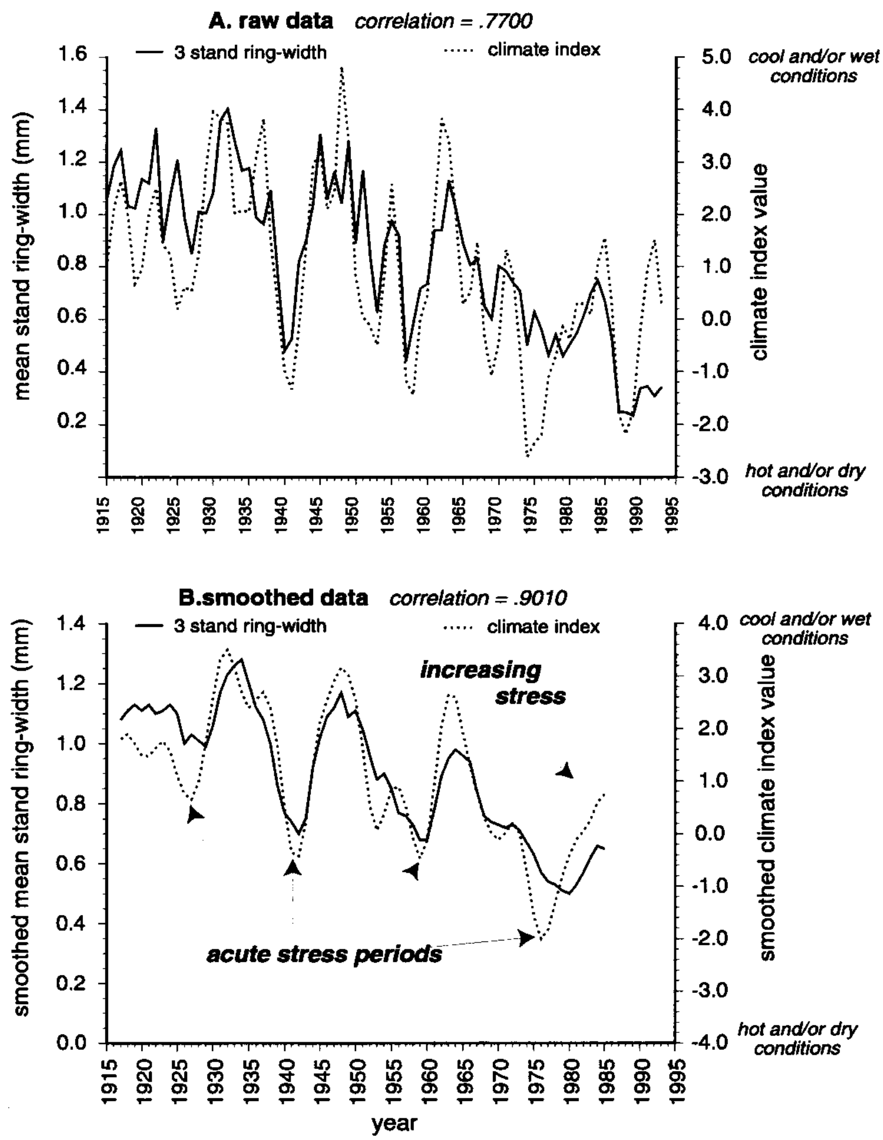
Both annual precipitation (Figure 3.12A) and summer precipitation (Figure 3.12B) have decreased during the entire 81-year (1906-96) period of record in Fairbanks. Summer precipitation, already marginal for forest growth across much of low elevation interior Alaska, has decreased at the rate of 17% per century at Fairbanks. Tree growth generally responds not only to the current year's weather but to several previous years as well. Figure 3.13 shows the trends in the multiple year precipitation and temperature index values that best match white spruce radial growth. White spruce growth is positively related to precipitation (greater growth in wet years) and negatively related to temperature (greater growth in cool years). Since the late 1970s both the precipitation and temperature index values have been moving strongly in an unfavorable direction, warming and drying, for white spruce growth (Figure 3.13). Because recent climate warming has started the growing season earlier and extended growth later, white spruce on productive sites near Fairbanks have become moisture stressed.

Figure 3.12 Precipitation trends at Fairbanks



Radial growth of upland white spruce trees closely follows the temperature and precipitation index derived from the Fairbanks climate data (Figure 3.13A). The smoothed trend of the white spruce climate index shows that the acute stress periods that were previously associated with the production of white spruce cone crops have been lengthened and exceeded by the climate change since the mid 1970s (Figure 3.13B), possibly resulting in less frequent cone crops. The combination of warming and drying are producing severe stress and decreased productivity in boreal forest trees unprecedented in the 20th century (Juday and Barry 1996). Elsewhere in Alaska, trees growing at the tree limit along the margin of tundra, which were previously limited only by warmth, are now limited by moisture stress (Jacoby and D'Arrigo 1995).

Figure 3.13 Relationship of mean radial growth of 3 white spruce stands at Bonanza Creek LTER and multiyear Fairbanks climate index



Wind Disturbance and Abiotic Stress

Coastal forests of Alaska respond not only to temperature and precipitation, but to wind as well. Wind is the primary disturbance agent in these forests (Veblen and Alaback 1996, Harris 1989). Coastal forests are highly susceptible to wind damage due to the combination of shallow root systems, poorly drained soils, and high winds—usually during peak rain intensity (Alaback 1990). Wind disturbance events typically are small-scale and involve single trees or small groups of trees—termed canopy gaps (Alaback 1990, Ott 1997). However, large-scale tree blowdowns do occur, especially along exposed coastlines (Veblen and Alaback 1996). The storms that deliver damaging winds to coastal Alaska are produced by the mixing of cold polar air with the warmer air of the North Pacific. A warmer sea surface intensifies the storm system produced (Salmon 1992). Since the late 1970s, a period of strong warming in southcentral and southeast coastal Alaska, the number of days with fastest wind speed > 50 km/hr (31 mph; moderate gale or stronger) increased dramatically (Figure 3.06).

Forest Insects

Biological disturbance agents of coastal forests respond to climate. The western black-headed budworm (*Acleris gloverana*) feeds primarily on western hemlock buds and current year's needles. This insect periodically defoliates large areas of western hemlock-Sitka spruce forest; it causes reduced tree growth, tree top-kill, and some whole-tree mortality (Hard 1974). Past black-headed budworm outbreaks affected trees over hundreds of thousands of hectares in southeast and southcentral Alaska, where it is one of the most damaging species present (Holsten et al. 1985). Growing season temperature appears to be a major factor controlling this insect's populations in coastal Alaska (Hard 1974). Large outbreaks are triggered by warm, dry summers (Furniss and Carolyn 1977).

The 1996 aerial survey of areas of major forest damage in Alaska identified 1.0 million ha (2.4 million ac) affected by insects (Holsten and Burnside 1997). Alaska contains 49.6 million ha (119 million ac) of forest land, of which about 24% is commercial forest land. Roughly speaking, an area equivalent to about 2% of all forest in Alaska and over 10% of commercial forest displays current or recent significant insect damage. This is an exceptional, if not historically unprecedented, level of damage. The ongoing mortality of spruce in southcentral Alaska caused by bark beetles (*Dendroctonus rufipennis*) currently involves 0.46 million ha (1.1 million ac) and is the largest forest insect epidemic in North America (Werner 1996).

The widespread outbreak of tree mortality in Alaska from stress-related insects[3] is also coincident in time with the onset of climate stress (Juday and Marler 1996). In the Bonanza Creek Long-Term Ecological Research (LTER) site in central interior Alaska, the tree-ring growth reduction caused by a 1993-95 spruce budworm (*Choristoneura spp.*) outbreak is unique in the 200-year record, supporting the view that outbreak levels of this insect are a new phenomenon caused by recent climate warming. In the monitored LTER stands snow breakage events in 1989 and 1990-91 triggered bark beetle attacks that occurred as tree growth was slowing markedly due to warming and drying. This suggests that climate change effects may be multiplicative, as one change (tree breakage from heavy snowfalls) sets the stage for another (insect outbreaks from damaged trees spread to undamaged stands because of warm weather and moisture stress).

[3]Insects that either cause stress to trees by thier attacks or insects that concentrate their attacks on already stressed trees.

Wildland Fire

Fire is the major natural disturbance agent in the boreal forest. Large scale insect outbreaks can weaken or kill trees over vast areas, often leading to forest fires. Most of the area burned (about 90%) in the Alaskan boreal forest is the result of natural ignition caused by lightning. Figure 3.14 shows the annual area burned in Alaska. In years with prolonged hot and dry periods of summer weather, Alaska experiences millions of hectares burned, mostly in a few very large fires. Peaks in area burned appear about every 10 years, typically with very little area burned between peak years. The trend in annual area burned in Alaska is related to summer warmth (Figure 3.15). The overall trend for the period 1955 to 1996 represents a moderate decline (34%) of average area burned annually. A portion of the decline may be accounted for by the maximum fire suppression effort in the 1960 and early 1970s. Since the mid 1980s about 80% of Alaska has been zoned for limited or no wildland fire suppression. However, because an approximately 10 year cycle of the record of area burned is evident in the Alaska record, care should be taken to compare intervals that start and stop at equivalent positions on the cycle. If estimated fire acreage values typical of the Alaska fire cycle are supplied for 1997-99, then the trendline over the 20th century would yield a 100% increase in average area burned annually.

Several factors operating together suggest that a substantial area should burn in Alaska in the next 1 to 4 years. These include: (1) anticipated greater number of periods of warm and dry weather, (2) a cumulative fuel/soil moisture deficit that has developed in the mid 1990s, and (3) extensive areas of dead vegetation. The relative proportion of area burned as a result of human-caused fire is gradually increasing in Alaska as population and developed area increase. A combination of increased human ignition sources, extensive penetration of forest land by suburban and intensified rural development, and prolonged warmer and drier weather set the stage for highly destructive wildland-urban interface fires. The Miller's Reach-Big Lake fire of 1996 destroyed the largest number of structures by fire in the history of Alaska.

3.3 Future Changes

Coastal Forest

Much of the risk to Alaska coastal forest from climate change scenarios associated with global warming involve (1) destructive winds, (2) tree mortality from insect outbreaks, and (3) changes in forest hydrology.

Recent forest mapping in the Tongass National Forest has identified large areas composed of trees that reproduced after the previous forest was flattened apparently by single windstorms in the past. The dramatic increase in gale winds (Figure 3.06) in coastal Alaska since the 1970s suggests that the risk of windthrow of trees will be much greater. To date, the increased frequency of storm does not correspond to an increase in the rate of formation of large-scale blowdowns in southeast Alaska. However, it is possible that canopy gap formation or expansion rates have increased as the number of days with storm winds increased. Additionally, the rate of blowdown around timber harvest units in the Tongass National Forest may have increased, but historic record-keeping systems are not sufficient to produce a reliable long-term time series. For 10 to 15 years following timber harvest, trees along clearcut edges in productive, low-elevation forests are more susceptible to wind disturbance

Figure 3.14 Annual total area burned in Alaska, 1955-1996

(source: Alaska Fire Service)

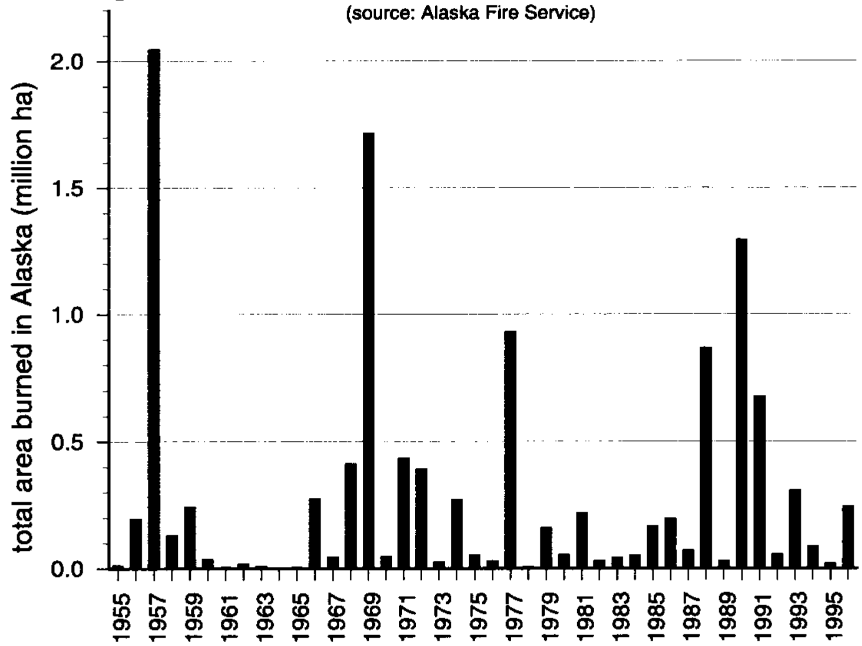
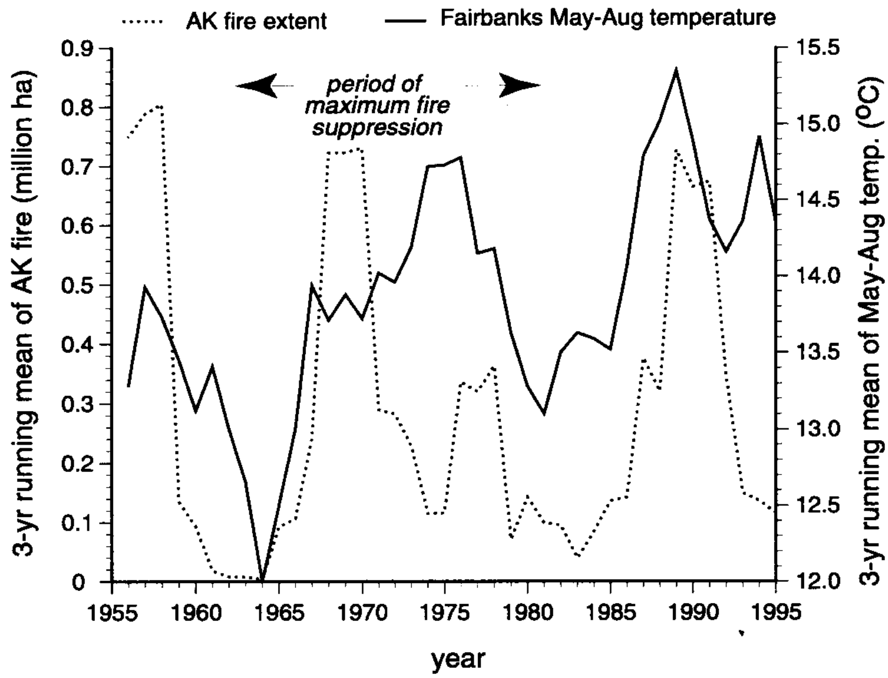


Figure 3.15 Relationship of mean summer temperature at Fairbanks and extent of area burned in Alaska



compared to trees in closed canopy forest. To date, a relationship between increased days with storm winds and increased formation of small forest canopy gaps or disturbance around the edges of cutting units has not been documented.

As climate warming occurs, insect populations that were previously restrained by marginal climatic conditions can increase rapidly (Fleming and Volney 1995). Insects can increase much more rapidly than the forest can respond, for example by adjusting the age or species distribution of trees. A transition period of increased tree mortality from insect outbreaks is a distinct probability in the Alaska coastal forest.

Most of the forest streams of coastal Alaska have short and steep watersheds resulting from the recent geologic uplift that characterizes most of the area. Precipitation has been so abundant and reliable that many streams with small watershed areas are important salmon producers or municipal or industrial water supplies. As the climate warms, the forest vegetation demands and moves more soil moisture into the atmosphere, reducing groundwater storage available for stream flows. An increase in the number of warm, dry weather intervals can make the problem acute.

Ultimately, a number of positive effects on the coastal forest could be associated with a warmer climate. These involve increased average tree growth and other forms of forest productivity, increased species diversity, and expansion of forest area following glacial retreat and colonization of tundra. These adjustments characteristically take some time, but the degree of intactness of the Alaska coastal forest ecosystem insures a high probability of success as long as the magnitude of change does not exceed the degree of adaptability of the organisms, especially of the vegetation. However, if the climate change is of such a magnitude as to require immigration of species not currently in or immediately adjacent to the region, then the survival challenge is considerably more severe. An increase of the mean annual temperature typical of Anchorage in the 20th century by the amount specified in Weller et al. (Chapter 2) would result in a climate that was no longer typical of boreal forest, but a transition type between boreal and temperate hardwood forest. The nearest source areas for propagules to establish such a vegetation type are located over half a continent away in the northcentral U.S. That would be far too distant to make (unassisted) any practical contribution to establishing elements of the temperate forest in Alaska.

The following potential changes in the Alaska coastal forest under the projected climate change scenarios are summarized according to confidence and degree of impact in Figure 3.16.

- Increased risk of widespread catastrophic windthrow, especially on outer coastal forest landscapes of southeast Alaska.
- More frequent, widespread, and damaging western black-headed budworm outbreaks causing damage to western hemlock.
- Increased windthrow damage of trees around the margin of clearcuts.
- Accelerated and expanded tree colonization of avalanche tracks and subalpine meadows and edges. Eventually, local limitations to Sitka black-tailed deer numbers will occur because of decreased summer subalpine meadow habitat in southern Alaska.

- Accelerated and more widespread tidewater and low elevation glacial retreat and forest and/or shrubland colonization at low elevations in southcentral Alaska. Widespread glacial retreat is followed by mountain hemlock treeline advance at moderate elevations in southeast Alaska.
- Continued and accelerating westward tree advance on the Alaska Peninsula and Kodiak Archipelago. Eventually western Alaska tree limit may be set by strong winds.
- Irregular northward expansion of the distributional limits of tree species currently confined to southernmost southeast Alaska, including western red cedar (*Thuja plicata*), subalpine fir (*Abies lasiocarpa*), Pacific silver fir (*Abies amabilis*), and red alder (*Alnus rubra*). Minor increases in elevation limits for these species will occur as well.
- Increased incidence and duration of warm temperature and/or low flow events in coastal forest streams causing anadromous fish mortality.
- Sustained high populations of Sitka black-tailed deer because of high winter survival resulting in local browse damage to tree regeneration.
- Continued low snow accumulations in most of low-elevation forested southeast Alaska resulting in reduced runoff and earlier peak flows in streams with low or moderate elevation headwaters.
- Continued gradual drying and subsequent oxidation of blanket peatlands accompanied by minor amounts of tree colonization.
- Continued heavy snow accumulations in much of moderate and high-elevation southcentral Alaska resulting in increased freshwater runoff in streams with moderate to high-elevation headwaters.
- Eventually, an increased risk of forest fire in southern southeast Alaska will develop where there is currently no fire history. Over the longer term the highly productive tree species Douglas fir (*Pseudotsuga menziesii*) would colonize such sites from current northern populations in north coastal British Columbia.
- Increased tree growth and average site productivity would be increased (previously non-commercial forest would meet the commercial threshold) as long as other factors, especially moisture, are not limiting. Higher elevation zones in the mountains might both warm sufficiently and experience sufficient precipitation to support these productive forest types.
- Appearance of new tree diseases, especially fungi, increase invasion in areas previously unaffected.
- Increased canopy gap formation from single tree and small group treefalls.
- Reduced abundance of shore pine as blanket peatlands (muskegs) and alpine habitats are reduced in extent.

4. Arctic Tundra

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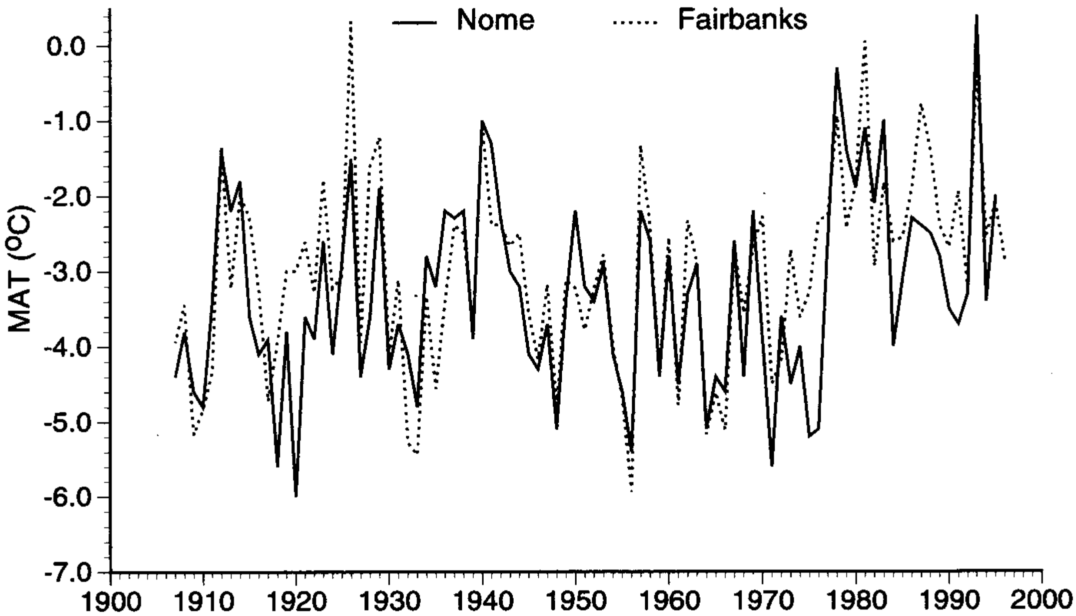
4.1 Introduction

Arctic tundra is made up of low growing lichens, shrubs, grasses, sedges, and other flowering plants adapted to a cold climate with a very short growing season. The arctic tundra region forms a belt around the polar regions of the northern hemisphere continents. Arctic tundra is a wildlife habitat of international significance, especially for caribou and migratory birds. The arctic tundra contains a large amount of stored carbon in frozen soils, but it has still not been determined whether the tundra is a source or a sink of atmospheric CO_2 now and under climate change scenarios. The Arctic tundra cannot shift northward with climate warming in Alaska, Canada, and Russia because it is bordered to the north by the Arctic Ocean, so it may be geographically squeezed under global warming scenarios. The arctic tundra contains major deposits of oil and natural gas that represent a significant portion of the national reserves of arctic nations. Petroleum construction, operations, and transportation take place in a sensitive tundra environment that itself will be affected by climate change. The most extensive land use in the arctic tundra is subsistence harvest of wildlife and secondarily of plants. Subsistence resources are major items in the daily diet of arctic residents, and the subsistence way of life is at the foundation of the identity, culture, and spiritual values of many arctic peoples. Some threatened and endangered species occur largely in the Arctic, but several migratory wildlife species of conservation concern find critical habitat in the Arctic.

4.2 Past effects of climate change

The Bering Straits region has attracted a great deal of interest from investigators of paleoclimates and paleoecology because of the area's role as a critical land interchange between North America and Eurasia and in the peopling of North America (Hopkins et al. 1982). The sequence of climate and vegetation events has been reconstructed from both coastal exposures and inland lake records which are discontinuous and sometimes difficult to cross match. Recent findings of intact plant communities which were buried under volcanic ash and lava flows offer exceptional new opportunities to reconstruct past environments on the Seward Peninsula. Sometime before 10,000 B.P. a transition occurred from herbaceous tundra to a dwarf birch tundra (Ager 1983). In the earliest stage of the transition, or prior to that, balsam poplar may have extended westward of current tree limits. Compared to other areas of Alaska, there is relatively little evidence of major vegetation response to climate change on the Seward Peninsula up to historic times. Nome was one of the major gold rush sites in the late 1890s, and continuous climate records are available for Nome from the earliest years of the 20th century. The 20th century record of mean annual temperature at Nome is nearly identical to Fairbanks (Figure 4.01), including most of the fine points of major cold and warm years. Fairbanks is boreal forest and Nome is in a tundra region, however, because summers are much cooler and winters warmer in Nome than in Fairbanks. These are optimum conditions for the development of productive tundra vegetation. In general, trees have been unable to grow or reproduce on the Seward Peninsula because of insufficient summer warmth, even though mean annual temperatures have been comparable to areas such as Fairbanks.

Figure 4.01 Nome and Fairbanks Mean Annual Temperatures, 1907-1995

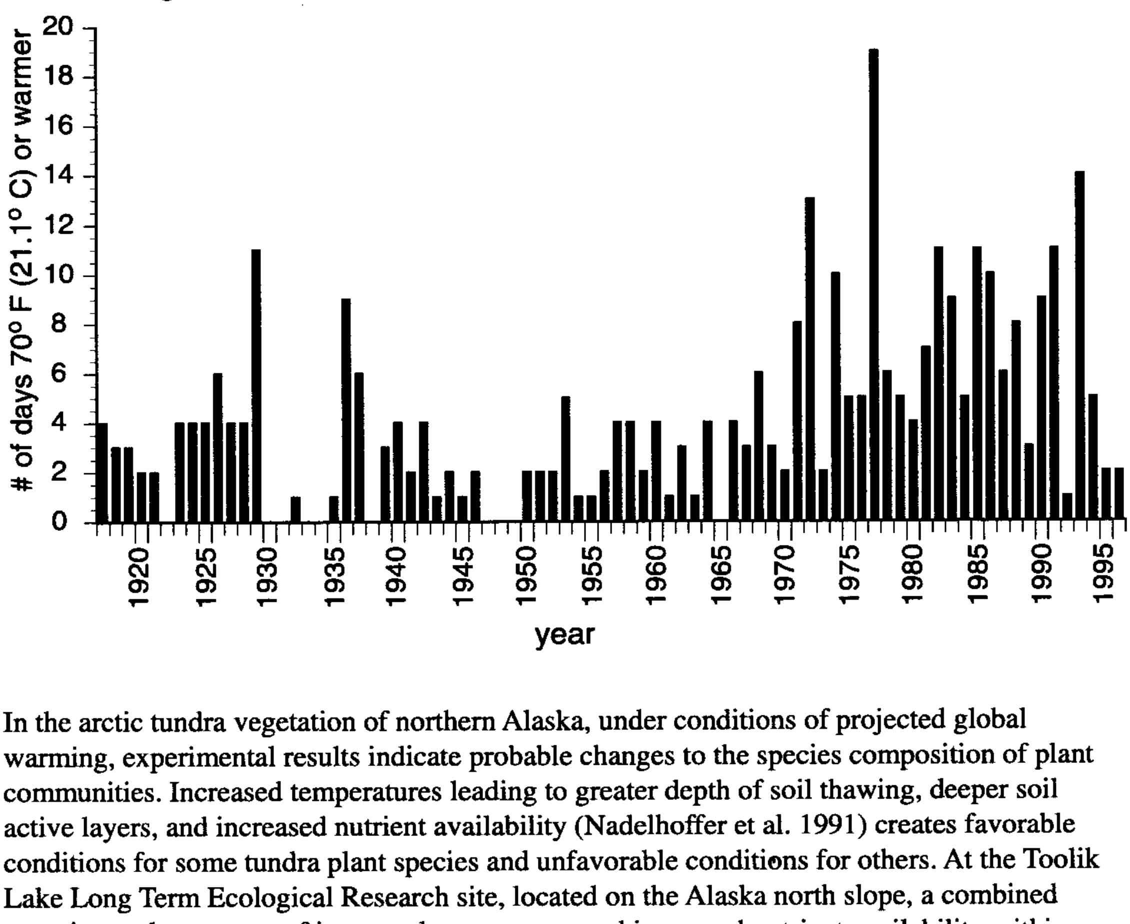


The tundra region is persistently cool and seldom experiences intense dry conditions during the short growing season but extreme warm and dry periods can occur, leading to large tundra fires (Racine 1979). During the past four decades, spring has arrived earlier and earlier in Alaska's arctic tundra. Data from Alaska's most northern weather station at Point Barrow indicate a trend toward earlier dates of snow disappearance and warmer temperatures during the spring months of May and June. Functionally, the warming trend appears to be associated with longer vegetation growing seasons, as evidenced by observed increases in the amplitude and timing of the seasonally cyclic atmospheric carbon dioxide concentrations measured at Point Barrow (Keeling et al. 1996). Similarly, historical satellite imagery indicates increased photosynthetic activity of arctic vegetation, suggesting increases in plant growth associated with the longer active growing seasons (Myneni et al. 1997). These relationships infer direct linkages between spring temperatures and phenological characteristics of vegetation growth in the arctic tundra. For example, the warmest spring in the May-June Point Barrow temperature record occurred in 1990. That year was accompanied by the earliest date of snow disappearance (14 May), a peak in the amplitude of annual carbon dioxide flux, and the highest June vegetation greenness index on the Alaska north slope as measured by satellite. The timing of snowmelt and the greening of vegetation is one of the most crucial factors in the health and survival of caribou, especially because it coincides with calving (Jorgenson and Udevitz 1992). The growth and condition of tundra vegetation is also strongly influenced by the timing of seasonal events (Shaver and Kummerow 1992).

4.3 Future changes

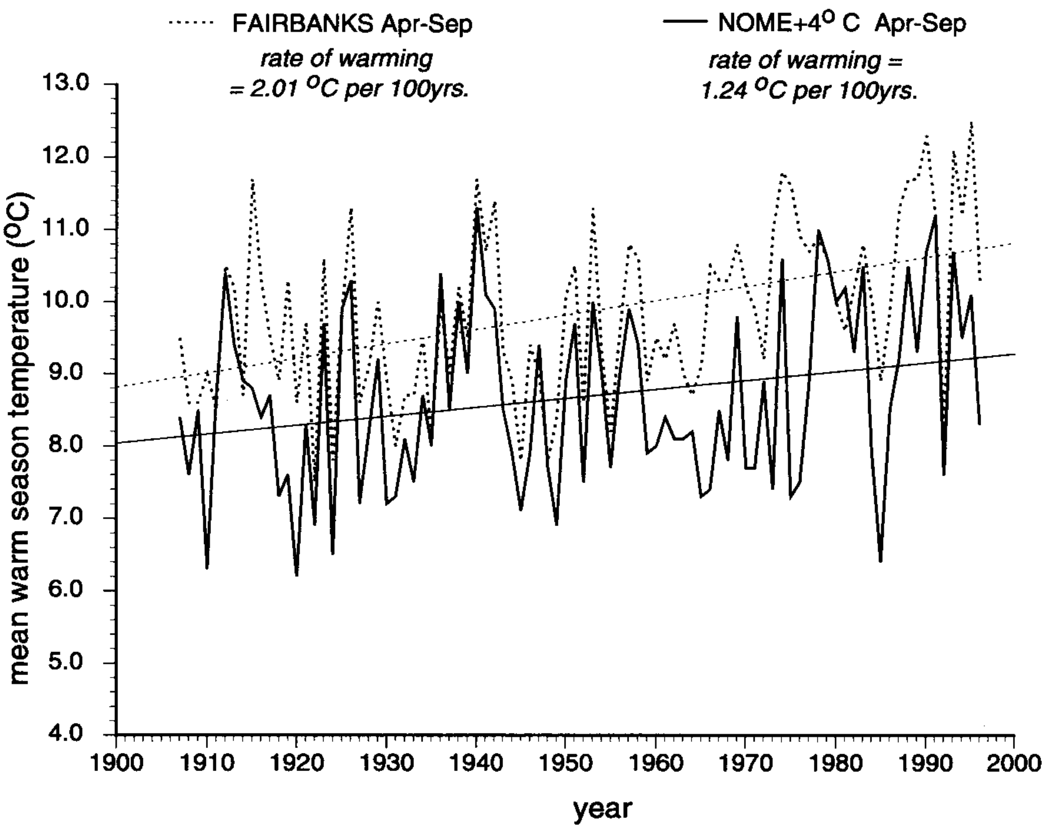
Forest vegetation currently occupies the base (eastern portion) of the Seward Peninsula, but further west where the summer atmosphere is cooled by the cold Bering Sea, trees are currently unable to grow. However, the number of the warmest summer days at Nome has increased dramatically in the last 20 years compared to the earlier 20th century (Figure 4.02). The number of warm days is beginning to approach the threshold that would permit tall shrub and trees to develop. Furthermore, Nome is a coastal station, and the effect of summer warming should be even more pronounced further inland. If summer temperatures of the 20th century in Nome were warmed by 4°C, the level of warming given in the scenario of Weller et al. (1995, Chapter 2), the summer climate at Nome would closely match that of Fairbanks (Figure 4.03). The Fairbanks area supports some of the most productive sites documented in the Alaska boreal forest. It is reasonable to infer, then, that well before Nome reached the level of Fairbanks summer warmth, (1) the existing tundra vegetation would be climatically stressed, (2) a significant risk of tundra fire would occur, and (3) tree invasion of the tundra would begin. Essentially, all but the highest elevations of the Seward Peninsula would support boreal forest. A greater frequency of winter ice storms would be likely as well.

Figure 4.02 Number of warm summer days at Nome, 1917-96



In the arctic tundra vegetation of northern Alaska, under conditions of projected global warming, experimental results indicate probable changes to the species composition of plant communities. Increased temperatures leading to greater depth of soil thawing, deeper soil active layers, and increased nutrient availability (Nadelhoffer et al. 1991) creates favorable conditions for some tundra plant species and unfavorable conditions for others. At the Toolik Lake Long Term Ecological Research site, located on the Alaska north slope, a combined experimental treatment of increased temperature and increased nutrient availability within a tussock-tundra community over a 9-year period resulted in a substantial decrease in the growth and biomass of cotton grass (Eriophorum vaginatum), a 90% increase in the total vascular biomass of a common dwarf-birch shrub species (Betula nana; Chapin and Shaver 1996), and a 30%-50% loss in species diversity, primarily in moss, lichen, and forb species (Chapin et al. 1995). This trend also agrees with historical pollen records that show decreased sedge abundance during warm periods of the Holocene (Ritchie and Cwynar 1982).

Figure 4.03 Comparison of actual Fairbanks summer temperatures and Nome summer temperatures warmed by 4 °C, 1907-1996



The primary expected or potential mid-term and long-term changes in arctic tundra due to global warming include:

- Higher rate and magnitude of temperature change compared to more southern latitudes.
- Warmer spring temperatures, earlier snowmelt, and longer growing seasons.
- Permafrost remaining dominant but with deeper soil active layers, increased available soil nitrogen, and increased decomposition of soil carbon.
- Increased dominance of shrubs, decreased abundance of grasses and sedges, and overall decrease in floral diversity.

- Southern areas of arctic tundra replaced by forest, including most of the Seward Peninsula.
- Loss of some shallow arctic tundra ponds and lakes.
- Increase in the frequency and extent of tundra fires, especially if warming is accompanied by summer drying.
- Changes in the abundance and/or distribution of wildlife species resulting from changes in the seasonal availability, quality, and/or distribution of tundra habitats.
- Changes in accessibility for subsistence users resulting from changes in snow and ice conditions on traditional travel routes.
- Changes in the environmental mitigation practices used by the petroleum industry resulting from changes in the dynamics and distributions of permafrost, ground water, and seasonal runoff.

4.4 Additional research needed

- Monitor the growth, development, and expansion of forests at the edge of the tundra on the Seward Peninsula.
- Monitor the expansion of shrub dominance on the north slope of Alaska.
- Document and monitor post fire recovery and recolonization of tundra habitats.
- Document changes to the seasonal availability and nutritional quality of forage species used by caribou, reindeer, and muskoxen.
- Document changes to the seasonal availability and quality of critical aquatic habitats used by fish and waterfowl populations.

4.5 Mitigation and adaptation measures

- Ensure adequate conservation and protection of the more northern arctic tundra habitats (include international cooperation with Canada and Russia) to accommodate refugia for plant and animal populations that become displaced northward as tree and shrub species expand into southern tundra regions.
- Implement fire suppression or fire prescription practices, depending on how various tundra habitats recolonize following fire (research need 4.4.3 above).

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5. Wildlife and Reindeer

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5.1 Introduction

Hunting and the consumption of wildlife are exceptionally important in Alaska. The Alaska Department of Fish and Game estimates that the average consumption of wild game by subsistence users in Alaska is 360 kg (800 lbs) per person per year. Hunting is a major activity for residents and visitors to Alaska, and the activities associated with hunting are a major source of income and economic activity. The pursuit and use of wildlife products is an important part of cultural identity for most of the Native people of the region.

Alaska is a major breeding destination for migratory birds, and Alaska sends birds to all the world's other continents. A significant proportion of world's birds use the Arctic. The Bering Sea region is a particularly productive part of the Earth's arctic region, and some of the species of animals found here do not occur elsewhere. Because Alaska has the greatest proportion of its surface area and productive resources devoted to strict nature conservation of any similar sized region in the world, it is the place where many large-bodied or wide-ranging species have their best chance of long-term survival on Earth. Alaska and the Bering Sea region are a bridge between two continents, and many wildlife species are exchanged between the continents only there.

5.2 Wildlife at Risk

Birds

The regional effects of global warming on the birdlife of Alaska are likely to be many, with influences both positive and negative on individual species, taxonomic groups, and communities. The task of predicting impacts on birds and other organisms of higher trophic status is difficult and necessarily speculative. The IPCC Scientific Assessment (Houghton et al. 1990) provides projections for change in the global and regional climate from enhanced greenhouse effect, and these have varying degrees of likelihood assigned to them dependent on model strengths and weaknesses that derive from the quality and availability of data. The first-order predictions are something in which we can be relatively confident; temperature and sea level would rise, precipitation and cloud cover would increase, growing season would lengthen, and land and sea ice would decrease both spatially and temporally. The second-order predictions about impacts to landscapes, ecosystems, communities, species, and populations are difficult to make because of our limited understanding of subjects from individual species biology through ecosystem functions. Even so, speculations can be useful in providing a framework for monitoring actual environmental change and as a way of identifying gaps in knowledge that may be vital to resolve in order to refine predictions and improve our environmental and resource decision-making.

Alaska supports relatively few winter resident bird species, especially in terrestrial ecosystems (Kessel and Gibson 1978). Much more important in terms of regional and global impact are the many migratory species that either breed in the state or pass through en route to and from their breeding grounds. All birds in Alaska would benefit to some degree from increased air temperature, as maintenance of constant body temperature is an important energetic expense, especially during nesting and the immediate post-hatch period (Myers and Lester 1992). Even marginal increases in average air temperature can lead to increased productivity through improved adult and juvenile survivorship. Additionally, lengthening of the snow-free season (Sharratt 1992) would increase production in species such as loons, swans, and raptors which take a relatively long time to reach the age of fledging. Events such as the early fall freeze-up in 1992, which led to high juvenile mortality of trumpeter swans (*Cygnus buccinator*, R. King, USFWS, personal communication), would probably become less common and/or less severe in a warmer climate. Re-nesting attempts would also be more likely to succeed with a longer growing season. Increases in precipitation are not likely to have much direct impact on birds unless they occurred as snowfall during the breeding season. Even a few degrees rise in summer temperature would not preclude the possibility of midsummer snowfall on Alaska's north slope and alpine areas. Increased frequency of storm events can have direct negative impacts that are more significant than the accumulation of minor long-term benefits of increased warmth. The lack of information about the wintering ecology of seabirds and waterfowl in the Bering Sea and Gulf of Alaska is of concern because storms may affect overwinter mortality, through both direct physiological stress and reduced food availability.

Major uncertainties remain in predictions of the magnitude and direction of climate change on wildlife as they may be controlled by community-level and ecosystem-level interactions. The patterns of plant growth and community composition will certainly change under increased temperature and carbon dioxide fertilization (Jefferies et al. 1991). Decomposition and nutrient fluxes will increase, but whether plants or soil microbes will be able to capitalize on the benefits of increased fluxes is unknown (Field et al. 1992). Grazers such as geese and swans may face reduced availability and quality of forage, as plants become nutrient limited in a carbon-rich environment and changes in plant-to-plant competition cause shifts in plant community structure. Insects, as cold-blooded herbivores, may be better able to track plant development, and their numbers may well increase to the benefit of avian insectivores (Ayres 1993). Most migratory birds use daylength cues for timing their northward movement, so that nest initiation and hatching correspond to peaks of food quality and availability. Earlier development of plants and insects relative to daylength may cause decreases in offspring survival as timing of hatching becomes uncoupled from resource availability (Myers and Lester 1992). All predictions about effects of climate change must be weighed against much less subtle anthropogenic degradations such as habitat loss, pollution, and unsustainable resource harvest (Paine 1993), both within Alaska and globally.

The expected direct effects of climate change on birds in Alaska are clear: temperature increases will generally increase survivorship through reduced exposure for adults and young during the nesting season, more benign winter temperatures will increase survival of overwintering species (Root 1993, Repasky 1991), and lengthening of the growing season will also lead to increased production, especially in those species, such as loons and swans, which have a long developmental vulnerability between hatch and fledging. Predictions of increased storm frequencies and intensities would tend to moderate the positive effects of warming and could lead to decreases in those species which are susceptible to catastrophic weather disruptions during the nesting season, migration, or in wintering aggregations. Second-order effects (influences modulated through food webs, changing nutrient availability, changes in whole plant communities, altered competition between species, and mutualisms), are generally much more difficult to predict. Such projections are derived through chains of deductive reasoning, which requires information on many aspects of the ecosystems' responses to climate change. Some of the needed inputs would include the seasonal quality and productivity of plants, seed set and fruiting, soil decomposition processes, insect population dynamics, freshwater and marine productivity and food webs, and predation pressure and sensitivity. Projections of such indirect effects require discussion on a case by case basis. It's useful to examine some major taxonomic groups and the community- and ecosystem-level changes that may affect them.

Loons: Warmer temperatures will mean increases in fresh water and nearshore marine primary productivity (Schindler et al. 1990). Increases in phytoplankton biomass will lead to increases in net productivity through the food web, including availability of small fish for freshwater birds that eat fish.

Seabirds: Much of the spring pulse of marine primary productivity in the Bering Sea appears tied to processes linked to warm currents and rapid retreat of the sea ice edge (Alexander 1992). Warming could lead to spatial and temporal unpredictability and dilution of this productivity event, with repercussions through the marine food web. Ocean surface warming trends in the North Sea are correlated with reduced production of phytoplankton, fish stocks, and seabirds (Aebischer et al. 1990).

Waterfowl: Along with a potential drop in forage quality and availability for the herbivorous members of this group, there may be long-term habitat degradation and losses with increases in sea level (especially in coastal western and northern Alaska where tectonic uplift of the land surface is much less rapid than in the southern parts of the state). Ducks would benefit from increases in numbers of insects and freshwater invertebrates.

Shorebirds: Increases in terrestrial and estuarine invertebrate food species would be likely in a warmer climate, but the increase could occur as a longer and lower amplitude period of food availability.

Raptors (birds of prey): A complex of trophic uncertainties makes it difficult to project secondary effects on top carnivores with any confidence, but general increases in ecosystem productivity should benefit raptors.

Passerines (songbirds): Insectivorous species will probably benefit from increases in insect production depending on the timing of food availability. Because plant fruiting and seed set would increase in a warmer climate, at least among plants not limited by nitrogen availability, fruit- and seed-eating birds would benefit.

Mammals

Small Mammals: Microtine rodents are an important part of many Alaskan land ecosystems. These animals account for more biomass and plant consumption per unit area on the tundra than any other vertebrate herbivore (Batzli et al. 1980). Even though caribou and waterfowl may be prominent herbivores in restricted locations and for comparatively short periods, microtines are active herbivores year round. Microtine rodents of the tundra show large periodic increases in population density (Krebs et al. 1973), and these increases affect the tundra environment by intense and destructive plant consumption (Batzli 1975) and increased densities of microtine predators (MacLean et al. 1974).

Most small mammals are active throughout the winter, consuming frozen green plant material in the space between the snow and ground surface. Sufficient snow depth to adequately insulate the subnivean space is crucial for the energetic balance, and therefore overwinter survival, of small mammals (Pruitt 1984). Decreases in snowfall would therefore negatively impact small mammal populations. Snow surface icing events also lead to increased mortality by causing CO_2 build-up (because this gas does not readily diffuse through ice). Recent results from studies on the North Slope show that experimental warming of tundra leads to increases in dwarf shrubs and decreases in formerly dominant grasses and sedges (Chapin and Shaver 1996). The decrease in grasses and sedges appears to be caused by increased grazing by microtine rodents, which benefit from increased shrub cover in avoiding avian predators (F.S. Chapin, personal communication).

Caribou: Caribou (*Rangifer tarandus*) are the dominant large herbivore of tundra ecosystems and an important economic and cultural resource of northern indigenous peoples. Accelerated climate-induced changes to the temporal availability, quality, and composition of forage resources will likely alter caribou distributions and population dynamics. Several potential effects of global warming can be individually projected, but the complexity of integrating these prevents us from making general conclusions about arctic caribou populations as a whole. Even without considering the long-term implications of landscape-level changes to the vegetative composition of the arctic tundra, global warming could impose both positive and negative effects on caribou populations in the near future.

Greater amounts of winter precipitation falling as snow would make winter foraging (cratering) more difficult, potentially reducing the carrying capacity of areas that caribou presently used as winter range. Warmer conditions could also increase the frequency of autumn or winter ice storms (freezing rain) which can effectively render forage plants unavailable and result in mass starvation. Warmer temperatures during summer could increase the frequency and intensity of harassment by biting insects, such as mosquitoes and warble flies, which diminishes the amount of time caribou can spend foraging, thereby potentially reducing body-fat reserves for over-winter survival. Finally, a warmer climate may create favorable conditions for invasion by exotic parasites or diseases.

Conversely, earlier snow melt and onset of the vegetation growing season would create improved foraging conditions for pregnant cows who are entering the energetically costly period of lactation. Increased quantity and quality of forage intake would allow a lactating cow to provide more energy and nutrients to growth of her calf, increasing calf weight gain and enhancing calf survival. Longer arctic growing seasons could also increase overall summer nutritional intake and increase the probability of cows attaining sufficient weight and fat reserves for subsequent conception and ultimate population growth of the herd. The integrated effects of global warming on caribou populations are expected to vary regionally, depending on future patterns of regional climate trends and anomalies which are poorly understood at this time, as well as the demographics and ecology of the respective regional herds. In the near future, global warming does not pose a threat of extinction to caribou, but the economic and cultural importance of the species requires a greater understanding of the direction, rate, and magnitude of future changes so that management of the species can be proactive.

Reindeer: Reindeer production is an important economic pursuit for Alaska Natives on the Seward Peninsula and has many desirable attributes as a sustainable resource production system. Reindeer grazing harvests natural vegetation efficiently without drastically modifying it. Markets for Alaska reindeer products are established and have expanded in recent years, although foreign competition has increased. Reindeer herding allows Alaska Natives a cash- and food-producing livelihood that uses many traditional skills and knowledge of the land.

Reindeer production in Alaska was reserved by law to Alaska Natives until a recent court decision and is concentrated almost exclusively on the Seward Peninsula, where reindeer have been tended for over a century. Reindeer herding on the Seward Peninsula has characteristics of both a subsistence activity and a modern animal product industry. The reindeer industry depends on natural, social, and economic factors for its existence, and a significant alteration in any one of these three factors may cause problems for the industry and the herding way of life.

The Seward Peninsula reindeer production system allows animals to range freely for most of the year, with annual roundups for harvest of antlers, herd census, culling, and veterinary attention. Reindeer numbers are known only approximately and vary over the short term, but in the mid-1990s the herd totaled about 20,000 animals on the Seward Peninsula. The tundra forage that supports reindeer was in excellent condition on the Seward Peninsula in the mid- and late 1990s.

Five recent or potential challenges to the health or survival of the industry are related to global change: (1) ice-coating of winter forage, (2) poor-quality forage in warm and dry summers, (3) caribou range expansion and capture of reindeer, (4) tundra fires, (5) forest expansion into tundra.

Ice-coating of winter forage:

During the winter, reindeer depend on access to range that is rich in lichens. The lichens provide almost exclusively carbohydrates as a source of energy to maintain body temperature in the winter. Reindeer can effectively paw through snow to reach lichens in the winter. Generally, temperatures are well below freezing in the fall when the first snow coats the Seward Peninsula, but occasionally in warmer years a freezing rain coats lichens and other tundra plants with a layer of ice. The ice cover makes forage critical to reindeer survival essentially unavailable for the entire winter. Such an event occurred on the Chukotka Peninsula in eastern Russia in the fall of 1996, leading to the death of thousands of reindeer. Freezing rain events are much more likely in a warming climate on the Seward Peninsula. Recent freezing rain/ice coating events occurred on Hagemeister and Nunivak Islands.

Poor-quality forage in warm and dry summers:

Reindeer obtain most of their annual budget of nitrogen, which is vital for protein replenishment to build muscle mass and skeletal tissue, during a short period in early summer. Reindeer get nitrogen from succulent early summer forage plants which mature slowly in the typically cool and moist weather of the Seward Peninsula summer. However, in years with warm and dry summer weather forage plants mature quickly and become fibrous with low nitrogen content. A diet of plants that are too fibrous nutritionally stresses reindeer and caribou because they are limited in when they can obtain their required nitrogen reserves. A succession of warm and dry summers will first severely stress reindeer nutritionally, and if warmer weather persists, cause displacement of palatable tundra forage species by indigestible shrubs and eventually trees. Sustained warmer summers would dry out the tundra and organic soils it grows on, leading to a greater risk of tundra fire. Lichens grow slowly and so are slow to recolonize burned areas.

Caribou range expansion and capture of reindeer:

Tens of thousands of wild caribou moved into wintering areas occupied by reindeer in the Kivalik and Buckland Valleys in the winter of 1996-97. Caribou are North American native members of the same species as reindeer. Once caribou and reindeer mix together a substantial portion of the reindeer may follow the caribou to their summer use areas far removed from the reindeer herding region. Reindeer that join caribou herds are essentially lost. Another undesirable consequence of the mixing is potential cross-breeding and the introduction of non-native genes into the Alaska wild populations.

Tundra fires:

Tundra is generally resistant to burning, but prolonged periods of above normal temperatures and below normal precipitation make the tundra capable of carrying fire across the landscape. Tundra vegetation, especially lichens, can be very slow to recover following fire. Lichens are the key vegetation for winter grazing by reindeer and caribou as a carbohydrate-rich source of energy. During the long recovery period following a fire in lichen-rich tundra, the carrying capacity for reindeer and caribou is considerably diminished.

During the summer of 1977 several lightning-caused fires burned across large areas of tundra on the Seward Peninsula (Racine 1979). One fire northeast of Imuruk Lake covered 96,000 ha (236,000 ac), and the total area burned was 359,000 ha (887,000 ac). Climate warming and drying on the Seward Peninsula would produce more frequent and prolonged conditions favorable for burning.

Forest expansion into tundra:

In Alaska the limit of tree growth is influenced to a large degree by mountains - the Brooks Range in the north effectively separates arctic tundra from boreal forest. Even significant amounts of climate warming would primarily result in relatively narrow bands of elevational expansion of forest vegetation. The Seward Peninsula is unusual in that it offers relatively modest topographic barriers to tree growth, and should the climate warm sufficiently, a considerable land surface area of tundra would be converted to forest. The current cool moist summer and relatively mild winter climate of the Seward Peninsula supports a relatively productive form of treeless tundra. A conversion of the Seward Peninsula from tundra to forest vegetation would result in dramatically decrease d production of palatable forage species for reindeer. Any significant expansion of forest into the productive tundra of the Seward Peninsula would represent a significant negative factor for reindeer production.

5.3 Future Changes

The major currently foreseeable changes in Alaska wildlife resources from projected climate warming include the following:

- A potential mismatch in the timing of important seasonal events such as spring snowmelt or the development of green vegetation and the arrival or movement of wildlife that depend on these critical events could significantly decrease wildlife productivity.
- Longer growing seasons would improve survival and productivity of some species.
- Changes in latitudinal species distributions would occur due to changes in habitat, generally involving northward movement, especially of mammals.
- Changes in insect numbers, including increased insect harassment of large animals such as caribou and possible appearance of ticks, could lead to new problems for important harvested species.
- Potential changes in migration routes might occur.
- Extreme weather events, such as storms and droughts, would become more common, often reducing wildlife productivity on a short-term basis.
- In Alaska forests, increased insect damage to trees and logging would reduce the extent of older forest habitats and cause population declines of wildlife that depend on them.
- An increase in the extent of productive early successional habitat and wildlife that can use would follow after extensive disturbance of forest and other vegetation by insects and fire.
- Warmer climates would cause upward movement in elevational distribution of vegetation and wildlife, leading to increased competition or local extinction of a few high elevation species.
- Extensive thawing of discontinuous permafrost accompanied by ground subsidence would increase the extent of wetland habitat.
- A change in the composition of boreal forest, resulting in decreased extent of spruce and increased total area of aspen and other hardwoods, would favor certain birds and browsing mammals and reduce birds, flying squirrels, and other species that depend on or are favored by conifer forests.
- A warmer climate would probably allow the spread of diseases, especially diseases of domestic animals, that currently do not occur in Alaska.

Any changes to wildlife caused by climate change must be understood against the backdrop of human natural resource management practices, such as hunting or forest management, that are often the major influence on wildlife productivity and distribution. Wildlife responses are a product of both climate variability and human resource practices. Particularly acute situations caused by either climate or human influences can increase wildlife sensitivity to the other. For example, a wildlife population at a low level because of heavy human consumption may be less able to persist or remain productive under the stress of an altered climate. Similarly, a wildlife population that has been reduced because of climate variability may not be able to withstand the same degree of habitat modification as if it were healthy.

Because global warming models based on greenhouse gases indicate that the earliest effects and the greatest rate and magnitude of temperature change is expected in Alaska compared to the rest of the United States, Alaska's wildlife may face special challenges. But two factors suggest that the prospects for wildlife in Alaska are good in the long term. First, Alaska has a history of abrupt changes in temperature, so a certain degree of adaptability of the wildlife and ecosystems is probably present as a result of these past events. Second, intactness of ecosystems is thought to provide a certain amount of resilience and recovery potential, so the fact that a larger proportion of Alaska is conserved in national-level reserves than anywhere else in the world provides some of the most effective mitigation of climate change effects to be found anywhere.

In summary, this report provides a limited overview of some possible repercussions of regional warming for Alaska terrestrial birds and mammals. Several of the above speculations about climate change effects are debatable, and they should not be regarded as predictions but rather as working hypotheses, best resolved with increased study and successive refinements in our knowledge of northern ecosystems. While overall prospects for Alaska's wildlife are good, local wildlife problems could easily become serious, both for people who wish to harvest or simply view Alaska's wildlife, and for the health of affected wildlife populations themselves.

5.4 Additional research needed

- Establish quantified linkages among regional-scale climate, vegetation phenology, forage quality, and caribou population dynamics.
- Monitor latitudinal incidences of ungulate diseases and parasites.
- Study the interaction of caribou and reindeer including factors that attract caribou into reindeer ranges and behavioral factors that combine or segregate reindeer and caribou.
- Study reindeer management and herding practices that are effective in sustaining herds in the face of climate change.

5.5 Mitigation and adaptation measures

- Put in place integrated wildlife monitoring programs that will provide the earliest possible warning of major changes in the status of wildlife populations so that short- and long-term management measures can be developed or applied and unnecessary stresses from human influences can be avoided.
- Adjust either wildland fire suppression or prescribed fire to reflect wildlife habitat needs on a regional basis in the light of altered climates.
- Develop a set of adaptive sport-harvest and subsistence management plans that accommodate a variety of potential climate-induced changes to caribou distributions and abundance.

- Develop an effective policy for caribou management on the border of reindeer grazing zones.
- Develop an emergency response plan to move reindeer from areas affected by ice coated vegetation to ice-free areas and/or emergency herd reduction or salvage measures in climatic emergencies.
- Develop better reindeer storage and handling infrastructure.
- Apply range management practices that favor tundra and retard shrub and tree development, especially on the eastern Seward Peninsula reindeer grazing regions.

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6. Human Land Use and Management

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6.1 Introduction

Human land uses in Alaska change ecosystems which are currently or soon could be affected by climate change. At the same time human uses of the land are affected by climate variation. In Alaska, humans use land at all scales and levels of intensity. Alaska is one of the world's notable tourist destinations; tourism is the 3rd largest sector in generating economic activity in Alaska according to some measures. The subsistence way of life, as it is practiced in some parts of Alaska, is rare in the world. Certain elements of subsistence are legal rights. The practice of subsistence is important to the world's heritage of native cultures. Alaska forest products are locally economically important and fill certain unique world needs. Forest management in its broad sense intimately affects other resources, such as fish and wildlife, through activities such as fire management, access roads, timber cutting, and other activities. Alaska supports a slowly expanding agriculture, including some unique subarctic products, and Alaska is one of the few places in the world where agricultural potential would increase under global warming.

Agricultural resources and practices:

About 30,000 acres of land in Alaska are currently in agricultural production, excluding grazing lands. Of that, 10% is located on the Kenai Peninsula, 35% in the Matanuska Valley, and 55% in the Tanana Valley. Principal crops in descending order of acres planted are: grass hay, barley, oats, potatoes, lettuce, carrots, cabbage, and other vegetables. All of these crops are grown in the Matanuska and Tanana Valleys, but grass hay and potatoes are the only commercial crops grown on the Kenai Peninsula. Yields of the main crops are: grass hay = 1.2 tons per acre, barley = 50 bu. per acre, oats = 54 bu. per acre, and potatoes = 21.5 tons per acre.

In addition to farmed land there are about 185,000 acres of pasture for cattle and horses. Reindeer grazing uses over 12,000,000 acres of land for 30,000 reindeer. Most of the herds are located on the Seward Peninsula with some located on Nuniviak Island and the Aleutian Islands. There are a total of 10,500 head of cattle in the state, of which 700 are dairy cows and the rest beef animals. There are 1200 sheep, 2000 hogs, and about 4000 chickens. The numbers of beef and hogs have tended to increase over the last few years while dairy cattle and sheep numbers have decreased. Reindeer numbers have increased in the last few years, but are far below the maximum numbers of the past.

The amount of land under cultivation in Alaska has increased steadily the over the last three decades with the exception of the early 1980's. During the early 1980's the state government encouraged clearing and planting of new lands in the Tanana and Matanuska valleys. This resulted in a short boom period for agriculture followed by a sharp decline. Aside from the short boom and bust period of the early 80's, there has been a steady increase in agricultural production, but at a slower pace compared to the increase in population.

The Kenai Peninsula and the Matanuska Valley are located south of the Alaska Range mountains. In that area the climate is tempered by the proximity to the ocean. As a result, summers are cool and winters are not as cold as in interior Alaska. The Tanana Valley is located in the interior of the state and has a continental climate, with warm summers and very cold winters. Growing seasons are shorter in Interior Alaska, but a greater number of heat units are experienced than in the coastal regions. Table 6.1 shows some of these different climatic characteristics of the different agricultural regions of Alaska.

Table 6.1. Climatological data for principal agricultural locations in Alaska (20 year averages).

Location	Precipitation in		Growing Degree Days (40°F)	Frost free days
	Total	Summer		
Tanana Valley				
Fairbanks	12.22	7.59	2138	95
Big Delta	12.18	9.58	2001	101
Clearwater	15.98	10.20	1708	55
Matanuska Valley				
Palmer	15.60	9.49	1938	124
Kenai Peninsula				
Kenai	18.63	10.12	1520	122

Recreation and tourism:

Recreation and tourism may be affected both positively and negatively by anticipated climate change scenarios in Alaska. Recreation and tourism are important to the Alaska/Bering Sea Region because they are an important sector of the economy. Tourism and recreation rank fourth in overall importance to Alaska's economy behind oil and gas production, government services, and commercial fishing (Neil Fried, personal communication.) Scenic resources and abundant fish and wildlife attract visitors to Alaska from around the world, particularly from the rest of the United States. Alaska contains numerous spectacular mountains including the highest mountain in North America, over half the land area in the U.S. National Park System, over 90% of the land area designated as National Wildlife Refuges, 25 designated Wild and

Scenic rivers, most of the nation's mountain and tidewater glaciers, over half the nation's coastline, and an abundance of marine and terrestrial wildlife. We hypothesize that climate warming and changes in precipitation patterns would generally result in increased recreation and tourism, particularly if infrastructures are built and maintained. Some localized and periodic reductions to recreation and tourism could result from catastrophic events such as floods, earthquakes, or other major events.

In many ways potential climate change impacts to recreation and tourism are a social/cultural consideration that may cross over into several other assessment headings. Changes in recreation and tourism also relate closely to climate effects to infrastructure and the coastal zone. Transportation systems, such as highways, trails, railways, bridges, airports, ships, and ports, and buildings, such as hotels, lodges, and visitor centers, must be constructed and maintained for tourism and recreational activities to flourish. Coastal zones are very important because the majority of recreational and leisure activities occur in these areas. Increases in tourism and recreation are also largely a result of marketing regional opportunities and settings.

6.2 Past effects of climate change

The decades of the 1980's and 1990's have been the warmest on record worldwide (Jones and Briffa 1992). The major agricultural areas of Alaska are generally located in the same regions that have experienced the long-term warming trend described in Chapter 3 of this report. Despite some cool summers, cumulative growing degree days in both the Matanuska and Tanana Valleys have increased noticeably. A regression of growing degree days against years shows an average increase of 24 and 40 growing degree days per year, in the two regions respectively. The number of frost-free days (days above 0°C [32°F]) have increased at all locations except Big Delta. Total annual precipitation has also increased, although primarily during the winter. Some stations have experienced slight increases in summer precipitation, while others have had slight to moderate decreases.

A comparison of grain yields from variety trials conducted by Dr. F. Wooding (1978) at Fairbanks and near Delta Junction found that, in years of adequate moisture, maximum yields were obtained when more than 1,750 growing degree days accumulated. Below that, yields dropped substantially. Variations in number of frost-free days and summer precipitation did not coincide with variations in yields. However, Sharratt (1992) calculated that more moisture was transpired from crops and evaporated from soil than normally fell as precipitation in the summer at the same interior Alaska locations. He found that grain crops largely made up the summer moisture deficit by using stored soil water, and barley yields increased in response to supplemental irrigation.

The more recent findings indicate that summer rainfall in much of Interior Alaska is currently marginal at best, and additional heat units may cause water stress on barley and other small grains. Potato yields were reduced at Delta Junction in years with high heat units, even when summer rainfall was normal. Comparison of potato yields with and without irrigation at Palmer shows that potatoes at that location need irrigation to reach maximum yields. Water is evidently currently marginal or deficient during the summer at most agricultural sites in Alaska, and unless increased summer temperatures are accompanied by additional precipitation, yields of non-irrigated potatoes and small grains will decline.

The Alaska Division of Tourism in the Alaska Department of Commerce and Economic Development supports the Alaska Visitor Statistics Program (AVSP). The Alaska Visitor Arrivals reports contracted to the McDowell Group show marked increases in visitation to Alaska between 1987 and 1995. The total number of people arriving in Alaska by aircraft, vessel, or vehicle during the summer of 1987 (June through September) was 705,886; the total in the summer of 1995 (May through September) was 1,357,894, almost double in less than 10 years. About 70% of all arrivals each summer are non-residents. In recent years the greatest increases in visitation have occurred in May, June and September. Visitor arrivals have dropped during fall and winter, particularly fall. (See AVSP tables and reports.)

Within the last decade increases have occurred in all three major modes of arrival to Alaska, domestic aircraft, cruise ship, and highway vehicle. Arrivals by domestic aircraft increased 90% from 402,075 in 1987 to 763,554 in 1995. Arrivals by cruise ship increased 74% from 163,469 in 1987 to 285,093 in 1995. Arrivals by highway increased 148% from 73,451 in 1987 to 182,212 in 1995. Though the greatest percentage change was by vehicle over the Alaska Highway, the greatest increase in numbers was by aircraft (AVSP reports). Over 300 cruise ships dock in Juneau now, and over 100 cruise ships dock in Seward.

The most popular recreational activity in Alaska is sport fishing. Recently the number of non-resident fishing licenses surpassed the number of resident fishing licenses.

Visitation to Alaska is limited somewhat because of the state's remote location. Families generally cannot afford to visit Alaska except during the summer season when school is out. Many groups save for several years before making the expensive trip to Alaska. As national demographics change with an increasing percentage of retirees, visitation to Alaska during the "shoulder months" could increase because of the sheer pressures to access the region. Some service sectors are marketing Elderhostel programs in the "shoulder season". Numerous tour companies are opening for business earlier in the visitor season or remaining available all year. For example, tour boat companies out of Seward are staying available year round, and they are actively marketing the gray whale migration in March and April. Some cruise ship companies are sailing to Southeast Alaska as early as April and as late as October 1.

6.3 Future Changes

Agriculture

An extension of the regression line out to project growing degree days for the next decade illustrates what would happen if the current trend continues. By the year 2000 the average growing degree days for a year could exceed 2600 in Alaska's interior, and reach 2300 in the Matanuska Valley. An increase of heat units of this magnitude would certainly allow a greater window in time for planting and harvesting crops which are currently grown in these areas and would make it possible to raise crops which are now marginal because they normally fail to fully mature. However, supplemental irrigation would probably be required in most areas.

Recreation and tourism

Given the climate change scenarios described by Weller et al. (Chapter 2) and by John Walsh (personal communication), the existing trends over the last decade (showing an increase in visitation to Alaska during the summer "shoulder months") are likely to continue at an accelerated rate. A longer snow free season and the expected warmer and drier spring seasons are likely to lead to increased tourism and recreational activities in the spring "shoulder season", particularly in May. The increase in precipitation as rain and the potential for increased extreme weather events in fall are likely to retard increases in tourism and recreational activities in late September, October, and November. Some "shoulder season" increase in visitation during September may continue as observed in recent years. Increases in precipitation as snow at higher elevations may attract more early season winter enthusiasts such as skiers and snowmachiners, but long dark and cold days during the heart of winter will probably deter large increases in visitation to Alaska. Changes in summer tourism and recreational patterns are likely to be affected more by marketing and changes to infrastructure than to actual or perceived changes in climate. Some visitors may be attracted to cool, coastal Alaska as a respite from increasing hotter conditions outside of the region. Also, as the public learns that Alaska is warming faster than temperate and equatorial zones, the general perception of Alaska as an icebox may melt away.

The demand for more services during shoulder seasons will likely increase. Existing services will have to extend seasons or new businesses will need to develop to serve tourists during this time. The tourism industry will push for earlier openings of visitor centers and other destinations. Accommodating such requests and pressures during a period of declining operating budgets will strain public agencies. In some cases the expansion of the visitor season is limited by management decisions. In other words the climate and conditions may be conducive to visitation, but area land managers limit shoulder season activity because of fish and wildlife sensitivity or limited budgets.

Much of the tourism and recreational activities in south coastal Alaska are marine oriented. Rising oceans could result in completely new shorelines. Places that are currently dry uplands could become submerged or seasonally and diurnally affected by tides. With limited shallow-angle shores in south coastal Alaska, users may be forced to concentrate land-based activities on less suitable areas. Increases in precipitation and violent weather events, coupled with increased use levels may result in increased search and rescue responsibility for state and federal agencies. Floods such as recent 100-year events sustained in southcentral Alaska, could interrupt or prevent recreational activities and tourism until facilities are reconstructed. As an example, numerous roads, campgrounds, bridges, and trails were damaged or washed out by the September 1995 flood in southcentral Alaska.

Although glaciers are retreating in general, they will remain a major attraction in the foreseeable future. The current retreat of some of the most popular glaciers like Portage and Mendenhall Glaciers, however, may alter visitor travel patterns. Agencies and tourism businesses will need to respond to these changes and restructure their services or infrastructure. For example, Chugach National Forest now provides a concession-operated tour boat on Portage Lake to enable visitors to see Portage Glacier as it retreats out of view from the visitor center.

Another major attraction for visitors is wildlife. Although not fully understood, global change affects fish and wildlife populations. Warming of the oceans and ocean current shifts could affect fish and marine wildlife distributions and abundance. Similarly, substantial warming and impacts to upland vegetation patterns could alter terrestrial wildlife habitat. Replacement of open tundra and alpine vegetation with shrub or forest cover could reduce viewing opportunities of wildlife. These changes could affect visitor destinations

As a winter destination, Alaska will become more attractive with increased snowfall and warmer temperatures. Tourism providers will seek to market and develop more winter recreational opportunities such as skiing, snowmachining, dog mushing, guided backcountry skiing, and helicopter-skiing, especially during early and late winter. Increased conflicts between different user groups and between residents and visitors will likely occur.

Summary of Expected Changes

Agricultural sector: Longer, warmer growing season improves agriculture potential; irrigation may be required to obtain the potential benefit to crops of warmer conditions

Tourism sector:

- A longer summer tourist season, generating more revenue and activity but greater impacts to resources, would occur in Alaska.
- Local disruption to visitors would occur due to changing features (glacial retreat, large-scale forest death) and weather extremes (storms, smoke from forest fires, etc.).
- Milder winters and decreased options elsewhere in the world will have a positive effect on winter sports in Alaska.

6.4 Uncertainties

At this juncture we are uncertain how great the effect of climate change would be on recreation and tourism in the Alaska Region beyond the direct human effects from improved access, an enlarged and diversified service infrastructure, and marketing. If climate change proceeds as expected, the changes are likely to be positive in general to tourism and recreation. The climate changes are likely to support the expansion of the visitor "shoulder season" rather than drive it. We suspect that negative impacts to recreation and tourism would be short-term and localized. We do not know how climate change will affect infrastructure like roads, railways, ports, and structures upon which tourism and recreation depend.

6.5 Additional research and monitoring needed

- Develop an information database on new agricultural pest species (including control measures) that would likely thrive in a warmer Alaska climate.
- Identify new crops that would be suitable for production in a warmer Alaskan climate. Identify any special measures needed to adapt them to high latitude production or cultivation in Alaska conditions.
- Identify new visitor pattern and markets that would be possible as the result of warmer climates both in Alaska and at points of tourist origin.
- Develop reliable statistics on tourists, including points of origin, visitor interests, knowledge of Alaska attractions, visitor plans, repeat visit potential, modes of travel, and economic impact.

The Alaska Division of Tourism has recently experienced significant budget reductions. As a result, the Alaska Visitor Statistics Program has been all but eliminated in recent years. These surveys should not only be continued to monitor trends in tourism and recreation, but additional research questions need to be included that ascertain whether existing climatic conditions and expected changes in climate affect people's decisions to visit Alaska.

It would be useful also for the state of Alaska to determine how well prospective visitors understand Alaska's general weather patterns and the effects of climate change on Alaska's environment. In other words, a social research tool could also be used as a public education tool.

Additional climate stations should and could be established around the state where people tend to visit. Also, ecosystems in key locations should be monitored for vegetative and habitat changes. A cross-section of ecosystems in the state from Southeast Alaska to Northwest Alaska should be monitored. Representative locations would include the southern part of the Alaska Panhandle, the northern part of the panhandle such as the Glacier Bay Ecosystem Initiative area, the Prince William Sound-Copper River Ecosystem Initiative area, Denali National Park, the Fairbanks/Poker Flats Research Area, and Noatak National Preserve in northwest Alaska. Most of these locations have ongoing or historic ecosystem monitoring programs.

6.6 Mitigation and Adaptation Measures

- Develop irrigation facilities in Alaska agricultural regions. Anticipate and resolve issues in water resource law
- Form partnerships with agricultural producers, marketers, and customers who currently produce and consume crops that could be produced in a warmer Alaskan climate. Develop and share expertise to handle these crops.

The primary means to mitigate potential adverse affects of climate change to the tourism and recreation industry in Alaska is through public education and proper design and location of transportation and visitor accommodations. The visiting public needs to become aware of the potential changes in Alaska's environment as a result of expected climate change. Roads and structures used by visitors should be located off sites with discontinuous permafrost and away from flood plains and wetlands. Infrastructure that is adversely affected by climate change factors should be rapidly repaired or replaced, or Alaska will acquire a reputation as a poorly maintained state with deteriorating, unsafe facilities.

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7. Marine Biological Resources

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7.1 Introduction

The fisheries of the Bering Sea region are among the most productive in the world (Tables 7.1, 7.2, 7.3, and 7.4). Over 28% of recent world total landings of fish, mollusks, and crustaceans have been harvested from the extended region (North Pacific Ocean, Bering Sea, Sea of Okhotsk, Chukchi Sea, and Gulf of Alaska). These fisheries support a variety of seabird and marine mammal populations and an array of commercial, subsistence, and recreation harvest effort. The ex-vessel value of Alaska's commercial fisheries alone exceeded $1.4 billion in 1995 (NPFMC 1996a). Processing contributes additional value to the fisheries sector. In addition to highly productive marine fisheries, the region includes extensive freshwater systems with important fisheries.

The marine and freshwater resources of the region have been used for subsistence for thousands of years. Whales, seals, sea lions, walrus, sea cows, various seabirds, Pacific salmon, Pacific halibut, Pacific herring, whitefish, pike, and burbot figured prominently in the pre-contact diets of native peoples. The initial commercial activities in the region focused on the harvest of fur seals and other pinnipeds, sea otters, and baleen whales. Incidental harvests of sea cows led to their extinction in the mid-19th century. The commercial fisheries for Pacific cod, Pacific salmon, Pacific herring, and Pacific halibut developed in the late 1800's. Large-scale harvest of most other region groundfish stocks did not begin until after the Second World War.

The productivity and sustainability of fisheries in this region is controlled by the interplay of biological, oceanographic, hydrological, and human processes. For example:

- the stock levels of any given species are affected by changes in primary productivity, inter-specific competition for resources, complex predator-prey relationships, and reproductive success;
- 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;

Table 7.1. Eastern Bering Sea (US EEZ) catches (1,000t).

	Pollock	Cod	Flatfish	Rockfish	Sablefish	Atka Mackerel	Herring	Halibut	Salmon (Total)	King Crab	Tanner Crab	Snow Crab
1970	1,256.6	70.4	230.8	76.8	13.0	1.0			157.8	3.9	0.5	
1971	1,743.8	45.1	313.6	31.6	18.0				117.4	5.9	0.1	
1972	1,874.5	43.3	216.8	38.9	16.3	6.0			78.0	9.9	0.0	
1973	1,758.9	54.4	198.9	15.5	8.9	2.0			65.6	12.2	0.1	
1974	1,588.4	63.8	182.1	36.4	6.7	1.0			61.3	19.2	2.3	
1975	1,356.7	54.4	174.4	25.2	4.5	13.0			63.5	23.3	3.2	
1976	1,177.8	54.7	159.8	28.9	4.6	13.0			111.8	29.1	10.2	
1977	986.0	36.6	113.7	14.1	4.6	21.0		0.6	139.8	31.8	23.4	
1978	985.7	45.8	211.3	11.0	2.0	24.0		0.6	177.1	39.8	30.3	0.8
1979	923.4	39.4	174.8	13.8	2.2	23.3		0.6	199.6	49.0	19.3	14.6
1980	1,016.4	52.0	180.0	7.0	2.0	16.0	21.6		232.5	68.3	17.1	18.0
1981	1,029.0	62.0	194.0	6.0	3.0	17.0	17.7	0.5	278.2	18.0	14.1	24.0
1982	1,013.9	57.0	184.0	3.0	4.0	20.0	24.9	0.7	255.3	4.6	5.6	13.4
1983	1,041.4	93.0	201.0	2.0	3.0	12.0	30.8	2.0	282.4	1.3	2.8	11.9
1984	1,180.6	133.0	236.0	2.0	3.0	36.0	22.9	1.4	300.5	2.7	0.7	12.2
1985	1,237.5	145.0	321.0	1.0	4.0	38.0	30.2	2.0	304.4	2.5	1.6	30.0
1986	1,235.1	141.0	302.0	1.0	7.0	32.0	23.7	2.7	277.0	5.7	0.1	44.5
1987	1,266.3	158.0	261.0	3.0	8.0	30.0	20.5	3.3	231.2	6.3	0.1	46.3
1988	1,271.0	198.0	396.0	4.0	7.0	22.0	20.1	2.2	243.0	4.2	1.2	60.9
1989	1,386.0	169.0	254.0	6.0	5.0	15.0	17.8	2.3	317.4	5.3	3.3	68.0
1990	1,426.0	171.0	162.0	21.0	4.0	22.0	20.3	2.6	314.4	9.7	29.4	73.5
1991	1,346.5	172.0	199.0	8.0	3.0	22.0	20.3	3.0	331.5	8.3	14.5	149.4
1992	1,438.4	206.0	248.0	18.0	2.0	47.0	26.0	3.1	312.6	4.2	16.0	143.3
1993	1,358.8	167.0	216.0	18.0	3.0	66.0	22.8	3.0	384.5	7.1	8.0	104.9
1994	1,421.4	197.0	262.0	20.0	2.0	69.0	30.7	2.6	393.7	0.2	4.1	68.1
1995	1,329.5	233.0	231.0	17.0	2.0	81.0	35.5	2.2	451.9	0.2	2.8	34.2
1996	1,218.2						32.5	2.5	409.1	3.9	0.9	29.9

Table 7.2. Western Bering Sea (Russian EEZ) catches 1,000t).

	Pollock	Pacific Cod	Flatfish	Rockfish	Saffron Cod	Herring	Halibut	Salmon	Crabs
1970	34.7	9.0	29.1		6.8			14.2	7.2
1971	18.9	6.5	11.6		2.7	4.7	0.3	20.9	2.7
1972	422.1	10.5	17.5		9.5	0.3		9.0	3.1
1973	364.9	21.0	10.2		9.5	0.0	0.1	13.0	
1974	427.0	17.4	9.9		13.4			17.7	
1975	265.2	7.3	7.8		1.7			26.1	2.0
1976	551.6	9.8	6.0	0.3	1.5			18.9	
1977	394.0	5.8	7.5		5.9	25.0	0.1	5.9	
1978	481.6	7.0	17.4	0.2	13.9	8.9	3.2	18.7	
1979	615.5	3.7	8.5	0.6	9.3	13.9	4.2	55.6	0.9
1980	928.0	14.2	20.8	1.2	14.0	12.8	0.3	14.8	0.8
1981	890.9	33.1	10.6	1.8	13.4	14.9	6.6	55.5	2.0
1982	1,019.1	62.2	12.0	0.5	12.9	12.9	2.9	18.8	3.0
1983	971.0	63.6	17.2	0.1	15.4	16.3	2.0	47.6	3.5
1984	785.9	97.5	8.0	0.1	16.1	17.4	2.6	29.4	3.2
1985	712.8	94.9	33.5	0.0	10.3	31.3	2.9	38.4	3.2
1986	936.7	117.7	39.9	0.0	8.9	21.0	5.0	24.1	4.8
1987	1,108.3	72.4	24.0	0.2	9.6	20.2	4.4	52.4	3.2
1988	1,291.7	70.3	27.9	1.0	10.5	15.3	2.5	21.8	5.8
1989	1,213.8	62.0	24.0	0.0	9.8	9.5	2.8	65.5	4.5
1990	928.4	89.2	26.8	0.1	15.2	16.3	3.0	16.5	4.3
1991	631.5	61.8	29.0	0.0	7.5	12.2	1.5	96.1	3.9
1992	702.7	110.0	25.5	0.0	13.5	2.4	1.4	29.9	0.6
1993	768.8	62.1	11.4	1.1	5.2	2.0	0.3	59.1	1.4
1994	369.3								
1995	407.1								
1996	510.5								

Table 7.3. Eastern Bering Sea (US EEZ) biomass estimates (1,000t).

	Pollock	Cod	Flatfish	Rockfish	Sablefish	Atka Mackerel	Halibut
1980	6,660	636	4,149	142	73	848	35
1981	10,820	1,058	4,595	142	82	982	35
1982	11,470	1,393	4,987	139	90	830	36
1983	12,280	1,608	5,290	141	121	747	37
1984	11,810	1,638	5,545	154	143	640	38
1985	14,330	1,577	5,406	192	166	551	41
1986	13,540	1,538	5,662	232	166	516	42
1987	13,990	1,496	5,914	270	135	599	43
1988	12,900	1,466	6,378	277	98	700	45
1989	10,880	1,339	6,340	294	131	866	49
1990	8,670	1,220	6,642	349	86	836	53
1991	7,030	1,063	6,818	334	58	1,045	56
1992	9,320	891	7,064	381	51	1,119	58
1993	9,240	857	7,252	381	35	950	59
1994	8,260	943	7,477	373	52	829	61
1995	8,080	1,060	7,068	395	43	699	63
1996	6,672	1,129	7,101	359	26	578	64
1997	6,500	1,590	6,873	589	36	450	65

Table 7.4. Status of Eastern Bering Sea fish stocks (1,000t).

	Mean Biomass	1997 Biomass	OFL	ABC	TAC	3-year Trend
Pollock	10,438	6,778	2,062.0	1,190.0	1,159.0	Down
Pacific Cod	1,364	1,590	418.0	306.0	270.0	Up
Yellowfin Sole	1,979	2,530	339.0	233.0	230.0	Stable
Greenland Turbot	448	118	23.0	12.0	9.0	Down
Arrowtooth Flounder	280	587	167.0	108.0	21.0	Stable
Rock Sole	1,187	2,390	427.0	296.0	97.0	Stable
Flathead Sole	403	632	145.0	101.0	44.0	Stable
Other Flatfish	595	616	150.0	98.0	51.0	Stable
Sablefish	95	37	5.6	2.7	2.3	Down
Pacific Ocean Perch	331	397	31.0	16.0	16.0	Up
Other Rockfish	161	193	10.0	7.0	7.0	
Atka Mackerel	699	450	82.0	67.0	67.0	Down

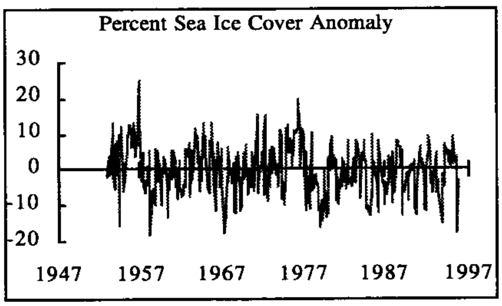
- changes in rainfall and runoff affect stream flow conditions which influence freshwater species as well as the freshwater portions of the life cycles of important anadromous species such as salmon;
- and, overall economic conditions and changes in demand for fish and fish products in key markets (e.g., Japan) can affect commercial fishing pressure and viability with attendant consequences for resource availability for subsistence and recreational interests.

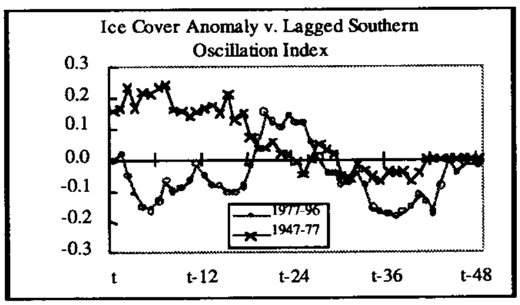
A review of historical records also indicates that this region is subject to considerable year-to-year variability in climatic conditions, dominated by changes in ocean-atmosphere interactions associated with the El Niño-Southern Oscillation (ENSO) cycle. Resulting changes in temperature, ocean circulation and productivity, sea ice, atmospheric circulation, and rainfall/runoff are associated with sometimes-dramatic changes in critical fisheries stocks and marine mammal populations. Information about the impacts of these natural climate swings can provide valuable insights into the vulnerability of the ocean ecosystem and fisheries (and other economically-important sectors) to climate change--where vulnerability is defined to include considerations of the sensitivity of a given system to an observed change and the flexibility of that system to adapt to or mitigate the effects of those changes. Some evidence indicates that, since the late 1970's, the region has been subject to a prolonged period of warm conditions—often referred to in the literature as a climate "regime shift"—associated with a strengthening and eastward displacement of the Aleutian Low. This "regime shift" may be a local manifestation of a multi-decadal cycle of natural variability (for example in ENSO). This extended period of warmer than average temperatures may reflect a long-term, secular warming trend. The current conditions may represent a long-term warming trend superimposed on a natural cycle of climate variability. Independent of their cause, the changes in atmospheric circulation and oceanic conditions associated with this "regime shift" have discernible consequences for critical ecosystems and populations, including fisheries and marine mammals.

This chapter provides an overview of the consequences of climate variability and change on the physical, biological, and human systems that characterize the Alaska-Bering Sea ocean ecosystem. For the purposes of this discussion, in addition to the open ocean and continental shelf regions, the ocean ecosystem is defined to include the freshwater rivers and streams, estuaries and coastal habitats which support critical fisheries, marine mammals and sea bird populations and the human communities which depend on them. After providing a description of current conditions and stresses, this chapter discusses the impacts of climate change in the context of several important species representing open ocean, anadromous, and freshwater species as well as selected marine mammals and sea birds. Following this exposition of specific impacts, we highlight some of the existing uncertainties and the research required to fill these critical information needs. Finally, we explore the need to integrate consideration of the current and anticipated changes in climate in a variety of resource management and economic development decisions both within the fisheries sector itself and in the context of the other ecosystems and sectors addressed at the June 1995 Workshop.

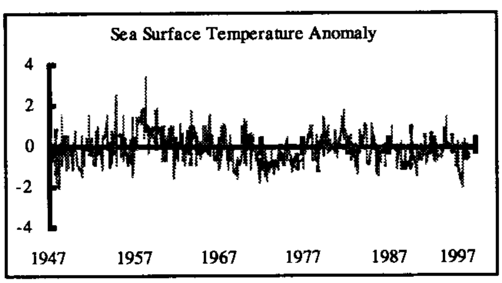
Alaska and Bering Sea. Shifts in temperature in the Bering Sea seem related to the location and intensity of the Aleutian low-pressure cell. In the Gulf of Alaska, periods of warm-ocean conditions appear to be associated with an eastward displacement and intensification of the Aleutian low and downwelling in coastal waters. Recent work by Trenberth and Hurrell (1994) suggests that the entire 1977-1988 period differs markedly from the 1946-1976 and 1989-1992 periods. The Aleutian Low was more intensive than normal in the 1977 though 1988. The deepening of the Aleutian Low is usually associated with warm coastal waters and high sea level (Emery and Hamilton 1985, Roden 1989). Another data series shows that the average pressure in an area 27.5° N to 72.5° N; and 147.5° E to 122.5° W was 1010.8 mb from 1976 to 1988; down from an average of 1012.9 mb, 1946 through 1975 (Pearcy 1992). In addition, sea surface temperature and temperature at depth showed an unusually strong and rapid increase in 1977 and 1978 in the northern Gulf of Alaska off Seward (Royer 1989) as well as off Kodiak and Bristol Bay (Rogers 1984).

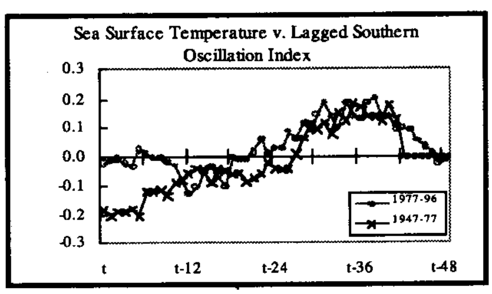
Several measures can be related to the decadal scale of changes that are important to biological oceanography (Niebauer 1988). Percentage of ice cover has changed from the 1970s through the 1990s. In addition, the correlation at short lags between percent sea ice cover and SOI has switched from positive (anti-El Niños associated with above average ice cover) to negative (El Niños associated with above average ice cover).



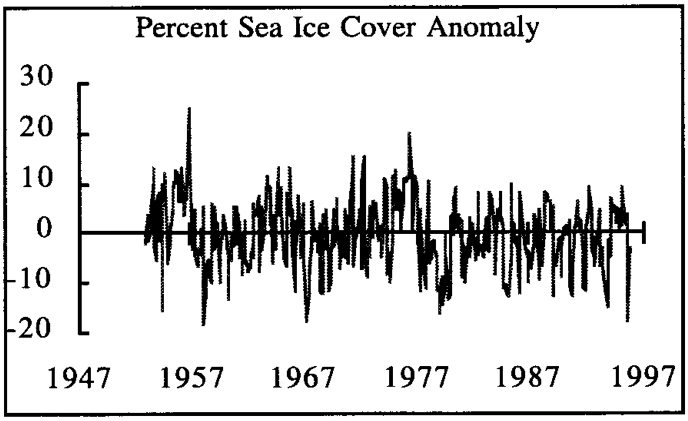


Also there is a long record of sea surface temperature (SST) from ship of opportunity data taken with a square centered on the Pribilof Islands. The newer part of the time series is from satellite charts. The SST record shows a similar pattern. Prior to the mid-1970s, El Niños were associated with increased SST at short (< 1-year) lags and decreased SST at long (30 to 42-month) lags. In recent years, the correlation structure has broken down at short lags, with El Niños often associated with depressed SST.





These general surface circulation patterns, in combination with freshwater inputs, contribute to upwelling processes that make nutrients abundantly available on the Bering Sea's continental shelf, leading to high levels of biological productivity. The strength of these upwelling processes, the direction of nutrient transport, and the extent and duration of sea ice coverage are influenced by the location and intensity of the Aleutian Low–a prominent atmospheric pressure feature. The Aleutian Low is a persistent low-pressure cell that is dynamically centered to the south of the Aleutian Islands. The mean position of the Aleutian Low is influenced by the position and intensity of climate events, including El Niño-Southern Oscillation (ENSO).

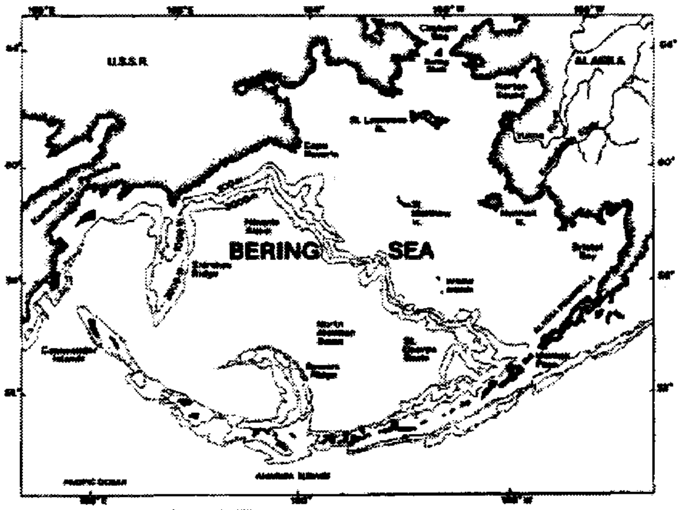


The El Niño-Southern Oscillation (ENSO) is a coupled ocean-atmosphere process characterized by periodic oscillations in ocean temperature and atmospheric pressure conditions in the tropical Pacific. Under usual conditions, westward trade winds tend to keep warm surface waters "stacked up" in the western Pacific Ocean, resulting in strong coastal upwelling along the eastern edge of the equatorial Pacific Ocean. El Niño refers to the "warm phase" of the ENSO cycle during which warm surface waters normally confined to the western Pacific expand eastward toward the coast of South America. These conditions are associated with a depression in the thermocline in the eastern Pacific which significantly curtails the usually strong upwelling of nutrient-rich waters. El Viejo or La Niña describe the "cold phase" of the ENSO cycle when ocean temperatures in the eastern Pacific are cooler than normal. These changes in oceanic conditions are coupled to a see-saw in atmospheric pressure gradients across the Pacific Basin known as the Southern Oscillation. An index, called the Southern Oscillation Index (SOI), provides a measure of the difference in sea level atmospheric pressure between Tahiti and Darwin, Australia. Negative values for the SOI are associated with an El Niño warm event, while positive SOI values are associated with cold phases of the ENSO cycle. These changes in the exchange of energy between the ocean and the atmosphere in the tropical Pacific produce changes in patterns of temperature and precipitation globally with effects felt in the Bering Sea (e.g., Niebauer 1988).

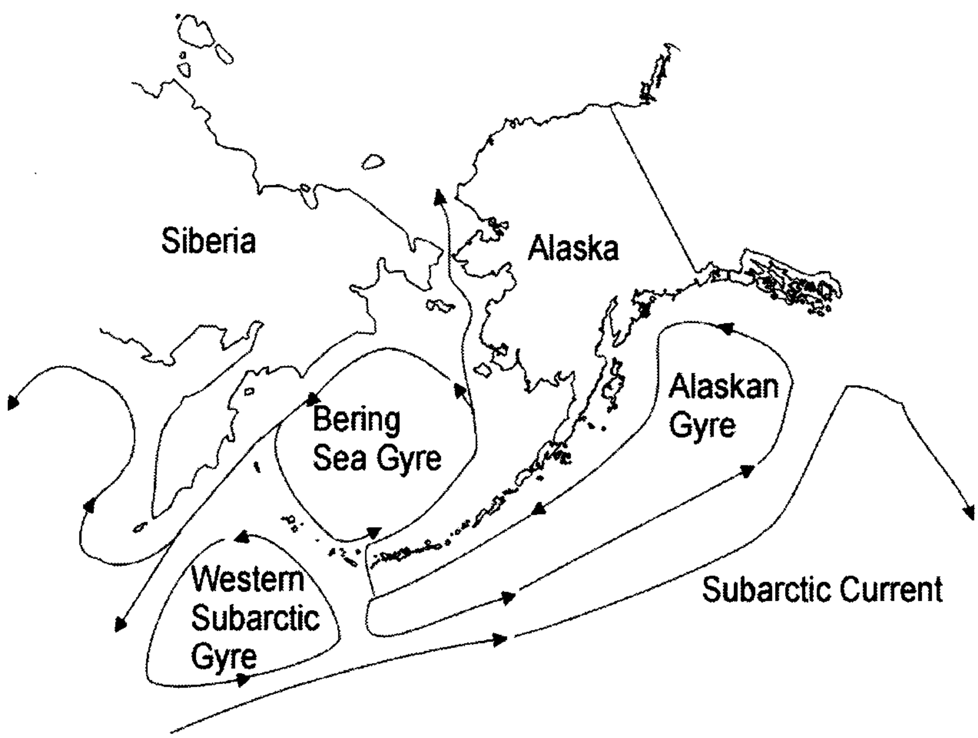
Decadal scale changes in ocean physics in the Bering Sea and Alaska Gyre— Evidence from several sources indicates that a strong climatic change occurred in the mid-1970s that influenced ocean dynamics and biological productivity. Strong shifts in atmospheric measures during the late 1970s resulted in warmer winter conditions that continued through the early 1980s. Consequently, the regime shift involved a general warming of waters in the Gulf of

7.2 Physical System

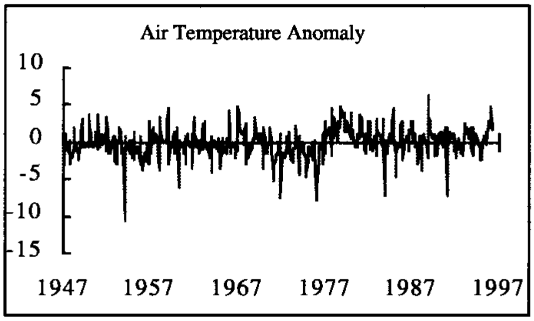
A broad shallow continental shelf covers the northeast half of the Bering Sea while the southwest half consists of a deep basin rimmed by a narrow shelf. The primary freshwater inputs are provided by the Yukon and Kuskokwim rivers, which drain over 400,000 square miles in Alaska and Canada.

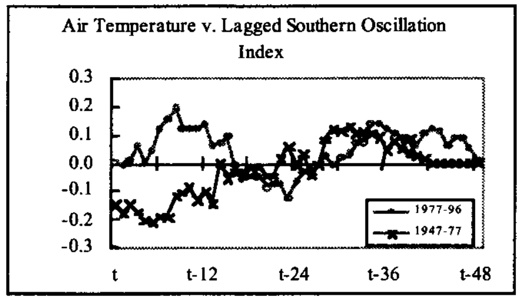


Surface circulation patterns include the eastward flowing Subarctic Current, and the counterclockwise Western Subarctic, Alaskan, Bering Sea gyres. North Pacific waters feed into the Bering Sea through breaks in the Aleutian Islands. Surface waters flow from the Bering Sea into the Chukchi Sea to the north, and along the Kamchatka Peninsula into the North Pacific.

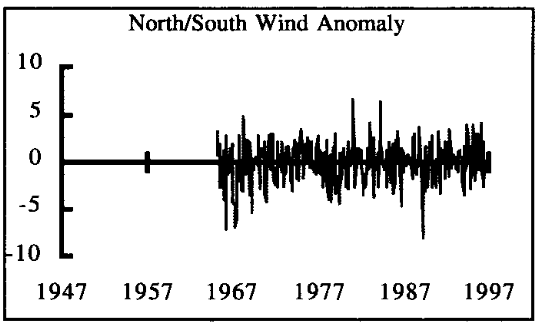


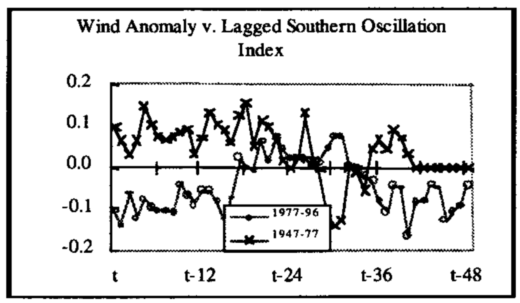
An air temperature time series from the St Paul Island airport in the Pribilofs also supports the hypothesis of a mid-1970s regime shift.



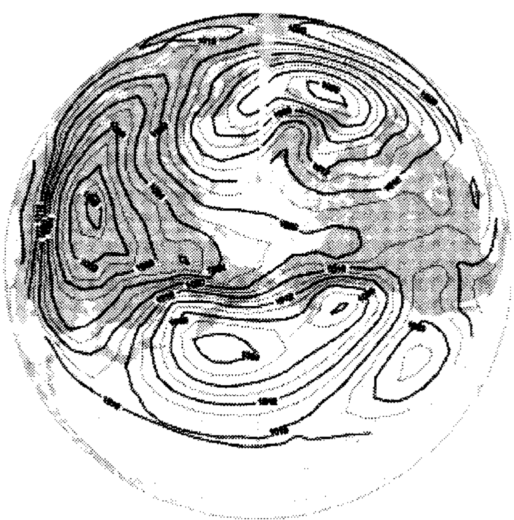


Similarly, an index of wind direction (derived from wind components from the north and south) at the St. Paul Island airport suggests that a regime shift occurred in the mid-1970s.

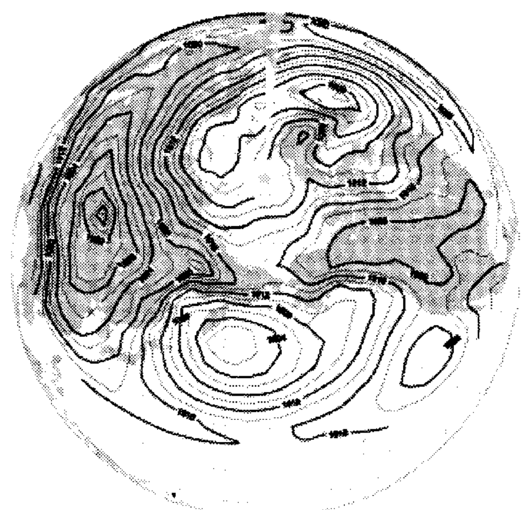




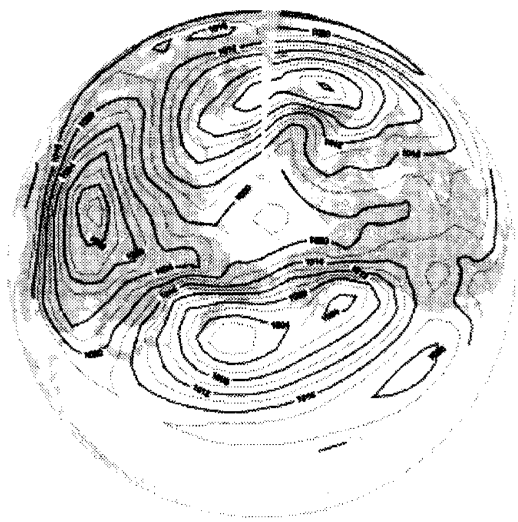
Anti-El Niño 1947-77 (Niebauer 1997)



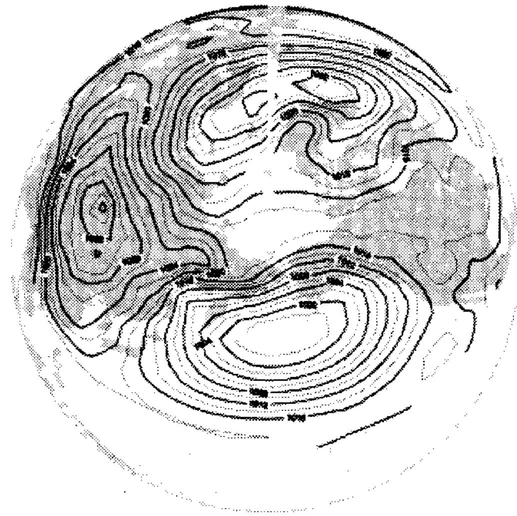
Anti-El Niño 1977-96. (Niebauer 1997)



El Niño 1947-77 (Niebauer 1997)



El Niño 1977-96 (Niebauer 1997)



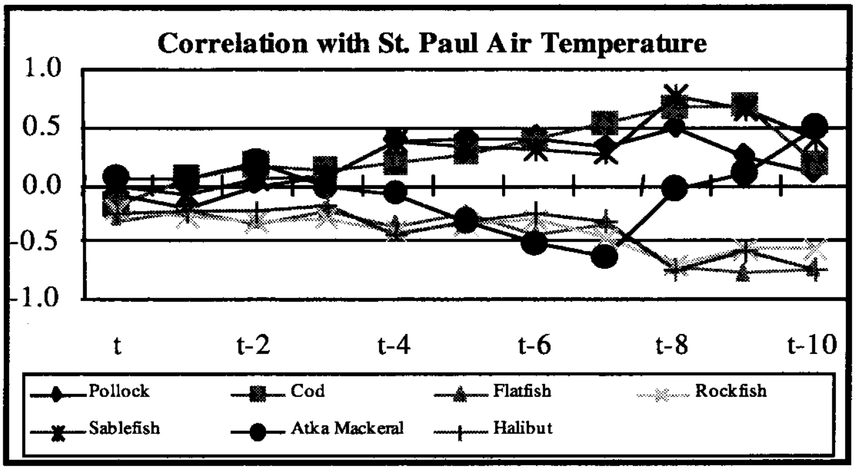
In the mid-1970s, the ENSO event coincided with a change in the 18-year lunar tide-cycle that is related to temperatures in the Gulf of Alaska (Royer 1993). Royer has developed a time series of CTD casts at the mouth of Resurrection Bay in the northern Gulf of Alaska going back to the early 1970s. This series indicates that an 18-year temperature cycle at depth that is correlated to the tidal (lunar) cycle of this period (Royer 1993). In the mid-1970s the ENSO event was coincident with the high temperature period of the 18-year cycle. The two events acting together caused unusually warm water.

Because changes in the frequency and intensity of El Niño events have a critical role in determining the impact of climate change on marine resources of the Bering Sea region, it is important to understand how climate change is likely to affect ENSO. Bakun (1996) hypothesizes that ENSO is driven by the temperature differential between the tropics and the poles. He speculates that global warming will decrease the temperature differential and may reduce basin-scale oceanic and atmospheric circulation, possibly reducing the productivity of the Bering Sea ecosystem.

7.3 Biological Resources & Processes

The productivity of 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. However, while the influence of abiotic processes is undeniable, the exact nature of the mechanisms involved is largely unknown or unobservable. Moreover, the influence of oceanographic processes may vary across life stages and through space and time, and may depend on the conflicting or compounding interplay of multiple processes.

Because the mechanisms whereby oceanographic processes influence biological systems are latent and dynamic, apparent relationships will be found between population abundance and observable variables which result from or are correlated with the latent processes. For example, the dynamic correlations between the abundance of principal eastern Bering Sea fish stocks and the mean annual air temperature (°C) at St. Paul Island airport in the Pribilofs can be represented by:



Although it is possible (remotely) that air temperature directly influences survival, recruitment, and growth, it is far more likely that air temperature is correlated (positively or negatively) with associated oceanographic factors that truly affect the biological stocks. Fortunately, from the perspective of statistics, the confidence in our forecasts of changes in populations does not deteriorate if we use a closely correlated proxy for an unobservable process. Note however, that while forecasts may be unaffected by the useful inclusion of proxy variables, the estimated coefficients may lack causal significance. Thus, model performance may collapse under conditions that disrupt the correlative relationship. Because these correlations are the univariate manifestations of multivariate interactions, they are at best tenuous. Consequently, the performance of models that incorporate proxy environmental variables frequently degrades ex post. That is, changes in the state of a suite of environmental influences cause relationships that were found to be statistically significant when estimated ex post to be uninformative to ex ante forecasts.

Fish & Shellfish

The effects of climate variation on some Bering Sea fish populations are fairly well known in terms of empirical relationships but generally poorly known in terms of mechanisms. Descriptions of such empirical relationships are found in Pearcy (1984), Beamish and McFarlane (1989), and Beamish (1995). Data on commercially exploited species dates back to the mid-1960's for some groundfish species and to the early part of this century for some stocks of Pacific salmon, Pacific halibut, and Pacific herring. Data on forage fishes and lower trophic levels are generally poor to non-existent.

In addition, there was a strong increase in the abundance of copepods in 1974 through 1977 in the central North Pacific Ocean, with continued good levels into 1980. These data were reported from the Ocean Station P data series along with a new index of the Aleutian low pressure zone from 1965 to 1980 (Beamish and Bouillon 1993). The copepod index varied with the intensity of the winter low pressure. The major driving factors for observed changes in each of these variables are hypothesized to be variation in the mean position and intensity of the Aleutian Low; warm periods can be thought of as El Niño periods and cold periods as anti-El Niño periods. During cold periods the Aleutian low is minimal and to the west. During the warm periods the low is strong and to the east.

While the regime shift in the environment has probably resulted in better conditions overall for many stocks, there are still many other factors which influence fish population size. In particular the size of the population itself has a large role in determining the amount of egg production. For walleye pollock in the Bering Sea, the cannibalistic nature of the adults adds another dimension of complexity, as does predation by other species.

Many fish populations appear to exhibit responses to the environment over different time scales than just the regime shift period. For Pacific halibut, there appears to be a long 30-year cycle in recruitment that may be influenced by the solar-lunar node cycle of Royer (1993). Walleye pollock in the Bering Sea appear to be affected by inter-annual changes in the environment, so that year-to-year differences contribute to year-to-year fluctuations in recruitment (Quinn and Niebauer 1995). On the other hand, walleye pollock in the Gulf of Alaska had good recruitment over a number of years in the late 1970's and then a long period of poor recruitment. The effects of climate change on the spatial distributions of fish populations are even less well understood. 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 threshold temperature ranges affect distribution. Temperature increases of a few degrees can shift distributions dramatically.

Groundfish

Several groundfish stocks in the eastern Bering Sea showed a strong change during the decade starting in 1977 or 1979 (Bakkala 1993, NPFMC 1996 a,b,c, NRC 1996). The total groundfish complex and its Acceptable Biological Catch (ABC) have increased compared to the mid-1970's. In particular, Pacific cod showed a 600% increase to about 1.1 million tons, while rock sole showed about a 350% increase. Pacific halibut, yellowfin sole, flathead sole, Alaska plaice, arrowtooth flounder, and Atka mackerel showed large, persistent increases in abundance during this period. Other species showing a pronounced increase include walleye pollock and mixed skate species. Pacific herring showed strong and regular recruitment increases following 1976 in the eastern Bering Sea and in various localities in the Gulf of Alaska, including Prince William Sound (Fritz et al. 1993). Hollowed et al. (1987) showed that many groundfish stocks exhibit synchrony in recruitment, most likely due to changes in environmental conditions. For example, the 1977 and/or 1978 year-classes were quite large for Bering Sea walleye pollock, Pacific cod, Pacific Ocean perch, arrowtooth flounder, Atka mackerel, and sablefish. This increase coincided with a large positive anomaly in air temperature in 1979 (Quinn and Niebauer 1995). Conversely, some stocks have had a negative response during this period. Greenland turbot, a species more adapted to colder climates, decreased from approximately 120,000 t to 10,000 t. King crab stocks in the eastern

Bering Sea and Kodiak declined during the 1980's, and this decline is thought to be due to a combination of factors including environmental effects, overfishing, natural mortality, and changes in reproductive parameters (Tyler and Kruse 1996). Some very limited information suggests that there has been a decline in some forage fishes (NRC 1996).

Pacific Salmon

The survival and growth of salmon depend on the influence of environmental factors in freshwater and oceanic life-stages. It has been long known that salmonid populations show responses to changes in climatic conditions (Pearcy 1984). This has been reinforced by recent retrospective studies using regression and time series analyses (Quinn et al. 1989, several papers in McFarlane and Beamish 1989, and Beamish 1995, NRC 1996, Adkison et al. 1996). Elevated stream temperature, stream flow rates, and air temperatures have been identified as beneficial freshwater factors (Rogers, 1984). The effect of the 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 inter-annual 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, negative Southern Oscillation Index anomalies have been reported by Quinn and Marshall (1989), among others. Unless accompanied by significant changes in the strength of ocean upwelling zones, changes in precipitation and temperature anticipated by Weller et al. (Chapter 2) can be expected to enhance salmon productivity.

Red King Crab[1]

The once large stock of red king crabs of the Bristol Bay region of the eastern Bering Sea crashed in the early 1980s and has not recovered. It is one of the few stock demises in that area. One suspicion is that the fishery was to blame for the crash because of the large landings that occurred during the late 1970s and early 1980s, and another possibility is that the demise was caused by oceanographic factors.

Tyler and Kruse (1997) looked at the January pressure anomalies for the North Pacific since 1966 for the area of the Pacific Ocean between 20° and 60° north latitude. Except for three years, the pressure was above average from 1966-1975 inclusive, and from 1976-1988 the pressure was lower than normal. It was during this intense low pressure that brood strength was progressively reduced. Because numbers of young decreased while catch of adults (males only; females are returned to the ocean) rapidly increased, there was scant replacement of spawning biomass. Of course, atmospheric pressure changes do not kill king crab, and so we have not found the specific cause of mortality. It is likely that a combination of events have acted simultaneously through the complex life history of the species to produce the lowered brood strength. Unfortunately, many measures will correlate with this nearly monotonic decline in brood strength and barometric pressure. Therefore, we suggest that further exploration of correlation statistics will only produce many significant correlations but no new understanding. Instead, we suggest the development of process studies.

The change in weather pattern that occurred in the mid-1970s coincided with a decrease in brood strength of red king crabs. An accompanying increase in water temperature was correlated to decrease in the red king crab stocks of Kodiak and Bristol Bay (Müter et al.

[1]Excerpted from Tyler and Kruse (1997).

1995), although their Kodiak relationship appears more related to availability of crabs to the fishery and changes in fishing effort. There are several hypotheses presented here that relate temperature change to change in productivity of red king crabs. The optimum temperature for embryo development of red king crabs is 3-8°C (Nakanishi 1985). For ocean fishes, hatch success is often highest at an intermediate temperature, with decreases at higher temperatures (Alderdice and Forrester 1971). Cumulative exposure to optimal temperature is sometimes necessary for both egg and embryonic development of some fish (Kruse and Tyler 1983), and so it may be for king crabs. In unusually warm years spawning may be skipped because a cool temperature cue is needed or degree of maturation is insufficient. The mechanisms of response to warming that might bring about a decrease in brood strength are manifold. Specifics for the red king crab are wanting, and so it is not possible to rule out hypotheses presented here.

Hypotheses relating survival and productivity to physical factors:

- A critical number of degree-days is necessary to bring on ovary maturation
- High temperatures will increase egg mortality
- After fertilization, cool temperatures will delay hatching
- High percentage of successful hatch is linked to an optimum temperature

Other physical factors that could be of major influence are advection and mixing. Advection is critical to the development of brood strength in processes related to hatching, to survival of zoea, and to the settling of the glaucothoe stage. The prevailing currents flow to the northeast along the Alaskan Peninsula toward Bristol Bay then turn northward (Stabeno and Reed 1994). Since high-profile, rocky bottom with attached fauna is critical for survival of the glaucothoe larval stage during settling, an increase in the strength of currents moving larvae away from this bottom type would increase mortality

Changes in concentrations of diatoms are generated by the mixing of nutrients into the euphotic zone. The mixing could be tidal or possibly be from Ekman upwelling along the north coast of the Alaskan Peninsula caused by winds from the northeast, though this is not documented. It is possible that the fertilized embryos of red king crab hatch only if there are concentrations of diatoms present, as though a chemical cue were necessary (T. Shirley, University of Alaska Fairbanks, Juneau Center, unpublished).

A period of high recruitment of the 1960s and early 1970s in the eastern Bering Sea stock of red king crab led to the high biomass of that species, making possible the major fishery of the late 1970s and early 1980s. This high recruitment level did not pass unchanged into the new oceanographic regime following the climate shift of the mid 1970s. That the decrease in productivity of king crabs was due to oceanic climate change seems likely, but is not proven. This hypothesis by no means discounts the density-dependent relationship proposed by Reeves (1990) and Zheng et al. (1995) with a critical stock-size below which the small size of the spawning stock interferes with recruitment productivity.

Marine Mammals

In addition to affecting the productivity and availability of intensively harvested fish stocks, climate change can be expected to affect non-target fish stocks, seabirds, and marine mammals. Trillmich and Ono (1991) document the effects of El Niño on the abundance and distribution of pinnipeds throughout the Pacific. Strong evidence exists for impacts from

British Columbia to Chile. While the authors speculate on the possibility of impacts on Gulf of Alaska and Bering Sea pinnipeds, the baseline data are not extensive, and the results that they report are not statistically significant.

7.4 Institutional Structure

The Bering Sea region's marine and freshwater fisheries are managed by various regional and national governments, and international treaties. Fisheries in the US Exclusive Economic Zone (EEZ) are managed by the North Pacific Fisheries Management Council under the guidelines of the Magnuson Fisheries Conservation and Management Act. The State of Alaska claims jurisdiction over freshwater fisheries and marine fisheries inside the three-mile state waters under the Constitution's equal footing clause and common law. However, because states lack authority to enter treaties, the federal government retains certain responsibilities for the management of transboundary stocks. In addition, the federal government has asserted authority to intervene in state fisheries management in order to guarantee provisions of the Alaska National Interest Lands Conservation Act (ANILCA) with respect to subsistence priority. The Canadian Department of Fisheries and Oceans (DFO) is responsible for the establishment and enforcement of catch limits in the Canada. Management of Pacific halibut is governed by a treaty between the U.S. and Canada. The Canadian and U.S. governments are currently engaged in renegotiating a treaty that governs management of salmon stocks near British Columbia and in the Yukon River. The U.S. and Russia are also engaged in negotiating their common seaward boundary in the Bering Sea.

7.5 Direct and Indirect Users

The Bering Sea region's biological resources provide many sources of human value. In addition to the direct values that arise from recreation, tourism, and subsistence, sport, and commercial harvests, and to consumers, these resources provide existence and option values. Each of these sources of value should be investigated.

Commercial Harvests

Eastern Bering Sea groundfish harvests in the 1950-1980 period were largely conducted by distant water fleets from Japan and the Soviet-bloc nations. During the 1950's, these fleets focused on yellowfin sole. When catches of yellowfin sole began to taper off in the 1960's, the distant water fleets switched to sablefish, Pacific Ocean perch, and various rockfish. Development of the technology for shipboard processing of surimi, a fish paste, led to the rapid growth of the walleye pollock fishery in the late 1960's and early 1970's. A rapid evolution of the commercial fishery was induced by the passage of the Magnuson Fisheries Conservation and Management Act of 1976 (MFCMA) and the concomitant expansion of various fishing vessel construction subsidy programs. The initial phase of this evolution was the development of a joint-venture fleet. Joint ventures consisted of US-flagged harvester vessels (generally 90-130' trawlers) that delivered to non-US-flagged motherships. The expansion of joint venture activities virtually eliminated foreign directed fishing by 1985. By 1990, the joint venture fleet was completely supplanted by fully domestic operations (shoreside, mothership, and catcher-processor).

The region fishery for walleye pollock exceeded 4.8 million metric tons of landings and accounted for approximately 5% of the combined world landings of fish, shellfish, and crustaceans in 1991. Pacific salmon, Pacific cod, Pacific halibut, sablefish, yellowfin sole, Greenland turbot, arrowtooth flounder, rock sole, flathead sole, other flatfish, Atka mackerel, Pacific herring, various rockfish and thornyheads, crabs, and weathervane scallops form the primary focus of current commercial fisheries in the Gulf of Alaska and Eastern Bering Sea. These same species, with the addition of Arctic cod and saffron cod, are harvested in the Western Bering Sea, Sea of Okhotsk, and Chukchi Sea.

The economic effects on commercial fisheries of changes in fish populations depend on the elasticity of demand for fish. When ex-vessel prices are inversely related to demand, the total revenue functions are dome shaped. Portions of the demand curve associated with upward sloping portions of the revenue function are called elastic. Portions of the demand curve associated with the downward sloping section of the revenue function are called inelastic. Increases in catch result in increased revenue where demand is elastic, but result in decreased revenues where demand is inelastic. Fisheries for Pacific halibut and Pacific salmon have been shown (Criddle 1993, and Herrmann 1993, respectively), to operate in the inelastic region of their demand curves thus increased landings will fail to increase revenues unless total demand expands. Although the current ex-vessel demand for walleye pollock is elastic, modest increases would cause demand to become inelastic (Herrmann et al. 1996, Criddle et al. in press). Whenever costs are an upward sloping function of catches, profit maximizing harvest levels will be even smaller than revenue maximizing harvest levels. Although formal demand systems have not been estimated for other region fisheries, it is likely that the demand for most of the remaining groundfish stocks is inelastic (or nearly so). The likely exceptions to this generalization are sablefish and commercial targeted crabs, high valued species with depressed harvests.

In addition to indirect effect of warming on harvest revenues, climate change can be expected to affect the effectiveness and cost of fishing. For example, if warmer air temperatures reduce the extent of sea ice cover in the Bering Sea, fishers may have improved access to seasonally aggregated stocks. That is, catch-per-unit-effort (CPUE) could be increased even without an increase in stock abundance

7.6 Additional Research Needed

Additional information that would contribute to improved decision making includes:

- expansion and maintenance of oceanic, atmospheric and hydrologic monitoring systems/programs to ensure access to critical information on the current state of the ocean-atmosphere system and the development of reliable data sets to support analysis of long-term trends;
- historical analyses and paleoclimate investigations of seasonal-to-interannual climate conditions in the region to determine whether the current "regime shift" reflects a cycle of natural variability (e.g., associated with decadal and longer patterns in ENSO) or could represent a permanent long-term trend;

- exploration of the predictability of seasonal-to-interannual climate variability in the region, particularly related to ENSO and the Aleutian Low system, and the potential benefits of such forecasts for fisheries development and management as well as marine mammal and sea bird conservation in the region;
- improved understanding of the impact of climate variability and change on precipitation in the region with particular attention to the influence of changes in rainfall-runoff patterns for the region's fisheries (especially freshwater species like whiting and anadromous species like salmon);
- improved understanding of the nature and consequences of changes in sea ice conditions, particularly in terms of: (1) fisheries, marine mammals and sea birds which rely on ice-edge productivity; (2) the impact of changing ice conditions on fishing access and safety (particularly important vis-a-vis subsistence users);
- improved understanding of the impact of climate variability on ocean circulation and productivity, particularly in terms of the impact of anticipated changes on the levels and health of critical stocks of fish, marine mammals, and sea birds for commercial, recreational, and subsistence use;
- improved understanding of current trends and anticipated changes in the state of ice-rich permafrost in the region and the role of melting permafrost on stream flow quantity and quality as well as impacts on supporting infrastructure;
- improved understanding of the potential consequences of climate change on severe storms and weather extremes;
- improved understanding of the influence of climate variability and change (in the context of other existing or anticipated environmental stresses) on inter-species competition;
- a more thorough understanding of the key processes and mechanisms responsible for determining productivity, species composition, distribution and abundance;
- changes in biodiversity and the influence of climate variability and change on those changes;
- exploration of the influence of the region on the global climate system with particular attention to the role of the region's ocean ecosystem as a sink for carbon (and, conversely, whether the region's terrestrial ecosystems might represent a potential source of carbon to the atmosphere associated with the release of clathrates in association with melting coastal zone permafrost);
- exploration of the region and/or some of its species as "indicators" of global change.

7.7 Integration with other Working Groups

The development of effective adaptation or mitigation options for the region requires the integration of information on current and anticipated changes in climate as a consideration in a variety of resource management and economic development decisions. In some cases, these are decisions that directly affect access to fisheries and marine mammals resources (e.g., determinations of allowable catch limits). In other cases, however, these decisions will be associated with activities which indirectly affect the ocean ecosystem and the resources it supports (such as the influence of changes in land use on freshwater, anadromous, and marine species). Many of these indirect consequences are discussed in the other chapters of this report but the participants in the Ocean System Working Group thought it would be helpful to highlight some of them here as well. The following section provides a list of some of the more critical policy decisions with consequences for the fisheries sector:

- changes in land use policies particularly with respect to those activities which involve either large-scale changes in vegetation cover (e.g. forestry) or resource extraction activities, such as mining, which affect stream flow quantity and quality as well as nutrient and freshwater flow in the near-coastal and shelf ecosystems;
- infrastructure maintenance and improvement policies which affect access to fishing and hunting grounds as well as commercial markets;
- infrastructure and resource transfer decisions which might increase (or decrease) the vulnerability of fisheries-dependent communities to climate change;
- water resource management decisions which affect stream flow quantity and quality as well as direct access to water resources for subsistence communities;
- economic investment and subsidy decisions particularly as they affect resource demand and industrial capitalization;
- land use and economic development decisions related to the development of and support for aquaculture/fish farming projects, particularly as they relate to salmon;
- infrastructure development and protection decisions which either increase or decrease the vulnerability of coastal ports and communities to the influences of climate change;
- national and international decisions related to fossil fuel use and access which could decrease the contribution of oil and gas resources to the region's economy and result in an increase in the region's reliance on fisheries resources and other development sectors;
- changes in tourism policies which affect access to critical habitats and resources;
- international negotiations which involve the exchange of fisheries resource access/ availability for other goods and services;
- and endangered species protection and enforcement activities on fisheries stocks analysis of the consequences of changes in marine mammal and activities.

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8. Subsistence Fisheries

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8.1 Introduction

Just as the physical and biological boundaries of the Alaska/Bering Sea region are merely constructs of convenience, the core of the region is inextricably linked to the world through social, cultural, and economic ties. The region produces nearly one-fifth of the world's fish and shellfish products, products that are largely harvested by distant-water fleets and marketed in North America, Japan, and Europe. Western and Interior Alaska, the Aleutian and Commander Islands, and Kamchatka and Russia's Bering Sea coast are, with the exception of a few pockets, among the least industrialized regions in the world. Consequently, the non-consumptive uses of the region's resource endowment and the continuation of the region's traditional cultures have international value.

8.2 Community Structure

The 56 communities that border the Eastern Bering Sea are each unique and will be uniquely affected by climate induced changes to the ocean system (Table 8.1). Four of the communities (Kotzebue, Nome, Dillingham, and Unalaska) are regional hubs with populations over 2,000. The remaining communities all have populations of less than 1,000. Forty-two of the communities, including Kotzebue, are overwhelmingly (>70%) Native. Four of the communities are predominantly (>70%) non-Native. In addition to demographic differences, the communities differ in economic opportunity. Median family income varies from a low of $11,339 in Savoonga to a high of $66,548 in Chignik Lagoon. Some communities do not participate in commercial fishing. In other communities, commercial fishing provides millions of dollars in annual revenues to local residents and hundreds of millions in revenues to non-residents. The commercial fishery may be largely dependent on a single species of salmon or herring or may target a diversity of species. While subsistence fishing and hunting play important roles in each of the communities, the choice of target species varies considerably between the communities.

In addition to communities that directly border the Bering Sea, many other communities are linked to the region. Interior Alaska and Yukon Territory, Canada are linked to the region through kinship, trade, employment, and reliance on salmon. Residents of Kodiak, South-Central Alaska, Southeast Alaska, Washington, and Oregon are linked to the region by their participation in commercial fisheries. Each of these regions will be affected by changes to the region's ocean system.

Over the next few pages, we attempt to provide an illustration of the type of baseline analysis that will be required for an assessment of the human impacts of changes in the region's ocean system. We have restricted our description to the Northwest Arctic Borough. Sources that could be tapped for additional baseline information include: Braund et al. 1989; Impact Assessment Inc. 1990a,b, 1994; Knapp 1990a,b; Northern Economics et al. 1990; NPFMC 1994a-i; and Waring et al. 1992a-c.

Table 8.1. Demographics and commercial fishing activity of BESIS region communities.

Population	(1990 Census)	Ethnic Diversity	% Native	Median Family Income	Value of Recent Commercial Catches
Western Alaska	Kotzebue	2,751	75.1	44,632	426,830
	Shishmaref	456	94.5	14,875	
	Diomede	178		14,375	
	Wales	79	88.8	19,063	
	Brevig Mission	198	92.4	18,333	
	Teller	151	86.8	16,750	
	Nome	3,500	52.1	49,491	130,408
	Golovin	127	92.9	17,500	32,537
	Elim	264	91.7	17,083	49,863
	Koyuk	231	94.8	18,750	1,956
	Shaktoolik	178	94.4	22,500	300,351
	Unalakleet	714	81.8	40,347	819,838
	Gambell	548		15,938	
	Savoonga	514		11,339	
	Stebbins	442	94.8	23,333	134,627
	St Michael	295	91.2	24,028	44,774
	Kotlik	461	97.0	22,083	814,345
	Emmonak	642	92.1	26,406	1,456,480
	Alakanuk	544	95.8	23,250	996,934
	Sheldon Pt.	109	92.7	19,375	243,365
	Scammon Bay	343	96.6	15,750	1,065,506
	Hooper Bay	845	96.0	18,125	77,085
	Newtok	207	93.2	15,000	186,911
	Tununak	316	96.2	22,708	18,519
	Mekoryuk	177	99.4	16,250	6,669
	Toksook Bay	420	95.5	23,125	692,017
	Nightmute	153	95.4	17,813	202,501
	Kwigillingok	278	95.0	15,000	131,567
	Quinhagak	501	93.8	17,969	739,849
	Goodnews Bay	241	95.9	13,958	359,298
	Platinum	64	92.2	16,250	110,748
	Togiak	613	87.3	15,781	355,494
	Dillingham	2,017	55.8	47,857	577,698
	Clarks Point	60	88.3	26,042	516,183
	Naknek	575	41.0	56,195	318,373
	King Salmon	696	15.5	62,152	1,210,113
Pribilof Islands	St. Paul	763	66.1	48,000	257,597
	St. George	138	94.9	26,000	77,061
Aleutian Islands	Akutan	589	13.6	31,875	32,529
	Atka	73	67.0	24,583	5,694
	Nikolski	35	82.9	17,250	
	Unalaska	3,089	8.4	61,927	6,182,037
	False Pass				1,252,110
	Cold Bay	148	5.4	51,539	314,283
	King Cove	451	39.2	63,419	13,547,542
	Sand Point	878	32.2	43,125	19,893,356
	Nelson Lagoon	83	80.7	51,254	3,556,800
	Ivanof Bay	35	94.3	21,500	
	Perryville	108	94.4	28,750	813,151
	Chignik	188	45.2	36,250	2,582,662
	Chignik Lake	122			535,304
	Chignik Lagoon	53	56.6	66,548	3,921,284
	Port Heiden	119	72.3	16,875	395,789
	Pilot Point	27	84.9	39,250	27,803

Subsistence

The harvest of wild foods plays a significant role in the diet of Alaska's rural residents. Subsistence resources provide a major portion of the diet, especially in small communities where transportation costs make the purchase of store bought foods prohibitive. However, subsistence resources and the activities associated with the harvest of these resources provide more than food. Participation in family and community subsistence activities, whether it be clamming, processing fish at a fish camp, or seal hunting with a father or brother provide the most basic memories and values in an individual's life. These activities define and establish the sense of family and community. These activities teach how a resource can be identified, methods of harvest, efficient and non-wasteful processing of the resource, and preparation of the resource as a variety of food items. The distribution of subsistence harvests establishes and promotes the most basic ethical values in Native and rural culture—generosity, respect for the knowledge and guidance of elders, self-esteem for the successful harvest of a resource, and family and public appreciation in the distribution of the harvest. No other set of activities provides a similar moral foundation for continuity between generations.

Climate change that may restrict access to subsistence resources, whether through changes in abundance or availability, will have profound implications for the cultural fabric of rural Alaska. Culture is learned; failure to transmit the knowledge and experience of subsistence activities between generations results in the loss of a cultural repertoire even should the resource again become available twenty years later. The preservation of subsistence as a valued cultural activity depends on the transmission of cultural information. Restoration of the resource will not automatically restore the behaviors and values associated with the harvest of that resource. For example, the current presence of buffalo on the great plains has in no way restored the profound constellation of behaviors, ethics, values, and beliefs associated with this resource in Cheyenne culture.

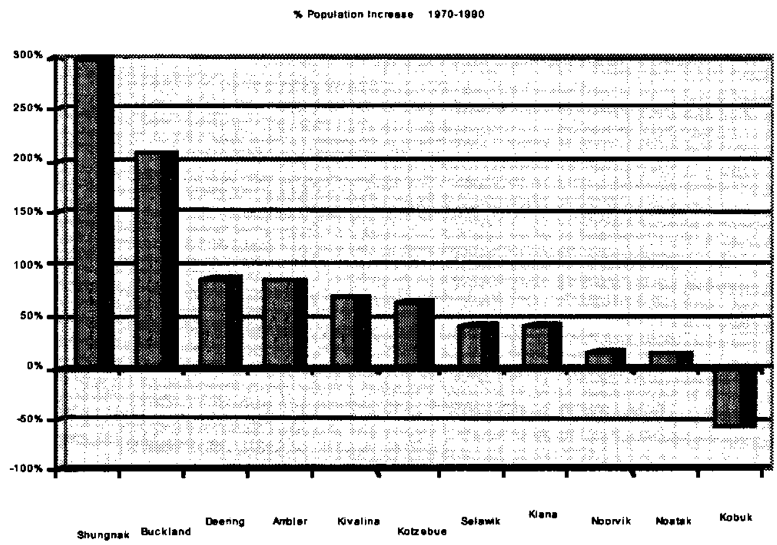
Northwest Arctic Borough

About 6,400 people live in the Northwest Arctic Borough, with about 85% of this total being Alaska Native, primarily Inupiat.

1996 Population Estimates (DOL)	
Ambler	298
Buckland	416
Deering	141
Kiana	394
Kivalina	349
Kobuk	78
Kotzebue	2,821
Noatak	413
Noorvik	575
Selawik	665
Shungnak	249
Total	6,399

Kotzebue, a hub that provides centralized transportation, commercial, and administrative services, is the largest community in the region. Regional demographic trends for the region during the period 1970 to 1990 indicate a substantial growth rate for the majority of communities.

Northwest Arctic Borough Communities Percent Population Growth 1970-1990.



Most of this growth is a product of natural increase, rather than migration. The one exception to this is the community of Kobuk, the smallest community in the region, which has a net loss of population during the last two decades. Very small communities often have difficulty sustaining their populations. In some cases, environmental factors such as erosion (by ocean or river) lead to the abandonment of a community. Other factors such as poor community infrastructure, especially the lack of running water, can also be major factors.

Half of the employment in the region is government-related (DCRA), with Maniilaq Association, the regional Native non-profit, being a major employer. The region's major private sector employer is the Red Dog Mine with about 15% of the region's employment but contributing about 30% of the region's total payroll. Red Dog Mine extracts lead, silver, and zinc and produces about 6% of the world's lead ore.

In its January 1996 overview, the DCRA's Research & Analysis Section notes that:

- ♦ Commercial fishing of chum salmon and trout, and fish processing at Kotzebue Sound Area Fisheries, provide some seasonal employment. One hundred and eighty-one area residents hold commercial fishing permits.

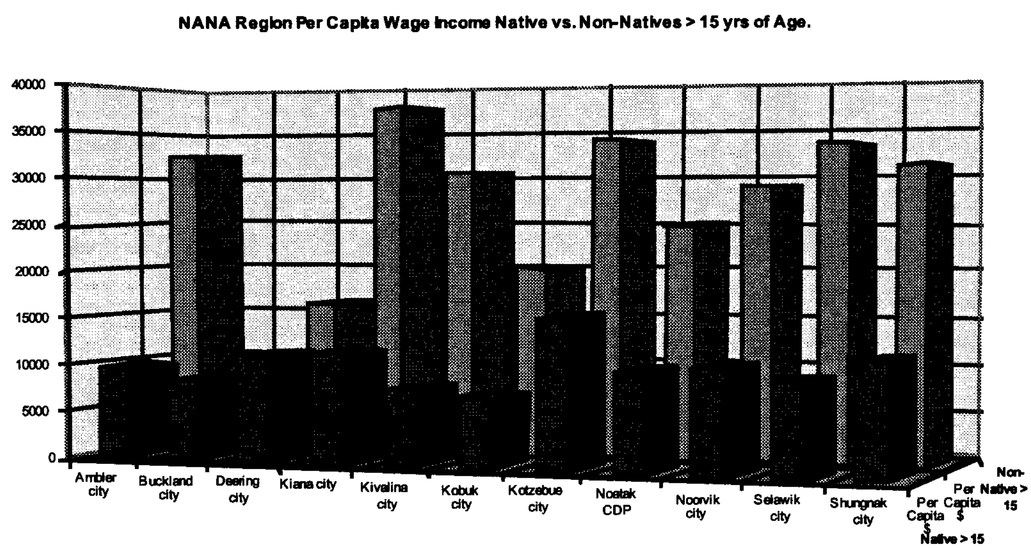
In outlying communities, cash employment is limited to the schools, clinics, local government, Maniilaq Association and some small retail stores.... Seasonal employment occurs with fire fighting, construction, barge operations, and fish processing in Kotzebue. An expanding Native crafts industry produces birch baskets, jade, ivory and caribou hoof carvings, fur pelts, masks, mukluks, parkas, hats, and mittens for sale throughout the state.

Reindeer herds are managed near Buckland and Deering providing some employment during harvesting. Often workers are paid in meat. **Most residents rely extensively on subsistence foods**. (emphasis added)

In 1994 the Northwest Arctic census region had about 16% of its workforce **un**employed. This was the highest rate in the state and about triple the national (and Anchorage's) rate. Most significantly, 42% of the adults surveyed in the 1990 decennial U.S. Census were not in the workforce. This is double the rate for a typical community in the U.S. The dynamics of these differences are also crucial. Excluding urban inner cities, most adults are not in the workforce because of child raising responsibilities or because of physical disabilities limiting their participation. In contrast discouraged workers, those that have sought employment to no avail, contribute to the high proportion in this region.

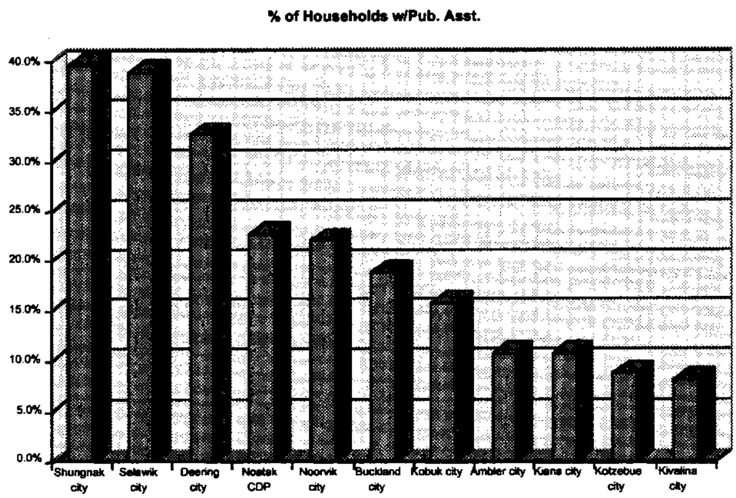
The returns from wage employment are also skewed with respect to ethnicity. Non-Native individuals over the age of fifteen are almost all wage earners and tend to have come to the community because of available specialized employment opportunities. Non-Native adults tend to be professional or highly skilled and educated workers that have relocated to take advantage of the high salary structures created to attract skilled workers (e.g., high school teachers) to this difficult environment (with respect to climate and available amenities). These workers tend to emigrate from the region when their jobs are eliminated. In contrast, Native adults (>15 years of age) have few employment opportunities within the community. The high proportion of Native unemployed and discouraged workers bring their average per capita incomes down considerably. As indicated below, the average Native adult earns about one third of the income of his non-Native counterpart. It must be noted, however, that the average full time employed Native adult would have a per capita income much closer to that of non-Native adults.

NANA Region Per Capita Wage Income



Complementary to the lack of employment opportunities in the region is a high dependence on public assistance. Public assistance include a multitude of programs ranging from old age survivor's insurance, unemployment, supplemental security income (for individuals > 62 years of age without eligibility for regular social security benefits), food stamps, WIC, Aid to Families with Dependent Children (AFDC), housing programs, and energy credits. There is enormous dependence on these sources of government transfers for rural communities in the Northwest Arctic region.

Percent of Households with Public Assistance



There are several key items that need to be kept in mind prior to an analysis of subsistence harvests. With the exception of Kotzebue communities in this region have:

- high unemployment
- high proportions of discouraged workers
- few jobs available in the community
- over half the jobs are from the government sector
- high dependence on public assistance and transfer income
- modest infrastructures
- high reliance on subsistence harvests

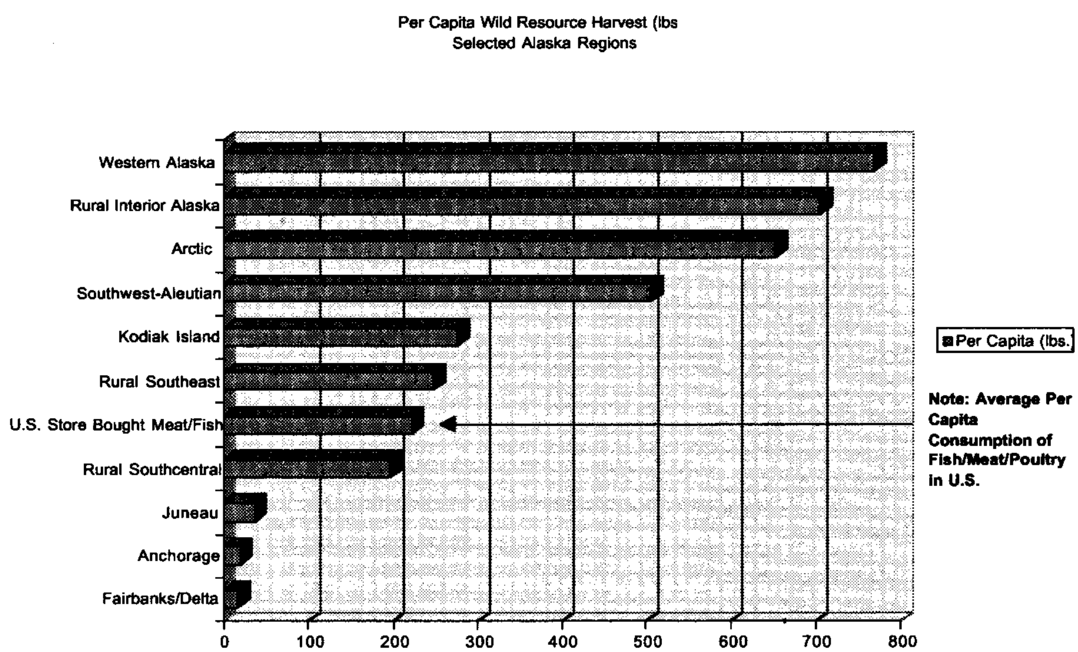
Harvest and Consumption of Wildlife Resources

Unfortunately, we only have harvest surveys for four communities in the Northwest Arctic region. Surveys were conducted during the 1990's, and the sampling design indicates the results are representative for the communities in question. While there are some differences in resource dependence among the four communities, all communities rely on a tremendous amount of fish, marine and land mammals to sustain themselves. Kivalina, a coastal community, is more dependent on marine mammals than are the other three communities. In contrast, Noatak, an inland riparian community, is more dependent upon land mammals, primarily caribou, than are the other three communities.

Per Capita Harvest (in pounds) by Resource Category

	Per Capita Pounds	Per Capita Pounds	Per Capita Pounds	Per Capita Pounds
	Kivalina	Deering	Kotzebue	Noatak
All Resources	761	672	593.0	461.0
Fish	253	228	238.0	179.0
Land Mammals	165	190	177.0	224.0
Marine Mammals	318	221	158.0	48.0
Birds and Eggs	11	24	3.5	4.5

Per Capita Harvest of Wildife Resources



The Arctic region annually averages about 650 pounds per capita in the consumption of wildlife resources. Rural Northwest Arctic communities are accessible only by air. Bulk items such as food are extremely expensive to transport. While Anchorage's food costs are about 25% greater than food costs for an average city in the U.S., food costs in the Northwest Arctic are about 300% above the national average.

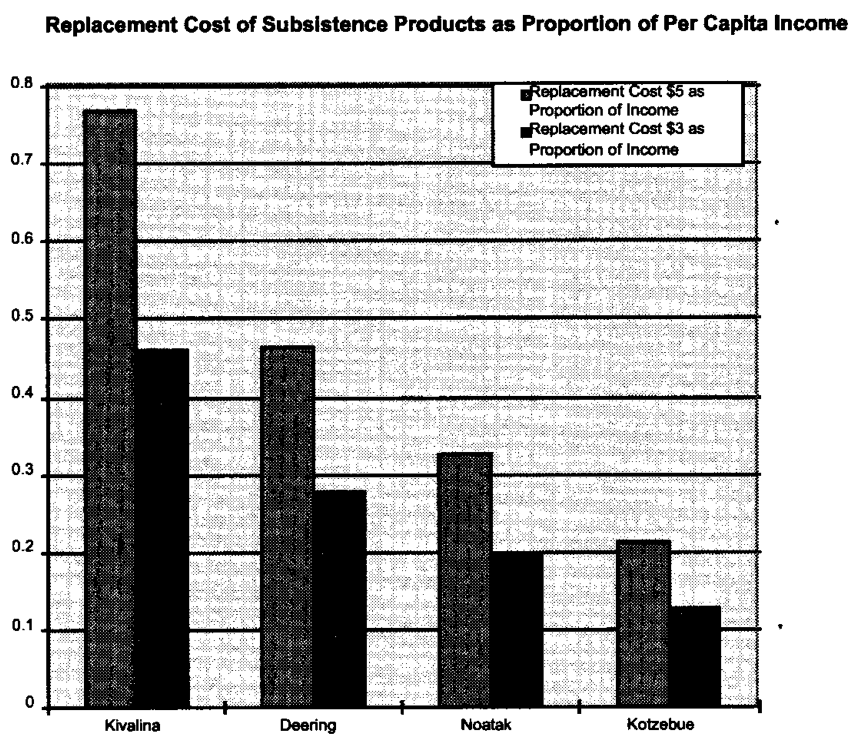
For the Arctic Region (which includes the Northwest Arctic, North Slope, and Calista regions), estimate an annual harvest of 10.5 million pounds of wildlife products per year. They point out that:

Attaching a dollar value to subsistence uses is difficult, as subsistence products generally do not circulate in markets. However, if families did not have subsistence foods, substitutes would have to be imported and purchased. If one assumes a replacement expense of $3-5 per pound, the simple replacement costs of the wild food harvests are:

Replacement Cost of Subsistence Products @ $3 & $5/lb

	Kotzebue	Deering	Noatak	Kivalina
Per Capita Income - 1990 Census	$13,906	$7,272	$7,089	$4,968
Replacement Cost $3/lb	$1,779	$2,016	$1,383	$2,283
Replacement Cost $5/lb	$2,965	$3,360	$2,305	$3,805

Percent of Income Required to Replace Subsistence Products



With per capita incomes ranging from $5,000 to $14,000 the total replacement cost of wildlife resources, in the four communities that have detailed harvest data, range from 13% to 77% of the **total income for that community.**

8.3 Additional Research Needed

Additional information that would contribute to improved decision making includes:

- comprehensive investigations of the vulnerability of the region's subsistence, commercial and recreational fisheries sectors to climate variability and change, where "vulnerability" is defined as a combination of sensitivity to change and flexibility to adapt and/or mitigate;
- improved understanding of the impact of sea level rise and other climate change impacts on fishing ports, coastal ecosystems, coastal communities, and related infrastructure;
- better information on demographics of subsistence communities, especially patterns of migration and the factors affecting it;
- consistent time series (historic and continuing) of multiple species surveys — especially important for subsistence considerations as well as understanding interspecific competition;
- investigations of the influence of emerging multinational investment strategies and business initiatives on fisheries in the region, particularly in the context of either ameliorating or exacerbating the impacts of climate change; and
- analysis of the consequences of changing state, national, and international legal frameworks and management institutions in either increasing or decreasing the region's vulnerability to the impacts of climate change on important species of fisheries, marine mammals, and sea birds.

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9. Coastal Systems

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9.1 Introduction

This assessment addresses coastal systems in the broader Bering Sea region, including mainland coasts of both Russia and North America from the Lena River to the MacKenzie River Delta, the entire coastline of the Bering Sea and the remaining coastline of Alaska adjacent to the Gulf of Alaska and Southeast Alaska. We define the coastal zone for the purposes of this assessment as the zone typically used by residents of coastal communities. We note that this definition is broader than that used for management of the coastal zone by state and federal agencies but we believe this definition is more appropriate for addressing dynamics of coastal systems associated with global change.

Topography and geomorphological processes vary substantially across this region. Much of the coast of the Bering Sea is dominated by river deltas and shallow bays and estuaries. A dominant deltaic feature of the region is the Yukon-Kuskokwim (Y-K) Delta, formed by alluvial deposits of the Yukon and Kuskokwim Rivers, which covers 79,280 km^2 of treeless tundra. Much of the Y-K Delta has extremely shallow topographic gradients. In contrast, much of the coast of western and northwestern Alaska is characterized by mountains and bluffs. On the north slope, topographic gradients are relatively shallow but because the coastline is not primarily of deltaic origin and tidal amplitude is small, coastal processes may be relatively less important on the north slope compared to much of the remainder of Alaska.

The Alaskan coast of the Bering Sea supports some of the highest concentrations of indigenous people living primarily a subsistence lifestyle at high latitude. Large concentrations of people also live in a few communities along the coasts of the Chukchi and Beaufort Seas. High densities of people depending on subsistence resources are undoubtedly associated with high productivity of foods in both terrestrial and marine habitats. Anadromous fish represent the principal source of both protein and calories for people in much of this region, although marine mammals play a much greater role on the Arctic coast. Indigenous people in this region have had significant contact with European/western cultures for variable periods, which combined with coastal and marine topography, results in substantial variation in economic opportunity and importance of cash income to overall economic conditions throughout the area.

One approach to regional impact assessment is to delineate potential disturbances to a region, characterize potential responses to such disturbance, and identify gaps in understanding of system dynamics that inhibit predictions of response to disturbance. Many potentially important disturbances in the Bering Sea coastal region fit within the broad context of global change. These include:

- climatic influences on tidal flooding, erosional and depositional processes;
- climatic warming and related effects on sea ice, snow cover, timing of spring thaw, and primary and secondary productivity;
- population dynamics and socioeconomic changes among people living in the Bering Sea region;
- human induced effects on migratory stocks (e.g., marine mammals, salmon, waterfowl) that use the Bering Sea region seasonally.

We focus on changes likely to occur within a time frame of a few decades, which is the frame of reference most relevant to stakeholders.

9.2 People of the Bering Sea Coast

The highest concentration of native people in Alaska occurs in coastal areas. Approximately 58,000 people live on the North American side of the Bering Sea, of which 60% are members of one of three Native populations. Major population groups in the greater Bering Sea region include Yupik, Aleut, and Inupiaq. The population on the Y-K Delta has doubled since 1960 (Wentworth 1994) and is among the fastest growing populations in the world. People living in the Bering Sea coastal region are distributed primarily in villages of 100-1,000 people, with a few regional centers of 2,000-4,000 people. None of these towns or villages occur on the road system, which increases expense of distribution of goods and services.

Potential for employment varies among areas. Commercial fishing provides about 10% of personal cash income in the Bristol Bay area, while oil development either directly or indirectly accounts for 50% of personal cash income on the North Slope. Employment is extremely limited on the Y-K Delta, with most employment associated with federal or state government or native corporations (U. S. Bureau of Economic Analysis). Limited employment is derived from commercial fishing. In 1992, the Community Development Quota (CDQ) program was initiated, allocating 7.5% of the catch from Bering Sea pollock and cod fisheries to villages on the Bering Sea coast. Recently, the program was expanded to other Bering Sea species, but it is currently scheduled to sunset in 1998. Funds from CDQs are contributing to economic development in the Bering Sea region.

Because of limited potential for employment in many coastal areas of the Bering Sea region much of the cash economy depends heavily on government transfers. Recent welfare reform legislation is of concern in the region because of limited potential for wage employment.

Relatively early stages of development of a cash economy means that people in the Bering Sea region depend on subsistence hunting and fishing for the majority of total calories (Schroeder et al. 1987). Therefore, changes in these resources will likely have a large impact on livelihoods of people living in the region. It is important to emphasize, however, that the modern subsistence lifestyle is heavily dependent on substantial cash income.

9.3 Future Changes

Numerous direct and indirect effects of global change are expected to influence the coastal zone of the Bering Sea region. Climate change is expected to produce substantially warmer temperatures in the Bering Sea region (Weller et al. 1995). Warming over the past 2 decades has substantially increased permafrost temperature and depth of thaw. Increased thawing in coastal areas will undoubtedly increase erosion of coastal peat. Erosion will be exacerbated by rising sea level and increased storm frequency and intensity forecast for the Bering Sea.

Coastal Processes and Erosion

Coastal areas of the Bering Sea region will be highly susceptible to changes resulting from both climate change and human induced changes. Low topographic relief over much of this area, combined with normally high amplitude tide cycles and high energy storm systems create the potential for substantial impacts on landscapes from slight increases in sea level and storm frequency. For example coastal areas on the Y-K Delta have been inundated nearly annually by storm surges during the fall period in the mid 1990's and in August during both 1995 and 1996. These fall storms deposit substantial sediment loads, significantly modifying coastal landscapes. In addition, these large storms likely increase erosion and ice scouring (fall storms). The storm in fall 1996 nearly flooded some houses in the coastal village of Hooper Bay. Storms during the normal nesting season can destroy nearly the entire nesting effort of several waterfowl populations.

Tidal amplitude along the coast of the Y-K Delta can be as large as 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. Aerial photography shows disappearance of up to 500 m of coastline in some locations, primarily exposed points, between 1950 and 1984. At Punyrat Point, 20 km south of Hooper Bay, 50 m disappeared between 1988 and 1993 (Sedinger pers. obs.). Erosion is also rapid on large former distributaries of the Yukon River, such as the Kashunuk and Manokinuk Rivers. At some points as much as 10 m of river bank have disappeared in a single growing season (R. M. Anthony pers. comm.). Erosion has forced movement of the village of Newtok in the central Y-K Delta. Such effects are likely to be especially pronounced on the Bering Sea coast itself because of generally shallow topographic gradients and high energy associated with storms in the Bering Sea. Increased frequency and intensity of storms in the Bering Sea, especially when coincident with increased sea level and seasonal high tides, is likely to increase erosion along the Bering Sea coast.

Erosion is also occurring along the north slope of Alaska. While tidal amplitude is reduced on Alaska's north slope, erosion may be substantial because of large seasonal storm surges. Erosion is exacerbated by thawing of permafrost and additionally by increased fetch associated with reduced sea ice.

Marine currents within the Bering Sea generally flow counterclockwise (Nelson et al. 1981) resulting in northerly flow along the Bristol Bay and Y-K Delta coasts (see Fig. 7.1, Chapter 7). These currents also produce generally northerly currents through the Bering Strait. Currents in coastal areas determine coastal sediment transport and the origin of terrestrial inputs into the Bering Sea. These currents also influence salinity because of their role in distributing fresh water inputs from the major rivers in the region, especially the Yukon and Kuskokwim Rivers.

Hydrological events vary seasonally throughout the region because of strong seasonal weather patterns and precipitation. Peak discharge from major rivers occurs in spring associated with snow melt in interior watersheds (McDowell et al. 1987). Severe flooding associated with high runoff and ice dams is common in villages along major rivers. Similarly, ocean currents vary seasonally. Sea ice slows currents within the Bering Sea, while strong wind driven storm surges are common during fall (McDowell et al. 1987). Fall storm surges may inundate coastal areas up to 16 km inland (Dupre 1980) and have caused famine in historic times because of the destruction of food caches. High hydrological energy associated with flooding events also produces the greatest risk of distribution of pollutants from industrial accidents.

Sediment deposition occurs at multiple spatial scales and plays an important role in habitat creation and landscape evolution. A series of barrier islands, resulting from coastal transport, extend along the central Y-K Delta coast. Large depositional zones coincide with bends on all rivers and sloughs. Deposition combined with erosion brings about rapid channel migration on time scales of decades to centuries. Rapid channel migration could impact village infrastructure as in the case of the village of Newtok. Channel migration also can destroy historical and archaeological sites. The Kavinik site near Chevak is rapidly eroding, and plans are underway to excavate the site to salvage artifacts. In general, dynamic landscape processes limit the maximum possible age of archaeological sites on the Y-K Delta.

Sediment is also deposited on terrestrial landscapes by storm tides, especially in fall. T. Jorgenson (unpublished) has recorded up to 4 cm of sediment deposited in coastal vegetation from a single flood event. Sediment loads decrease steadily along a transect extending inland from the coast. Sediment deposition undoubtedly plays an important role in maintaining levees along channels. Sediment deposits likely increase soil aeration and reduce soil water content, which in turn, influences plant distribution. These levees are important foraging habitats for geese because they support arrowgrass, a key food plant for geese.

Inundation of low lying coastal areas is also of concern, particularly along the Y-K Delta where much of the coastal area is currently subject to tidal inundation during storms. Sea level increase of only a few centimeters will inundate thousands of square kilometers of the coastal fringe of the Y-K Delta as well as increasing frequency of inundation by large storms in additional areas.

Sea Ice

Because of the importance to subsistence activities, changes of sea ice distribution are of special concern to residents of coastal areas in the Bering Sea region. Hunting of marine mammals occurs directly from shorefast ice in spring and distribution of ice influences migration patterns of marine mammals. There is substantial concern that retreat of sea ice from Alaska's north slope will enable whale migration to occur farther offshore, making whales unavailable to subsistence hunters (T. Albert 1992 unpubl. memorandum).

Extent of sea ice in the Bering Sea during winter has declined over the last 2 decades, which reflects an apparent state change in sea-surface temperature of the Bering Sea in the late 1970's. Southern limit of sea ice frequently extended as far south as Nunivak Island before the state change but only infrequently since. Distribution of winter ice influences distribution of marine mammals, and ice retreat in recent years is reducing access to marine mammals by subsistence hunters in the region. Ice conditions during spring influence timing of spring snowmelt and initiation of plant growth. Timing of snowmelt has important consequences for productivity of geese, an important subsistence resource.

Subsistence Resources

We have already discussed potential impacts of changes in sea ice distribution on hunting of marine mammals in coastal areas. Numerous other potential impacts on harvest of subsistence resources are likely to be associated with global change.

With few exceptions (e.g., bowhead whales and some waterfowl populations) subsistence harvest throughout the region is not surveyed annually, but total subsistence of fish in villages at the mouth of the Yukon River ranged from 1,983 lbs. per household for the villages of Emmonak and Kotlik to 7,633 lbs. for Sheldon Point (Wolfe 1981). Chum salmon were the predominant fish species in the subsistence harvest. Harvest of salmon on the Yukon and Kuskokwim Rivers and in Bristol Bay is regulated and monitored because of commercial value of these fisheries. No monitoring of subsistence fisheries on the central coast of the Y-K Delta occurs because these fisheries have little commercial value. Salmon in rivers on the central Y-K Delta coast, however, likely originate in the Yukon River and are shared with subsistence and commercial fishermen in the upper Yukon River (Criddle 1996). Furthermore, growth of the human population on the Y-K Delta could be increasing subsistence salmon harvest. This should be of interest because residents of the Y-K Delta rely on these fisheries.

Better data exist on harvest of migratory birds because of concern about these populations (O'Neill 1979, Raveling 1984) and because of international agreements relating to their protection. U.S. Fish and Wildlife Service has conducted harvest surveys in villages on the Y-K Delta since 1985 (Wentworth 1994) and a statewide summary of subsistence harvest of some waterfowl species was conducted in 1995 (Wolfe and Paige 1995). Klein (1966) conducted the first systematic survey of harvest of migratory birds on the Y-K Delta. Waterfowl harvests were generally lower in the 1980's (Wentworth 1994) than during the 1960's. It is unknown whether decline in harvest resulted from lower waterfowl population levels or changed hunting behavior. Waterfowl harvests since the mid 1980's have been proportional to population size (Sedinger 1996), suggesting that availability of waterfowl to hunters influences harvest.

Waterfowl are among the most closely monitored populations because they are of international importance and are a federal government responsibility. Therefore, waterfowl are surveyed annually in most important breeding and migration areas. Population trend data from these surveys extend back to at least the 1960's. Populations of geese declined substantially in the 1960's and 1970's, owing to overharvest on both wintering and breeding areas (O'Neill 1979, Raveling 1984). Reductions of harvest outside Alaska and management of predator populations have increased growth rates of these populations with the exception of emperor geese, which have not responded to management. High levels of lead shot ingestion have caused severe declines of several species of sea ducks nesting on the Y-K Delta. These declines have caused one population, spectacled eiders, to be listed as threatened and brought about restrictions on hunting activity.

Arctic Pollution

The greatest concern about pollutants is that global change will enhance entry of pollutants into arctic food chains, ultimately contaminating subsistence foods. Global atmospheric circulation is transporting pollutants from temperate zone industrial areas into the Arctic. Additionally, substantial concern exists for transport of pollutants by river from Russian industrial areas directly into the Arctic Basin. Improved technology and declining tensions with Russia are allowing closure of numerous U. S. defense sites and concern exists among arctic residents about residual contaminants associated with these sites. Changes in sea ice distribution and storm patterns are likely to influence transport, although in unknown ways. Increased flooding may transport raw sewage from village sewage lagoons into subsistence food chains. Changes in hydrological patterns and storm systems may increase rates of release of naturally occurring toxicants (e.g., heavy metals or naturally occurring hydrocarbons).

Socioeconomic Changes

Economic and social changes in human societies both inside and outside the Bering Sea region have the potential to profoundly affect the region over time periods of decades or less. For example, development has substantially altered wintering habitat of many populations of waterfowl that nest in Alaska. For some populations of geese these changes have been beneficial, e.g., adoption of grain agriculture has improved overwinter energy balance and population dynamics for some populations. Oyster mariculture and industrial salt production in Mexico, however, could negatively impact brant nesting in Alaska.

Market processes driven by influences outside the Bering Sea region impact coastal and marine ecosystems and humans associated with these systems in the Bering Sea area. Salmon farming has increased the supply of salmon worldwide, substantially reducing prices of chum and other salmon. Reduced prices have had important negative economic consequences for commercial fishermen in the Bering Sea area. The massive factory trawler fishery in the Bering Sea has unknown consequences on nontarget fish stocks (bycatch) and other species of marine birds and mammals. Such effects could negatively impact coastal residents directly by reducing subsistence resources or indirectly because fishing or hunting activities are restricted under the endangered species act.

Oil reserves exist in the Bering Sea and Norton Sound, in addition to those on the north slope of Alaska. Economic or strategic concerns could, in the future, favor development of these fields. Such development would likely have a positive impact on the economy of the region, although it would bring about a shift to an increasing dependence on the cash economy and possibly reduced subsistence. Coastal areas of the Y-K Delta are among the potentially most sensitive in the world to oil spills because of high tidal energy, low topographic gradients, and productive grazing ecosystems that extend to the edge of the normal high tide line.

Understanding social and economic change in villages is of fundamental importance to understanding global change in the Bering Sea region. Employment is still very limited in many villages. Education is in flux as villages incorporate more traditional knowledge into the curriculum while seeking to improve learning of basic skills. Infusion of cash and availability of food in village stores has reduced the apparent importance of subsistence hunting and fishing in the minds of many young people. Some young people appear to prefer recreation in the village to traditional subsistence activities practiced by the generation preceding them. Rapidly expanding population is straining housing, infrastructure, and social institutions in many villages. A vigorous sovereignty movement is altering the relationship between state and federal governments and village residents. Responses of residents of the coastal areas in the Bering Sea region will impact the relationships between these people and coastal ecosystems. Likewise, the response to changes in resource extraction, commercial fishing, and other economic development will have important implications for sustainability of villages in the region.

9.4 Uncertainties

Uncertainties about impacts of global change in the Bering Sea region exist in the full range of projections from changes in climate and sea level to socioeconomic dynamics. Improving forecasts of climate are of fundamental importance; in particular, improved understanding of air temperature dynamics, storm surges, and sea surface temperature is essential for predicting climate-related impacts in the Bering Sea region. Forecasting cyclonic storm patterns by global climate models has improved, but additional refinement of temperature prediction is necessary.

Prevailing marine currents in the Bering Sea are reasonably well studied. Response of such currents to changes in prevailing winds and sea surface temperature requires additional study. Additionally, increased understanding of storm surges is necessary to predict the impact of rising sea level and increased storm activity on inundation and erosion of coastal areas. We have a poor understanding of coastal sediment transport, which could offset some erosion at the regional scale. At a minimum, it is important to use remote sensing to document changes in coastal geomorphology that have occurred over the last 4 decades.

Most trophic interactions, such as those between herbivores and plants or between predators and prey are too poorly understood to predict how global change will alter ecological communities and subsistence resources. For example, warming of the active layer is projected to increase plant growth which could either: (1) increase herbivore populations if food is limiting, or (2) reduce herbivore populations if increased carbon accumulation reduces forage quality. Marine ecosystems are even more poorly understood, and it is not currently possible to predict how changes in sea surface temperature, marine currents, and storm activity will affect these ecosystems. Of particular concern to subsistence hunters is the effect of changing ice dynamics on movements of and access to marine mammals.

Dynamics of the human population and socioeconomic changes will likely have major impacts on the Bering Sea region over the next few decades. Yet, understanding these changes has received relatively little attention. Changes in the size of the human population of the region alone will undoubtedly influence subsistence resources. We cannot currently predict whether greater employment opportunities will increase (because of increased cash flow) or decrease (because of reduced available time) subsistence harvest. Additionally, development of mineral extraction and industry in the Arctic has unknown consequences for subsistence resources. The current level of debate indicates our poor understanding of these relationships.

9.5 Additional Research Needed

Clearly, there is a fundamental need to improve our understanding of major climatic drivers including temperature, precipitation, and storm patterns. It is also important to improve understanding of how oceanographic variables such as sea level, temperature, currents, sediment transport, and ice dynamics will respond to climate change. Virtually all trophic interactions in both terrestrial and marine ecosystems require research if we are to predict how populations of important subsistence animals will change in the next few decades. Improving understanding of dynamics of animal populations used by subsistence hunters and likely impacts of global change on these populations will require coordinated efforts by population biologists, ecosystem scientists, climatologists, and oceanographers. Understanding ice dynamics and how animals are likely to respond to changes in ice distribution will be very important to residents of coastal areas of the Bering Sea region. It is important to understand how changes in hydrological patterns, marine currents, and water temperature might contribute to release of natural or anthropogenic contaminants.

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10. Permafrost

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10.1 Introduction

Approximately eighty per cent of Alaska is underlain by permafrost. Much of this permafrost is warm and ice-rich and some of it is currently thawing (Osterkamp 1994; Osterkamp and Romanovsky 1997). If the current climatic warming continues, additional ice-rich permafrost will thaw creating thermokarst terrain. This is an uneven surface topography consisting of pits, troughs, mounds, and depressions (which may be filled with water) that forms as a result of thawing large volumes of underground ice. Thermokarst terrain severely impacts human and animal activities and can damage or even destroy the infrastructure and ecosystems that rely on the permafrost for a foundation (Osterkamp 1982, 1994).

The ice in ice-rich permafrost occurs primarily in the top 10 to 15 m of permafrost. Since permafrost thaws slowly from the top downward in response to warming at its surface (sparse data indicates values <0.2 m yr-1; Osterkamp and Romanovsky 1997), the problems caused by thermokarst terrain will be long-term. They would begin at the time that thawing starts and can be expected to last for a century or more. The amount of vertical settling produced by thawing ice-rich permafrost depends on the amount of ice in the permafrost.

In Interior Alaska, maximum values for subsidence of the ground surface because of thawing ice-rich permafrost are in the range from 5 to 10 m (Osterkamp et al. 1997).

The past is replete with examples of the effects of ice-rich permafrost on human activities and ecosystems (Pewe 1982; Osterkamp 1982, 1994; Osterkamp et al. 1997). These include:

- ♦ Abandoned and damaged houses in Alaskan communities (Fig. 10.1).
- ♦ Abandoned building at a radio transmitter site near Fairbanks.
- ♦ Abandoned hospital in Kotzebue.
- ♦ Abandoned and damaged roads and bridges (Fig. 10.2).
- ♦ Specialized and more expensive construction methods for roads, airports, pipelines and other structures (Fig. 10.3).
- ♦ High maintenance costs for roads, buildings and airports.
- ♦ Shortened lifetimes for roads and airports requiring short reconstruction cycles.
- ♦ Relocation of roads and airports caused by the presence of ice-rich permafrost and other related factors such as land slides.
- ♦ Thermokarst damage to agricultural fields.
- ♦ Increased sediment loads and siltation in rivers (Fig. 10.4).
- ♦ Destruction of trees in the boreal forest (Fig. 10.5).
- ♦ Ecosystem damage and destruction such as that occurring in the Tanana Flats, Mentasta, Healy and Cantwell areas (Fig. 10.5).

Figure 10.1. This house damaged by thermokarst in the Fairbanks area had to be abandoned.

Figure 10.2. Thawing of ice-rich permafrost and the resulting thermokarst caused this road to settle which required repeated patching to keep the road in service.

Figure 10.3. Trans-Alaska pipeline showing the above ground portion of the pipe supported by naturally refrigerated pilings. This expensive construction mode was required because of the presence of ice-rich permafrost which had to be kept frozen.

Figure 10.4. This river bank in ice-rich permafrost has been undercut a distance of several meters. The bank will eventually collapse putting trees, shrubs, organic material and large volumes of silt into the river increasing the sedimentation problem.

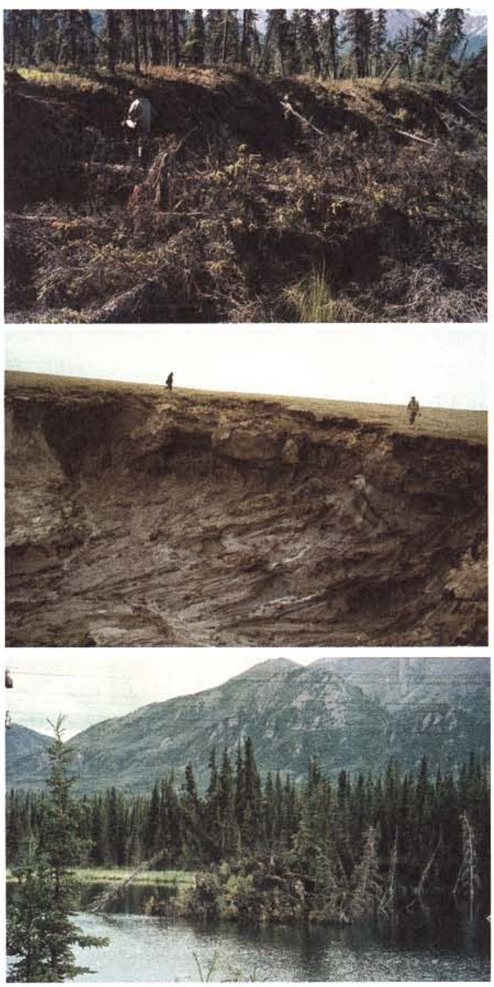

Figure 10.5. Examples of how existing ecosystems have been destroyed and are being replaced by new ecosystems as permafrost thaws:

a. Active thermokarst that is altering the boreal forest near Tok, Alaska, in an area of warm, discontinuous permafrost;

b. Active thermokarst in an area of continuous permafrost on the Gydan Peninsula, Russia;

c. An active thermokarst that has resulted in a pond. More than 5 m of vertical settling occurred. Note the dead trees in the water and tilted trees on the island, indicating that settling is still in progress (photos by Tom Osterkamp)

These impacts are a direct result of thawing ice-rich permafrost, subsequent settlement of the ground surface and creation of thermokarst terrain. Individuals have most often abandoned or moved houses and cabins when the effects of thaw settlement made them unusable. In a few cases, innovative designs were developed to retard or reverse the thawing which allowed continued use of the structures.

The human infrastructure that is affected by changes in the permafrostconsists of the basic installations and facilities on which individuals, families, communities and governments depend for their continuance and growth. In a broad sense, these systems include providing for food (including subsistence activities), water, waste disposal, transportation, communication, education, health and medicine, power, and goods and services for society. Disruption of these systems, including increased costs as a result of climatic warming, would have negative impacts on individuals and directly influence social, economic and political functions.

Much of the public infrastructure in Alaska has been placed under the Alaska Department of Transportation and Public Facilities (DOTPF) which is responsible for design, construction and maintenance of most roads, airports and many public buildings. Local government, federal agencies and industry are also responsible for design, construction and maintenance of the infrastructure. In 1990, in a cost-cutting move, the Alaskan legislature dissolved the DOTPF research laboratory which was involved in geotechnical research on permafrost. This may have led to the failure of remediation schemes used in recent road reconstruction efforts over ice-rich permafrost. Current and future projects where thermokarst degradation has occurred or is expected to occur include:

- ♦ Chena Hot Springs Road near Fairbanks which is being reconstructed because of thermokarst damage to the roadway. However, no special precautions are being taken to mitigate thermokarst problems. Pavement failures are expected soon after construction.
- ♦ The Deadhorse Airport runway and taxiway are being reconstructed because of settlement due to thawing permafrost. That permafrost has warmed about 4°C during the last decade.
- ♦ The recently proposed route for a road or railroad into Kantishna is over warm ice-rich permafrost and some of that permafrost is currently thawing (Osterkamp 1994).

Thermokarst reduces the useful lifetime of highways and airports and many highway and runway sections on permafrost must be releveled and repaved on a 6 to 8 year cycle. It is sometimes necessary to shorten airport runways due to a lack of funds for pavement repair which necessitates the use of smaller and more expensive aircraft. Some airports and road sections have been abandoned because of thermokarst problems.

It appears that engineers have few solutions to thermokarst problems. The policies of the DOTPF and other state entities and federal agencies have resulted in large maintenance costs for Alaska and direct public impacts. Apparently, there are no studies evaluating these policies.

10.2 Current and Future Changes

Continuous and discontinuous permafrost

While global and climatic changes are ongoing processes in the earth system, scientists have several reasons for concern. Global climate has warmed since the mid to late 1800s (Hansen and Lebedev 1987). In the circumpolar Arctic, permafrost has generally warmed, particularly in Russia, China, Alaska, and western Canada. In Alaska, the continuous permafrost warmed 2 to 4°C over the last century (Lachenbruch and Marshall 1986). Indications are that the discontinuous permafrost also warmed during this time period (Osterkamp and Romanovsky 1997). Climate and permafrost in many areas of the circumpolar Arctic continue to warm particularly in Alaska and parts of Eastern Russia in the Bering Sea region (Fig. 10.6).

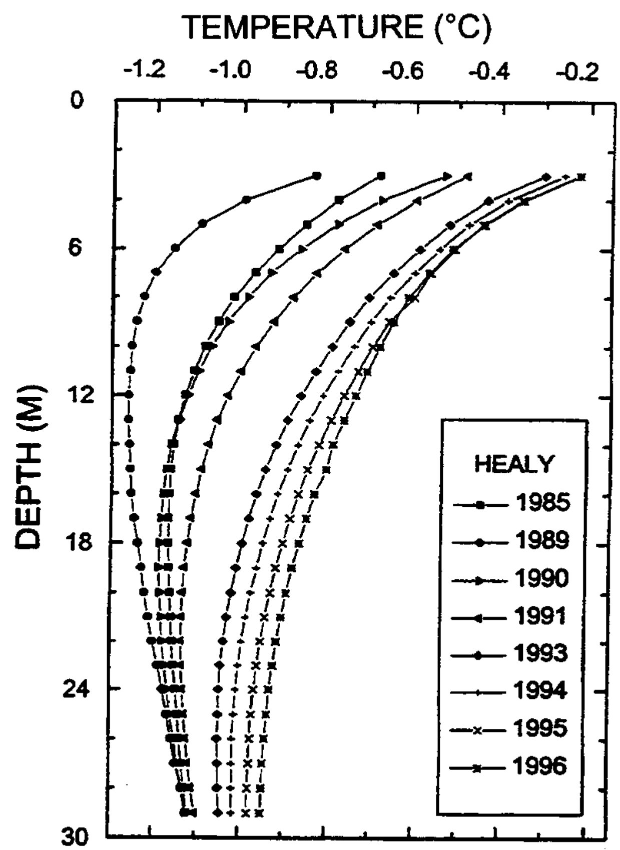

Figure 10.6. Temperature profiles in permafrost at a site near Healy, Alaska showing the warming of the permafrost that has occurred since 1989. Thermokarst has developed in this area in response to the warming.

All of our permafrost research sites along a North-South transect from Prudhoe Bay to Glennallen warmed between the mid to late 1980s and 1996 (Osterkamp and Romanovsky 1996,1997). In the continuous permafrost region, the warming ranges up to 4°C in the active layer and at the top of the permafrost. In the discontinuous permafrost region, the warming is typically between 1 and 2°C. At some of the sites, permafrost is presently thawing at both the top and bottom.

Thawing of ice-rich permafrost has been identified as the primary problem for infrastructures. Continued warming will cause additional permafrost to thaw. The effects of thawing ice-rich permafrost in response to climatic change will be superimposed on the effects associated with the infrastructure. Current climate scenarios predict 5°C additional warming in the next half century for northern regions. These results are causing considerable concern about the future of permafrost in Alaska and the impacts associated with warming and thawing of the permafrost.

An expected climate scenario for the Bering Sea region has been outlined by Weller et al. (Chapter 2) which indicates about a 5°C warming with the winter warming larger than the summer warming and with more precipitation in both the summer and winter. Air temperatures and depth of the snow cover influence permafrost temperatures. If the depth of the snow cover increases with no change in air temperatures then permafrost will warm. If there is an increase in air temperatures as well as depth of the snow cover then the effects of this climatic change will be magnified over that of an increase in air temperatures only.

The impacts of a climatic warming of this magnitude (5°C) will differ considerably for the continuous and discontinuous permafrost zones of the earth. A central paradigm of current research is that thawing permafrost will result in the release of carbon deposits frozen in the permafrost and that these deposits will lead to increased fluxes of trace gases to the atmosphere creating a positive feedback loop. Figure 10.7 is a schematic showing some of the relationships between climate, soil and permafrost, biota and human activities.

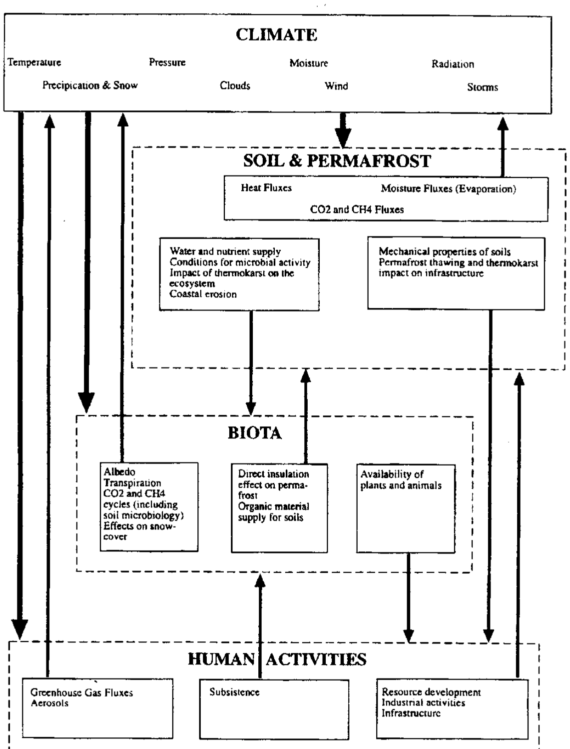

Figure 10.7. Schematic diagram showing relationships between climate, soil and permafrost, biota and human activities.

Some of the continuous permafrost has warmed almost continuously since the mid-1980s. However, mean surface temperatures are still typically colder than -5°C so that only warming of the permafrost is expected with no widespread thawing anticipated except that which will be associated with localized sites such as south facing slopes, with possible thickening of the active layer and with two-dimensional heat flow effects as in the banks of rivers and lakes. Increases in the depth of the snow cover would lead to a greater warming of the permafrost than indicated by a warming of air temperatures alone.

Thaw lakes, eolian activity, vegetation, and coastal, geomorphic and hydrologic processes in this region may be sensitive to climatic warming (Brown and Andrews 1982). If the active layer thickens by thawing of the near-surface permafrost, this will result in the release of carbon currently stored (frozen) in the permafrost leading to enhanced production of carbon dioxide and methane gases. Where the permafrost is ice-rich, this thawing will produce subsidence of the ground surface resulting in thermokarst terrain commensurate with its ice contents and thickness of the new active layer. This thermokarst would result in some damage to the ecosystem.

Permafrost temperatures in the discontinuous permafrost zone south of the Yukon River in Alaska and on the south side of the Seward Peninsula are very warm, typically within 2°C of thawing (Osterkamp 1994). Data from a north-south transect of Alaska shows that all of the sites south of the Yukon River warmed between 1989 and 1996, a period with unusually heavy snow fall (Osterkamp and Romanovsky 1997). The warming ranged from > 1/2°C to about 2°C at the permafrost table. At some of the sites, permafrost is presently thawing at both the table and base in response to this warming.

If these data can be extrapolated to other areas, then it can be inferred that the discontinuous permafrost south of the Yukon River and on the south side of the Seward Peninsula has recently warmed and that much of it is currently thawing.

The impacts of thawing permafrost on human activities and the physical environment will differ depending on the permafrost ice content.

- If the permafrost is not ice-rich, warming and thawing of the permafrost will be limited to thermal effects and to the effects of converting the ice to water. Impacts on the infrastructure will be relatively minimal.
- Where the permafrost contains massive ground ice or is ice-rich, extensive thaw settlement (resulting in thermokarst) is expected. The magnitude of this thaw settlement has been observed to exceed 5m and to reach 10m, in some cases, of vertical settling of the ground surface. Induced thaw settlement is presently responsible for damage to houses, roads, airports, military installations, pipelines, and other facilities founded on ice-rich permafrost.

Engineering Concerns in Permafrost Terrain

The surface vegetation (moss) and underlying organic soil are usually destroyed or severely damaged during construction. This vegetation and organic soil insulates the permafrost from the effects of summer warming and its removal causes the permafrost to warm by several degrees and the active layer to become deeper or for a talik (thawed layer) to form. Once a talik forms the permafrost thaws continuously (throughout the year) from the top downward inducing thaw settlement if it is ice-rich. A heated structure on the permafrost will enhance thawing of the permafrost.

Induced thaw settlement is presently responsible for damage to houses, roads, airports, military installations, pipelines, and other facilities founded on ice-rich permafrost. Any natural increase in the MST of permafrost and subsequent thaw settlement would create severe maintenance problems for facilities in Alaska adding to effects already being observed. Some structures, airports and roads might have to be abandoned if funds are not adequate to continue repairs (Esch and Osterkamp 1990).

The physical and mechanical properties of permafrost are generally temperature dependent and, for warm permafrost (permafrost within one or two degrees of thawing), depend strongly on temperature. Most of the engineering concerns related to a climatic warming can be classified into those related to an increase in permafrost temperatures, those related to increases in the active layer thickness (annual thaw depth), and those related to the degradation of the permafrost.

Engineering concerns related to a general warming of the permafrost result primarily from the decrease in mechanical strength, especially compressive and shear strengths, and the increase in creep rates of frozen ice-rich soils. Ad-freeze bond strengths between permafrost and piles or structures are also strongly temperature dependent. As an example, piling designed for a permafrost temperature of -4°C will experience a 70% loss in load capacity if the permafrost temperature rises to -1°C. Because of the presence of unfrozen soil pore water solutions in warm permafrost, the problems may be expected to be even more severe as the temperature of warm permafrost approaches the thawing point. Reliable methods of predicting permafrost temperatures over the life of a facility and information on the physical and, especially, the mechanical properties of warm permafrost are needed to help evaluate these problems.

Systematic increases in the thickness of the active layer may be expected to lead to thaw settlement of underlying ice-rich permafrost. Increased frost heaving during winter and increased frost heave forces on pilings may also be expected when the active layer thickness increases. Better understanding of the processes associated with active layer development are needed to evaluate this problem. The effects of saline soil solutions found in coastal and other areas on freezing and thawing in the active layer need to be understood.

Active layer thicknesses generally depend, among other factors, on the amplitude, timing and duration of temperatures during the thaw season. Therefore, climatic predictions must address changes in seasonal temperatures to be helpful in evaluating active layer problems.

As noted above, continued climatic warming and increases in the depth of the snow cover will eventually cause much of the discontinuous permafrost in Alaska to thaw. Thawing begins with thickening of the active layer and, eventually, a talik (a layer of ground that remains unfrozen throughout the year) develops when the thaw depth exceeds the depth of seasonal freezing. Continued thawing at the permafrost table results in continued thaw settlement in ice-rich permafrost. The effective length of a piling in the permafrost will decrease while the frost heave force on the piling reaches its maximum. Thermokarst terrain, increased downslope soil movement and landslides, and other terrain features common to degrading permafrost may be expected to appear (Osterkamp 1982). Roads, airfields, railway embankments and other foundations on degrading permafrost may be subject to continuing deformations as a result of the thaw settlement. Accurate predictions of the climate-permafrost response at a regional level are needed to assess the timing, duration, and severity of these problems. New and innovative engineering designs will be required to solve them.

Ecosystems effects

In areas of ice-rich permafrost, thaw settlement and the development of thermokarst will destroy the substrate on which the current ecosystems rest dramatically changing the nature of the ecosystems. It has been observed to result in damage to the ecosystems and sometimes in the total destruction of the ecosystems and their conversion to other types of ecosystems. Most of the following impacts have already been observed and are not speculation.

- Destruction of trees and reduction in area of boreal forests (Fig. 10.5 and 10.6).
- Expansion of thaw lakes, grasslands and wetlands (Fig. 10.6).
- Destruction of habitat for caribou and terrestrial birds and mammals.
- Increased habitat for aquatic birds and mammals.
- Increased rates of coastal and riverbank erosion (Fig. 10.4).
- Clogging of salmon spawning streams with sediment and debris (Fig. 10.4).
- Increased slope instability, landslides, erosion.
- Talik development with increased depth to water table.

The infrastructure also has some effects on the landscape and biota which may change as a result of climatic warming. For example, small birds are known to migrate along north-south highways. In areas of low hydrologic gradients, the roadbed can dam the surface water flow causing the death of trees and thereby modify the ecosystem on that side of the roadbed.

In the short term, ecosystems will change dramatically as ground surface collapse up to several meters will cause soil disruption, changes in topography (thermokarst), local flooding, tree die-off, and forest stand re-initiation. Resulting decreases in slope stability will increase erosion, mass wasting and sediment loading of streams.

Longer term consequences depend on depth of permafrost, hydrologic changes via modified local topography, greater infiltration, and less runoff, and resulting changes in vegetation colonization and succession. Deeply frozen soil may take decades to thaw, lengthening the transition period and delaying the attainment of any new steady state. Following thaw of near-surface permafrost, soils without water tables perched over permafrost may be drier than they are currently, likely promoting fire and fire-tolerant species in lieu of white spruce.

In the Tanana Flats south of Fairbanks, for example, Jorgensen (1997 unpublished data) has observed that graminoid species replace birch and spruce in areas temporarily flooded by thermokarst. Poorly drained areas may remain flooded longer, resulting in larger and more numerous wetlands and thermokarst ponds. Permafrost thaw ultimately will have beneficial results as well. Because of greater infiltration and less water table perching, watersheds containing only unfrozen soil will be less prone to flash flooding during rainstorms. Where sufficient moisture is available, warmer soils will promote greater productivity of newly established forest stands. Engineering of roads and structures will be easier and less expensive after permafrost has completely thawed.

Other impacts

Other impacts that were considered included increased snow fall, increased frequency of storm events and increased run-off, glaciers and frost heaving. Increased snow fall would decrease visibility, increase snow removal costs and possibly lead to increased frequency of road and airport closures. Increased run-off from storms, increased precipitation and increased flooding would create problems for bridges and culverts and drainage structures. This would add to the problem of increased discharge from glaciers. Wetter soils may lead to increased frost heaving of structures. However, these potential impacts are considered to be of minor importance compared to the major impacts associated with thawing ice-rich permafrost.

10.3 Uncertainties

Uncertainties associated with the above potential impacts are primarily related to the predictions of current climatic models, a lack of knowledge of current conditions and a lack of information on the economic impacts of thermokarst on the infrastructure. The spatial scales of current climatic models are too large for use by design engineers who need information on temperature, precipitation and wind at local scales for design purposes. Information on current conditions, particularly climate and permafrost is sparse in Alaska. There are few primary climate stations in Alaska, an area quite large compared even to the size of the contiguous U. S. Information on temperatures in permafrost on the Alaskan side of the Bering Sea come from two sites, one at Nome and one at Bethel. The next closest sites are more than 400 miles to the east.

Costs of thawing permafrost do not appear to have been evaluated. These costs appear to be staggering. Some idea can be obtained by considering that the original cost of the Trans-Alaska Pipeline was $900 million dollars for a conventionally built pipeline buried in the ground. The final cost was over $7 billion dollars, an eight-fold increase, largely because of the presence of unavoidable ice-rich permafrost along the route. Another example is a 1 km length of Farmer's Loop Road adjacent to the University of Alaska at Fairbanks built on ice-rich permafrost where in excess of $5 million dollars has been spent on maintenance and reconstruction of the road without solving the problems.

Thermokarst could lead to the abandonment of villages in low-lying areas. Relocation of these villages would be a major economic impact. The DOTPF had to move their maintenance facility at Gardiner Creek because of damage to the buildings by thawing and settling of the ice-rich permafrost.

Direct costs to the public of thawing ice-rich permafrost have also not been evaluated. As noted previously, some homes have been damaged or abandoned because of thermokarst. There are increased costs associated with shorter airport runways. There is clearly lost time and increased wear and tear on vehicles because of rough roadways and it is believed that some lives may have been lost because of rough roadways.

If the climate does not change from the current condition where air temperatures in Alaska have been warmer for the last twenty years (since 1976) than the previous twenty years and where snow cover has been unusually thick during the last decade (Osterkamp and Romanovsky 1997), then permafrost will continue to thaw. The data base on permafrost temperatures is too sparse to predict the distribution of this thawing.

10.4 Additional Research Needed

Climate

Thorough analyses of recorded climatic data in the Bering Sea region is needed to assess the timing, magnitude and distribution of recent climatic changes and those during the last century, particularly changes in air temperatures and snow depth. Remote stations that are not influenced by local anthropogenic changes need to be established. Climate models should be verified using data through the mid-1970s and should be capable of predicting the changes that occurred at that time. Improved high resolution climatic models need to be developed to improve climatic change scenarios, to improve predictions of seasonal changes in air temperatures and precipitation and to improve the spatial resolution of the models for engineering design purposes.

Permafrost

Investigations of the current and past state of the permafrost in the Bering Sea region are needed to develop an improved understanding of how permafrost has responded and is responding to changes in climate over the last century. The processes by which permafrost thaws are poorly understood. For example, data on heat and mass flow during talik formation and the creation of thermokarst are almost nonexistent. More information is needed on the distribution of ice-rich permafrost and on the formation of thermokarst since thermokarst is responsible for most of the engineering concerns in permafrost regions.

Engineering

Engineers need to know the state of the permafrost at the project site and what will happen to the permafrost during the life of the project. Information on the properties of warm and thawing permafrost will be needed. At some point, strategy should shift from mitigating the effects of thawing permafrost to that of causing the permafrost to thaw. Methods for pre-construction thawing of the permafrost need to be identified and developed. New and innovative engineering designs for construction on warm and thawing permafrost will be required. Geophysical methods for detection of ground ice and potential thermokarst areas are available (Kawasaki and Osterkamp 1985). Policies and personnel for their use should be developed within DOTPF.

Policy and Economics

Current policies of the DOTPF and federal and state agencies for construction on permafrost terrain carry associated costs and have a direct impact on the public. These policies, costs and impacts need to be identified and documented. For example, case studies of pipeline, road and airport design, construction, repair and reconstruction are needed to define the costs and impacts of policies during a climate warming scenario and to identify new policies that would reduce these costs and impacts.

10.5 Mitigation and Adaptation Measures

Research is needed to identify the problems, impacts and costs of a climatic warming associated with maintaining the public infrastructure and develop ways and means to mitigate the negative effects of a climatic warming.

Programs are needed to inform the public, develop an awareness of the potential problems and provide aid in identifying problems and solutions not only in the major population centers but also in the many villages in rural Alaska.

State and federal agencies should identify areas, sites and facilities that may be subject to the negative impacts of climatic change. These should also be rated according to the severity of the impacts expected for them.

Changes in current policy of the DOTPF and federal government could help to mitigate the effects of thawing ice-rich permafrost. For example, purchase of the necessary land and easements for a construction site or route selection is currently done just prior to the construction project. This policy does not allow sufficient time to carry out inexpensive mitigation measures prior to construction. One method would be to strip the vegetation and organic soil at the ground surface five years or more prior to construction to let the permafrost thaw naturally. Installation of a gravel pad or roadbed for summer use could be done during this period. This method would allow the location of the ice-rich permafrost to be determined and the top several meters to thaw naturally.

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11. Non-Renewable Resource Development, Transportation, and Energy

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11.1 Introduction

The Western Arctic is supplier and source for a large fraction of the non-renewable resources for the rest of the world. Alaska, Northwestern Canada, and the Yakutia Republic in the former USSR, contain large reserves of oil and gas and also contain vast coal resources, only a portion of which have been explored, discovered, or exploited.

The several predicted effects of climate change on the production, storage, and transportation of oil, gas and coal, on mining, and on infrastructure have important implications both negatively and positively for the economy of the northern hemisphere.

Climate alone is not and will not be an over-riding determiner of the distribution of infrastructure and non-renewable resource development. Rather, human needs and the economic viability of various mines, oil fields, and industries will drive the need for infrastructure. These are inherently political and economic decisions, not scientific decisions. Political and economic decisions will evolve from a competition for fiscal resources. It is within the framework of economic competition that climate-change enters the decision-making process by affecting the costs of doing business or the costs to support human needs.

An economic activity such as a mine or oil field will be judged on the basis of its return on investment and it must compete with similar activities throughout the world for investment dollars. If, for example, thawing of permafrost reduces the costs, the activity becomes more viable. If that thawing increases the costs, the activity is less likely to secure the necessary investment funding. Both increases and decreases in costs of doing business are likely to occur as a result of climate change.

The public decision process, however, is rarely driven by considerations of fiscal return on investment. It is determined rather by social costs, protection of minority interests [from abuses by majority interests], solution of problems beyond the capability of the private sector to solve, and issues of the general welfare. It is to the several governmental bodies that those negatively affected by climate change will often resort for assistance. In the event of major infrastructure losses and social dislocations, the public will probably seek political responses to the problems. Rational economic decisions to climate change problems may be overridden by governmental responses.

In Alaska, for example, taxes and revenue sharing from petroleum production and its infrastructure have represented about 85% of state government revenue and a substantial portion of local government revenue. The North Slope Borough, and numerous villages within the borough, depend on petroleum taxes to provide their citizens with the preponderance of their energy, jobs and services. Citizens of the Fairbanks North Star Borough, for example, derive 36% of their payroll from petroleum (ISER Review, September 1996).

Alaska's existing and developing mines employed 2,580 persons statewide in 1997 and project employment of 3,285 in 1999 (Alaska Minerals Commission 1997). Across the Western Arctic petroleum and mining sustain a substantial level of domestic and export economic activity and the jobs necessary to sustain the population. The combined employment of mining and petroleum averaged about 10,000 in 1996 (Alaska Economic Trends, April 1997).

Energy production by means of hydroelectric systems, fossil fuel, and other less-standard techniques, will be affected by changes in glacial melt, river flow, transpiration, snow accumulation, precipitation, average wind speed, changes in annual temperature, solar radiation, changed physical access to fuels, and impacts on the infrastructure of power generation and transportation.

In Alaska most of the several hundred small rural villages satisfy their total energy requirements with petroleum products imported by boat. Climate effects on the river systems, port facilities, and hindrances or improvements in ocean transportation will have vital impacts on the energy needs and transportation of supplies for the future vitality of these communities.

Rural community residents are supported in large part by governmental transfers (Huskey 1992). For example, in 1995, Norton Sound region received $7,541,000, the Interior region received $5,952,000, and the Lower Kuskokwim region received $7,657,000 which constituted about 60% of the total (Alaska Economic Trends). As climate alters the environment, local residents may be unable to support themselves from subsistence or market sources, leading to considerably magnified effects upon the level of state government transfer obligations.

In addition to the direct effects of climate change, several other associated industries are affected. Principal among these are the insurance and banking industries. The destructive storms recently inundating the Atlantic coast of America have brought US and foreign insurance companies to conclude that their financial risk analysis process, which is based upon past experience, is inappropriate for a changing climate. Natural disasters were 94% more frequent during the 1990s than they were in the 1980s. While the jump may result from normal variations, the increase matches the patterns predicted for global warming.

Seeing these changes as a possible preview of the costs that a changing climate may impose on society, insurers must set their premiums in anticipation of major future losses and change their strategies for dealing with long-term investments. Rising sea levels, changing storm paths and intensity, and storm surges will erode and breach the beaches protecting the huge amount of both insured and uninsured coastal property on the North Pacific, Bering Sea, and Sea of Ohotsk coasts. Rising insurance costs could adversely affect the creation of new infrastructure, jobs, and other elements of the economy based on its creation and maintenance. Changing insurance company and banking investment patterns will affect the creation of new or replacement infrastructure and businesses in the Western Arctic.

11.2 Current and Future Changes

Water resources

Water resources in Alaska will be affected by a myriad of offsetting or enhancing effects that will vary widely across the state. Predictive capability, both in terms of global circulation models and in regional circulation models is insufficient to ascertain which areas of the state will be wetter or drier. Thus, only broad generalizations are possible.

Precipitation Trends

Global-circulation models generally predict 50-100 percent increases in precipitation in high latitudes. Although the increases may be less than this overall in Alaska, precipitation increases statewide in the range of 10-30 percent are commonly expected. Locally, however, precipitation is controlled by storm tracks interacting with the mountain ranges of the coastal and interior Alaska. This interaction may result in large precipitation shadows in which precipitation is locally decreased at the same time that increased temperatures are causing higher rates of evapotranspiration. The result may be local areas that are significantly drier than has been typical this century, whereas the state will be generally wetter overall.

At least for the southern half of the state, the position of the Aleutian low determines which areas receive more or less precipitation. An easterly position feeds cyclonic storm tracks into Southeastern Alaska. A more westerly position of the Aleutian low feeds storm tracks into south-central and Western Alaska. (See also Chapter 7.) During the 5-year period 1977 - 1981, for example, Pacific winter storms delivered large volumes of snow to the Kenai Mountains in South-central Alaska. This increased snow resulted in positive mass balances for Wolverine Glacier in four out of the five years, in spite of increased melting brought on by slightly higher temperatures. During the same time, Gulkana Glacier in the Alaska Range had a positive balance in only one year.

In Northern Alaska, warmer temperatures, a longer ice-free season, and more open water on the Arctic Ocean will lead to increased rates of evaporation. This evaporated water will then be available for delivery as rain and snow in coastal and uplands areas. During both winter and summer, precipitation is likely to increase.

Permafrost and the Effects of Thawing

Thawing of permafrost in Interior and northern Alaska will increase rates of infiltration and amount of storage in aquifers and the active layer. This will generally result in decreased flood peaks and increased base level flows. The reduction of peak flow caused by increased infiltration of rain into the aquifer is likely to be offset, however, by increased frequency and quantity of precipitation. Similarly, the increase in base level flow may be offset by increased rates of evapo-transpiration and by decreasing volumes of melt water from glaciers. Base level flow reductions associated with recession of glaciers will be most severe in basins with small glaciers that disappear during a warmer climate.

One of the biggest impacts of melting glaciers and snow fields may be to the hydropower industry. Most of Alaska's major hydropower sites obtain large volumes of water from melting glaciers. Glaciers are an excellent buffer in the rainfall-runoff relation, slowing their melt as rains increase during cool, rainy weather and increasing their melt when rains stop during hot, dry weather. As glaciers become significantly smaller, flow variability will increase, resulting in the need for larger reservoirs to meet power demands during low-flow periods.

Summer base level flow in streams is critical to water transportation. A warmer climate is likely to yield a longer shipping season in most of Alaska's major rivers. Some streams draining areas with decreased runoff, however, may have periodic summer flows too low to permit barge traffic. Most north-flowing rivers in Alaska have no winter base level flow; the rivers stop flowing from December until spring breakup in May or June.

As the climate warms, aquifers may develop in alluvial fans along the front of the Brooks Range. These may lead to more persistent winter base level flow. This increased winter base level flow may produce icings in streams, ditches, and culverts that are currently free of icings during much of the winter. Icings along roadways will generally increase maintenance costs.

In the interior basins, such as the Fairbanks region, permafrost under the valley bottoms acts as a confining layer to retard the flow of deep ground upward into the stream. Slowing this upward flow in the valley bottoms is important to maintaining water levels under adjacent hill slopes. As the permafrost thaws, flow to the creeks is less impeded, and water tables under the hills decreases. In the Fairbanks area, thawing of permafrost in the valley bottoms may result in many wells having to be deepened or drilled in new locations.

Sewage Disposal

Increasing exploration and development of Alaska's mineral and renewable resources and its growing population will put increasing pressure on sewage-treatment facilities. The effects of climate change, however, are likely to be largely positive and will partially offset the impacts of the larger system capacities that will be required to meet the expanded demands. Less extensive permafrost, increased depth to the water table, and increased ground-water fluxes will generally enhance the performance of systems that discharge to the subsurface. Increased stream flow, particularly base flow, and decreased ice cover will enhance the aeration and dilution of effluent from waste-disposal systems that discharge to streams.

Water Engineering, Design, and Effects

Water is a construction material in northern Alaska, where fresh water is applied to the land surface to create ice roads. Warmer temperatures on the North Slope will decrease the amount of fresh water that is locked up each winter when many lakes freeze nearly to the bottom. This will leave more water available for construction of ice roads. Although more water will be available, a shorter season of freezing will result in less time during which the roads can be used.

Although water is used for ice roads, it may pose a hazard to conventional roads, pipelines, and other infrastructure. Storms are likely to be more frequent and more intense with warming. Bridges and culverts designed for the climate of the mid-twentieth century may be under-designed for the 21st century. Migrating stream channels, which generally shift during periods of high flow will also be a hazard. Of particular concern are the roads and pipelines built across alluvial fans in mountain regions. There floods are often quick and intense, and flood frequencies are poorly defined. Channel avulsion may quickly shift the flow into an area where the infrastructure is not adequately protected. The Trans-Alaska Oil pipeline has already been exposed in one such area.

11.3 Oil and Gas

Oil and gas exploration and production will continue to shape the direction of the Western Arctic economy. The petroleum industry is the largest component of the Alaskan economy, in recent years contributing roughly $15 billion annually, or 70% of Alaska's gross state product (Institute of Social and Economic Research 1997). Current stresses on the Alaskan economy arise from the continued decline of petroleum production from the North Slope, which peaked in 1988. Possible new exploration and development in the northeastern National Petroleum Reserve in Alaska may offset this decline in the future.

Exploration and Development

Almost 30% of the nation's undiscovered technically recoverable conventional oil resources are estimated to occur in Alaska (U.S. Geological Survey 1995). Current pressures on the petroleum industry include the need to locate and develop new resources in increasingly hostile and environmentally sensitive locations throughout the Western Arctic. Off-shore and ice-rich remote area exploration and drilling involves use of more complicated technologies which dramatically increase costs. In Alaska, the Kuukpuk, Thesis Island, Jones Island, Sandpiper, North Star, Endicott, Liberty, Badami, and Pt. Thompson units on the North Slope, a sizable portion or all of the units lie off-shore. Continuous changes in land and ocean climate conditions will require completely changing the engineering techniques originally devised for present environmental conditions.

Decreased ice cover, changes in wind and ice drift patterns, release of previously shore-fast glacier ice all provide threats to shoreside or off-shore infrastructure affecting the cost and complexity of off-shore Arctic oil extraction. Providing ice reinforced structures and ocean bottom pipelines capable of resisting the forces of ice islands and the ice pack will be necessary. Transportation of petroleum field development and maintenance supplies will change and may become much more difficult as well.

Transportation

Because increasing technologies permit smaller surface disturbance in the development of oil fields, the greatest impact from changing climate will be effects on maintenance of the transportation infrastructure needed to deliver the petroleum to refineries and the market. Sustained production of petroleum in Northern Alaska will require increasing demand for sand and gravel to maintain haul roads, pipelines and airports that deteriorate due to melting permafrost. Rising sea levels and coastal erosion may affect the locations near Cook Inlet and elsewhere in the Western Arctic where refineries are currently located on shore-side locations, and likewise may affect the associated port facilities. With reduced sea ice, however, there may be an increased probability of ocean transportation of crude oil and liquefied gas which could lower costs and increase markets for these Arctic resources.

Consumption, Demand, and Market Trends

International commitments to reduce greenhouse gas emissions imply potentially substantial economic losses for Alaska's petroleum industry, a major contributor to the state's economy and a significant source of nationwide production. Alaska has the two largest producing oil fields in North America, accounting for 25 percent of U.S. production (State of Alaska 1995 b.1). Royalties and taxes on oil make up nearly 85 percent of the funding for state government, and the oil and gas industry contributes both directly and indirectly to virtually every sector of the state's economy (State of Alaska 1995 b.5).

Ironically, the very dependence of the state's economy on petroleum creates an unfavorable investment climate by increasing the vulnerability of the petroleum industry to higher tax rates (State of Alaska 1996,6). High exploration and production costs have discouraged some companies from staying in Alaska. Declining productivity of the North Slope, which is expected to decrease at a rate of about 5 percent per year, has state and industry officials investigating the possibility of constructing a natural gas pipeline to supplement area income. There are possibilities, however, that improved technologies and new discoveries may reduce the rate of decline in total production.

Climate change can increase the demand for oil to generate energy for cooling in lower latitudes. Increased temperatures in Arctic areas may decrease the local fuel requirements, but while total per capita consumption may still be high, the total consumption is low in the North compared to southern areas.

Policy

Politically, measures to reduce greenhouse gas emissions such as a carbon tax, may provide a strong incentive for petroleum producers/exporters and the citizens of Alaska to unify around the objective of achieving special subsidies or exemptions. Other stresses such as rising sea levels and coastal degradation in areas such as Prudhoe Bay, may lead to requests for disaster relief. Because of the importance of petroleum to the Alaska economy, political developments affecting oil prices or consumption can be expected to have large but unpredictable impacts.

Mining

The mineral industry in the Western Arctic has some of the greatest resource potential in the world as yet largely untapped. Advancing technologies and geological concepts and access to new areas in the Russian Far East make it feasible to pursue mineral targets that were previously impossible. Economic and political decisions related to changing climatic conditions will determine when and whether these targets are exploited.

In Alaska, the most important economic minerals are, in order, zinc, gold, lead, coal, sand and gravel, building stone, silver, copper and jade/soapstone. In 1996, the value of Alaska's mineral production was estimated at $551 million (Alaska Minerals Commission 1997). The benefit to the nation is significant; Alaska's Red Dog mine (located North of Kotzebue, Alaska), for example, is the world's largest zinc producer and supplies approximately 7 percent of the world's production.

In many ways the mining industry will benefit from increased average temperatures. Easier access to, extraction and transportation of ore may result. Although placer operations currently provide about two-thirds of the gold being mined, future production is expected to shift to lode deposits. The removal of overburden in open pit mining of lode deposits will be eased greatly by climate warming (Swainbank 1997). Increase in temperatures will decrease costs of fuel, extend the mining season, decrease maintenance costs on equipment, release water for various cooling and washing functions and may possibly reduce the need for and cost of snow removal. Underground placer mining efforts, practiced chiefly in the Russian Far East will be adversely affected by the loss of the stability provided by permafrost (Swainbank 1997). The work season for small-scale placer mining will be increased.

One of the largest future stresses on the production of mineral resources may arise from thawing permafrost and the resulting decay of the support infrastructure. There will be an increasing demand for sand and gravel for the repair of road/trail/railroad systems, and building stone/rip rap to repair and stabilize coastal erosion and river channels and bridges. This will come at a time when the industrial minerals sector will be under increased pressure to support a deteriorating infrastructure in the rest of the Western Arctic. There may be a shift in the present market for industrial minerals, from the private sector (petroleum production, timber roads) to the public sector (repair of roads and airports). Changing patterns of energy consumption induced by climate change may divert interest to the extraction of Alaska's extensive coal deposits. Alaskan coal is considered an untapped national resource whose size probably exceeds 40 percent of the total coal resources in the rest of the United States (Stricker 1991).

Other Pressures on Petroleum, Transportation and Energy Industries

- Loss of infrastructure from natural disaster including storm surges aggravated by sea-level rise.
- Effects of weather variables on buildings and roads conditions.
- Reduced costs of snow and ice removal and reduced frost damage to roads and bridges.
- Sea-level rise may require raising most bridges to ensure sufficient under-clearances.
- Sea-level rise could infiltrate the base of roads & streets necessitating added reconstruction costs and large additional costs to petroleum field and mining facility owners to improve drainage, raise yards and pump sewage.
- Reductions in frost damage to roads, in road maintenance and in road reconstruction.
- High humidity weaken alumina cement, and low humidity and high evaporation rates lead to plastic cracking of concrete
- Increased air pollution may pose threats to metals and other building materials
- Stresses on settlement ponds and containment areas for hazardous wastes from industry production activities.
- Decreased life of vehicles and other metal objects owing to increased use of salt for snow and ice mitigation
- Potential abandonment or relocation of industrial sites may be required as a result of climate change
- Changes in availability of water, may affect the viability of industrial facilities dependent upon that resource.

- Increased need for sea ice location information and ice cover assessment for changing sea routes
- Changed need for plotting hazards to shipping of ice island drift.
- Negative effects on stability of existing oil and gas pipelines.
- Water resource changes could reduce or increase use of barge traffic, thereby changing traffic on competing transport modes such as railways or roads.
- Changes in building design to accommodate to climatic change. These could include road layout affecting the placing of buildings, greater use of new, more weather-tolerant materials.

Stresses On Solid Waste Infrastructure

The solid waste management infrastructure in Alaska will be affected by three stresses of a warming climate change: increased solid waste generation during the period of change, loss of existing solid waste disposal sites, and changes in future solid waste disposal sites.

Flooding/ coastal changes

Rising ocean water levels will flood many existing repositories of solid waste. The area more affected will be in the southwestern part of Alaska in the Kuskokwim and Yukon River lowlands where large areas (and the landfills in them) will be flooded. Many of the villages and cities in the area will be forced to relocate or cease to exist altogether as separate entities. Impacts will go far upstream on many Alaskan Rivers due to their low relief and the fact that communities are located right on the rivers for their primary access.

Similar extensive effects will be seen in areas of the Seward peninsula and around Barrow. Other areas in the South central and Southeast will have more localized impacts but effects could be considerable depending upon the location and elevation of their landfills. The Matanuska/Susitna Valley and the Anchorage areas (with over half the state's population) will be spared from having their current landfills inundated since they are at sufficient altitudes.

Such sites would be especially vulnerable during the period when shorelines are moving and wave action will be eroding a front preceding shoreline advance and exposing currently stable buried waste. Another problem that can occur is leaching of contaminants from landfills that become under water or where the water table rises into the waste zone and leaches contaminants to the surface or other parts of the aquifer. The final impact to the environment from situations such as these could range from insignificant (in areas where non-toxic organics are leached to the ocean or large rivers with strong currents) to serious (where toxins are leached to areas where flow conditions are stagnant in estuaries or marshes or where critical human uses are involved, etc.)

The opportunities to address the problems of landfill flooding will be seriously hampered because it will happen at the same time that communities are concerned with relocating their homes, schools, businesses, infrastructure, etc. (as explained below or will soon to be abandoned will be competing with needs that are more primary to subsistence, i.e., a family, collectively, a community concerned with moving to another city or the lower 48 states is not going to place high priority on dealing with the waste dump left behind.

Waste Generation

A second and perhaps the largest stress on solid waste during a major climate change will be unprecedented waste generation due to abandonment and rebuilding of communities and infrastructure. As mentioned above, rising waters will cause this in current to future tidewater areas and in the discontinuous permafrost areas south of the Brooks Range.

Information needed to evaluate the magnitude of this increased waste generation is probably in existence and rough estimates could be compiled. It will be necessary to build new structures. The communities needing this rebuilding can be tabulated and the construction industry can estimate wastes generated in this process. Roads, railroads, power distribution systems, sewers, etc. will need to be constructed or reconstructed and factors for waste can be gotten from those involved with such current construction.

Information can also be obtained on structure and infrastructure demolition and salvage to come up with factors on unusable wastes resulting from these efforts and the potential toxicity of these wastes. Uncertainties involve the timing and the specific demolition/reconstruction sites. Reuse of materials might be possible if relocations are gradual (over a 50 year period) and new site/old site locations are economically close (just uphill).

However, this may not be the way it happens. For the coastal areas at least, the impetus for change will often be those storm events causing swift and unrecyclable damage. Here again, uncertainties will be whether a structure is severely or only partially damaged and whether the person or business decides to rebuild in a totally different community rather than the original inundated site, e.g. in Anchorage rather than Bethel. In the interior, increased frequency of large wildfires may be the deciding damage/reconstruction factor. Permafrost melting will produce large scale damage and rebuilding of the infrastructure, but timing of impacts will be more gradual and predictable, recycling more technically advanced and locations in current or adjacent corridors.

Landfill Site Availability

The availability of landfill sites will gradually increase in interior Alaska as discontinuous permafrost melts, ground settles, and those areas change from permafrost wetlands to something drier. In areas where tidewaters will encroach far inland, current sites will be eliminated (these may be in communities which will need them most). Moving waste materials from areas where sites are being eliminated to areas where sites are being created will be difficult.

Real Estate and Banking Industry

A 1 m sea-level rise if it occurs, is likely to cause major problems on the coastal plains-producing coastline recession of up to several kilometers, displacing coastal infrastructure, villages and depriving many industries and people of their land and resources. The intrusion of saltwater into coastal ground water supplies, erosion of flat land, and storm damage to ports and other coastal facilities will have impacts on government, law, the insurance industry and the availability of capital to accommodate changes.

Although there are few analysis of such impacts, there is every reason to believe that if climate change were to occur at the high end of the projected ranges, the consequences could be serious for many parts of Alaska. A minor sea level rise could cause population displacements in the river delta regions of Alaska as well as in the state's largest city, Anchorage.

Sea level rise and increased run-off in streams and rivers may have a significant, if not devastating, effect upon state, federal, and international banking industries and global financial markets. Loss of property from natural disasters such as the predicted storm surges, an increase in sea levels, and changes to fresh water availability and drainage could result in significant loss of financial value due to the resulting destruction or from population migration (Hertsgaard 1996).

According to some weather models, even a small rise in global temperatures can be devastating to regional and global ecosystems. Increased melt waters from Alaska's vast glacial networks may cause significant river flooding and mud slides, forcing surrounding populations to relocate. Real estate values may plunge in such areas and rise abruptly in areas capable of absorbing such migrating populations.

Coast and river real estate are particularly vulnerable to the effects of global change. Indeed, financial investments in such areas are at risk and the capital markets may be stressed beyond available funds in their ability to make resources available for required clean-up and reconstruction. "... Financiers have come to realize that they have at risk literally trillions of dollars worth of insured property and long-term investments." "Peter Blackman, assistant director of the British Banker's Association, prepared a memo...that warned that more than half of current bank lending is 'affected by environmental factors' and that within the 20 to 40 year 'lifetime of loans granted today, climate change is forecast to have a dramatic impact..."(Hertsgaard 1996).

Governmental and business policies relevant to such matters will need to be developed that protect both lending and real estate institutions as well as corporate interests and the private citizen. Future development in areas particularly vulnerable to the impacts of global change may be in jeopardy in securing sufficient capitalization.

Energy production/ distribution/storage/consumption/markets

Governmental policies initiated in response to climate change may have affects on the structure of energy investment. Response strategies to change may cause some Arctic countries to become more reliant upon nuclear power while others may rely more on renewables. More energy-efficient fossil-fuel technologies, or shifts among types of fossil fuels can affect investment and consumption.

Non-climate-related environmental factors may also act as constraints on the rapidly increased reliance on non-carbon energy systems such as hydroelectric power or nuclear power. A serious constraint on increased reliance on nuclear power will be satisfying public concerns regarding safety and the adequacy of waste disposal. Increased construction of hydroelectric projects may require considerable human resettlement and flooding of important ecological resources. This is a particularly interesting issue as water availability, timing, glacial melt, and precipitation will be affected by global change.

Climate variability and a change in heating/cooling requirements will produce losses or gains depending on the area. Changes in requirements will produce changes in the level of pollution and change the transportation requirements. Storage of fuel in coastal areas may require new design criteria and siting requirements to preserve the safety of the storage facilities.

As Alaska's economy is almost entirely dependent upon the oil industry, any future regulations which limit the extraction, transportation, and subsequent use of these fossil fuels may have a devastating impact on the state's economic stability. Moreover, according to a recent IUCC report, a proposed tax on the carbon content of oil, coal, and gas might discourage the use of and hence exploration for fossil fuels. Such a tax might also curtail or seriously delay the proposed Alaska gas pipeline construction and limit the exploration and overseas export of Alaskan coal products.

Permafrost thaw will also impact the energy industry. In the case of North Slope oil production and transportation, thawing permafrost may cause significant problems for existing pipeline systems throughout the state. A rise in river levels, due to increased precipitation and/or increased glacial melt, would require additional engineering studies and perhaps reconstruction of threatened sections of pipeline and related infrastructure.

Off-shore drilling and production islands may be threatened by changes in ice movement and changes in the pattern and flow of ocean currents, as well as by inundation. The ease of shipping may increase with decreases in average ice thickness, but may be threatened by an increase in the number of free-floating glacier pieces and ice islands. Petroleum exploration and field transportation now conducted over seasonal ice and snow cover may be in jeopardy raising the cost to the environment and increasing the need for new technologies for oil exploration, production and transportation.

The delivery systems for electrical energy throughout Alaska may need significant modification as ground-based high and low-tension distribution poles may become unstable due to thawing permafrost, flooding, and increased erosion in river bottoms. Predicted increases in wind speed, which have already damaged certain stands of Alaska's forests and the potential for increased rime-ice formation, may also require the redesign or more frequent replacement of distribution lines. Regulations and policies which take into account these considerations may be needed to avert these negative impacts. Hydroelectric generation may be a clean and viable option, yet unknown scenarios in glacial melt may make assessment of the alternatives difficult.

Ocean Navigation: Navigation Aids/Charts/Bathymetry

Ocean shipping will be affected by ice cover and timing of break-up, changes in storm frequency, intensity and paths. Weather changes may affect prevailing wind velocities and directions requiring adjustments in sailing directions and coast pilots. Ocean shipping will also be affected by changes in ocean currents, tides and changes in bathymetry requiring perhaps an increase in the frequency of coast line surveys and the replacement and change of navigation aids. The capital costs of changing these public facilities and services will be an additional burden on government.

As precipitation changes & glacial melt occurs, river water levels may be affected greatly and ocean levels will change. River courses will be affected by permafrost thaw and erosion effects of changes in currents and bank collapse Increased river transportation may supplant or complement existing road and rail transportation methods.

Trans-Arctic shipping may become a high priority and a much easier endeavor in a warmer climate with reduced sea ice extent and thickness. The Northwest Passage and more likely the Northeast Passage may have increased use. Extending the shipping season and ports served will require an increased level and extent of navigation aids and ice monitoring.

Water Supply/Quality/Distribution/Sewage Disposal/Floods

Changes in the availability and location of potable water supplies due to changes in weather patterns could alter population distribution and jeopardize industrial facilities dependent on these supplies. Changes in water levels throughout Alaska's river system could reduce or increase the conduct of barge traffic, thereby changing traffic on competing modes such as aircraft, roads, and railways. Flooding rivers may require relocation of many rural and native Alaskan communities, fish camps, and other settlements leading to a breakdown of the community's infrastructure and thus the existing social and cultural frameworks.

Predicted rapid population growth will by itself tax the world's fresh water supply well into the next century. The predicted growth in the Western Arctic's population in the same period will also place increasing demands on the water resources. Increased warming in winter and increased evaporation may have a profound effect on the water cycle.

Rising sea levels may cause leaching and intrusion of salt water into coastal community fresh ground water reserves making them unfit for human consumption. Communities may have to reduce pumping of water to prevent aquifers from being refilled with sea-water. Concentration of salts from run-off and reduced levels of water supply in drier areas may both impair the quality of available drinking water. The associated costs of protecting coastal communities from such disasters and preventing constant land erosion would be enormous and place cultural and historic sites, potentially valuable tourist attractions, and fishing centers at risk. On the other hand, shipping in some localities, such as shallow ports on the Bering Sea, would benefit from a higher sea-level. Additional investments would be needed to adapt existing sewage and water supply systems to accommodate increased demands placed upon these infrastructures.

Changes in the timing of water cycles and the volume of precipitation may directly and adversely affect human health. Increases in flooding and storm surges associated with sea-level rise may increase the pollution of water supplies from incursions into solid waste and sewage systems. Melting permafrost may also increase the incidence of water-borne disease by leaching of disposed wastes into ground water supply systems. If water quality were to diminish, public health services would have to address outbreaks of several existing Northern diseases. A reduction in quality might engender the incidence of opportunistic diseases not now normally found in the North. Wide-scale disruption of communities could include psychological stresses on environmental refugees and place enormous pressure on existing public health facilities and workers. The economic impact of such scenarios would place additional financial demands on the insurance and banking industries.

11.4 Uncertainties

The spatial distribution of the effects of a changing climate are too poorly known to make conclusive plans for dealing with the site-specific effects of the changes. Changes in precipitation will be positive for some areas of the state and negative for others. Rates of permafrost melting will vary greatly, depending on local terrain, temperatures, snowpacks, vegetation cover and other factors. Current monitoring stations for ground water, surface water and water quality are too sparse to enable researchers to detect changes that probably are already occurring.

A principal difficulty in constructing studies of the likely impact of climate change on human habitat in the Western Arctic is the fact that many other factors largely independent of climate change, e.g. demographic trends, technological innovation, evolving cultural tastes, employment opportunities and transportation modes, may significantly shape where and how people will choose to live and work in the future. Changes in the requirements for resources will determine many of the eventual affects in the North. With climate unfortunately the only thing we can be sure of is that all other things will not remain equal.

One can reliably predict that certain Northern societies will be more vulnerable to climate changes than the highly industrialized areas because they are already at the limits of their capacity to cope with climatic events.

Significance of rates of change

If the rate of change in climate is rapid, it could overwhelm our ability to adapt and modify our technologies, laws, financial and human support structures. This impact could cause human migration and would lead to conflict over resources. Capital equipment, buildings, industrial plants all are designed with set lifetimes and then one normally replaces them. If the rate of change is so rapid and severe to require abandoning structures and facilities before the end of the a normal lifetime, much greater costs may be incurred and the society's ability to respond may fail. The potential seriousness of the affects are beginning to receive notice even from those who may have to bear the cost of mitigation such as James Browne, the President of British Petroleum, who stated that "It would be unwise and potentially dangerous to ignore the mounting concern." (San Jose Mercury News 1997)

11.5 Additional Research Needed

Careful analysis of the economic issues related to climate change is a high priority for further research leading to identifying the economic and social stakeholders, development of effective strategies to mitigate the effects and appropriate decision making by the stakeholders. Research and development related to energy efficiency technologies and non-fossil energy options also offer high potential value. In addition, there is also a need for research on the development of sustainable consumption patterns.

The information needed to refine the magnitude of climate change impacts on solid waste sites are the location, size, and elevation of the existing landfills throughout the state. This information should exist for operating landfills and could be put together. More difficult is assembling this information for inactive landfills especially ones containing hazardous wastes (both public and private agricultural, hatchery, mining, industrial, military, etc.) chemical or radioactive wastes.

Substantive research concerning the specific impacts on Alaska's non-renewable resources is needed. This paper merely skims the surface of potential impacts and suggests areas of concern. An action plan representing the interests of the state and federal governments as well as industry needs to evolve as a result of shared concerns and ongoing partnerships.Finally, a survey of the vulnerability and resiliency of water basins is needed to support water-use planning in the event that climate change has its predicted impacts.

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12. A Framework For Integrated Assessment

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12.1 Introduction

The preceding chapters identified the major pathways by which changes in the global climate, coupled with other global changes, may affect people in the north and the role of the north in the world economy. Most of the links between global change and human impacts involve large cumulative uncertainties. We are doing well if we can confidently predict the direction of probable change.

The proposed approach to integrated assessment framework reflects the large uncertainties associated with the causes of ecosystem change and the intense concerns of Native peoples in the region that the Bering Sea ecosystem will continue to sustain their cultures. We can combine research, local knowledge and an adaptive approach to policy development to improve the chances that the Bering Sea ecosystem will continue to sustain Native peoples in the region and serve as an important contributor to the economies of Alaska and the nation as a whole. This chapter presents a draft framework for an approach to integrated assessment of ecosystem changes in the Bering Sea. The elements shown in the framework are discussed in some detail in the preceding chapters. The intent here is to show how the human impacts of global change are likely to result from a combination of environmental changes and human responses

The proposed approach of integrated assessment is based on the premise that we are more likely to develop sound public policies if we can distinguish between true uncertainties and the uncertainty that arises from difficulties in simultaneously taking into account multiple sources and pathways of change. An example of true uncertainty may be, for example, that we do not understand enough about ecosystem processes to relate pollock harvests to steller sea lion population changes. An example of uncertainty due multiple sources and pathways of change is how aggregate subsistence harvests of all resources will change over the next 20 years. If we can pool our understanding of the processes that we think may be affecting each type of subsistence resource, we will be better able to assess the likelihood of simultaneous decreases in multiple subsistence species.

Finally, the proposed approach reflects the limited funding currently available to support research and the application of indigenous knowledge in the Bering Sea region. We can more effectively use these dollars if we develop a common understanding of the full range of environmental changes and their potential implications for human well-being.

12.2 Major Pathways of Ecosystem Change

Dramatic declines in Steller sea lion, harbor seal, spectacled eider, and Kittiwake populations have caused Native people in the region along with scientists, environmental organizations, and wildlife managers to worry that the Bering Sea ecosystem as a whole has become unstable. The coincident growth in pollock stocks has led some people to link large pollock harvests with ecosystem changes. People are also concerned that concentration of contaminants in marine mammals may have affected their health.

During the same period that the pollock stocks expanded, however, air temperatures increased over the eastern Bering Sea, reducing the extent of sea ice. This change may have decreased the surge in primary production associated with the retreat of sea ice. We do not know the relative contributions of climate change, harvests of resources, and even the possible role of contaminants in the observed changes in the Bering Sea ecosystem. We also do not know the relative contributions of climate change and forest management practices on tree mortality due to insect outbreaks.

The costs of taking the wrong actions, or not taking the right actions, are potentially enormous. The culture, social relationships, and livelihood of Native residents in the region are inextricably bound to the region's biological. If commercial fish harvests in the region are mainly responsible for declines in marine mammal populations, for example, then failure to reduce commercial harvests may mean an end of subsistence harvest activities that form the core of Native culture and a primary basis of valued social relationships.

At the same time, commercial fishing industries annually harvest thousands of tons of pollock, salmon, herring, cod, and flounder. If declines in marine mammal populations are mainly the result of climate induced ecosystem changes, then actions to reduce commercial harvests may mean the unwarranted loss of millions of dollars to the fishing industry and to the communities which are closely tied to that industry.

Ecosystem changes in the Bering Sea region are not limited to the ocean. Large areas of ice-rich, discontinuous permafrost are subject to thawing (e.g. south side of the Seward Peninsula, see Osterkamp paper). The resulting landscape would likely be poor habitat for reindeer and caribou, both of which are important to the mixed subsistence-cash economy of the region. Reindeer and caribou populations could also be affected by a potential increase in the frequency of storms that produce icing and snow crusting conditions.

Communities themselves are subject to the effects of coastal erosion and inundation resulting from storms in the region. Understanding how changes in the frequency of such storms may change is of concern to residents, insurance companies, and agencies charged with the responsibility for maintaining the public infrastructure.

A substantial decrease in the extent of sea ice could also make marine transportation a viable option in the Arctic. The transport of petroleum products through Arctic waters introduces new opportunities and risks.

The forests of the Bering Sea region constitute another environmental change of concern. Coastal and Boreal forests are important as habitat for subsistence resources and themselves constitute commercial resources.

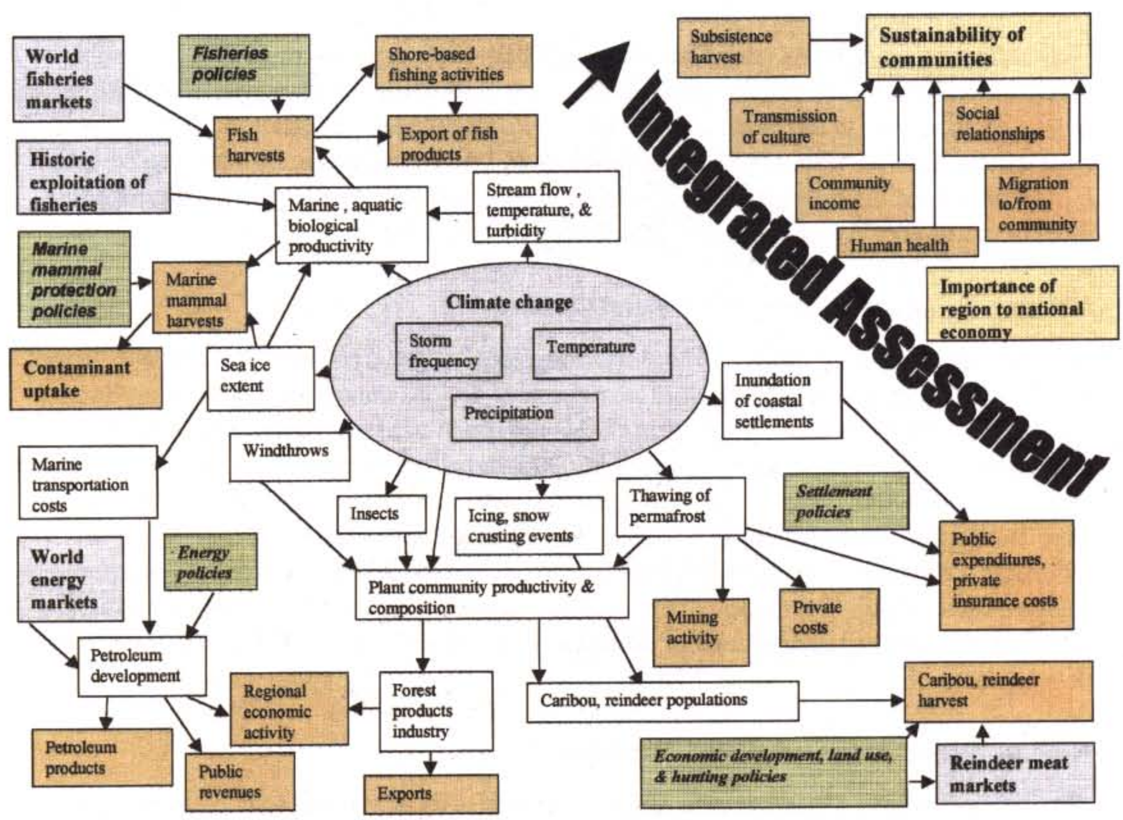
12.3 Uncertainties

We know too little about the Bering Sea ecosystem to be able to explain, much less predict, ecosystem changes. The observed changes in the ecosystem, however, are too alarming to ignore. We therefore need to devise an approach to action which both recognizes the large uncertainties and which simultaneously builds and applies knowledge of the ecosystem.

The approach suggested here distinguishes between uncertainty about a specific pathway by which ecosystem change may occur, and the cumulative uncertainty stemming from the large number of such pathways we need to take into account at the same time. We can reduce cumulative uncertainty by clearly describing each causal pathway. In particular, we need to identify how each causal pathway is related to an outcome of direct importance to people.

12.4 Integrated Assessment Framework

Figure 1 is an attempt to illustrate the pathways of major interest to an integrated assessment of ecosystem changes in the Bering Sea region. My intent is to provoke discussion. I expect, and indeed hope, that Figure 1 will substantially change as a product of discussions. I have attempted to incorporate major pathways identified by other workshop authors.



The sustainability of communities in the region and the importance of the Bering Sea region to the state and national economies are my suggestions for the two principal ***targets for assessment***. I am not suggesting that all Bering Sea Impact Studies research include a human dimensions component. Rather, I am suggesting that all research have a logical connection to either the sustainability of communities in the region or to the economic importance of the region to the state and the nation (or to regional economies in the Russian Far East).

The ***drivers of ecosystem change*** (shown in bold letters) include climate, world fisheries markets, historic exploitation of fisheries, world energy markets, and reindeer meat markets. While there are additional drivers of change, my intent here is to identify the drivers most likely to interact with climate change to produce human consequences.

Policies which may affect outcomes of the ecosystem drivers are shown in Figure 1 in bold italics. Relevant policy areas include: fisheries, marine mammal protection, energy, land use, hunting, settlement, and economic development.

The ***human implications*** of ecosystem change appear as gray boxes in Figure 1. Note that nine of these human implications are directly associated with physical and natural processes: fish harvests, shore-based fishing activities, marine mammal harvests, caribou and reindeer harvests, regional petroleum economic activity, petroleum products, public revenues from petroleum production, mining activity, both public expenditures and private insurance costs as well as direct private expenditures associated with damage to human structures.

I have shown five ***dimensions of human well-being*** with gray boxes in Figure 1: subsistence harvest, transmission of culture, community income, human health, social relationships, and migration to and from the community. These six concepts are not intended to be comprehensive with respect to human well-being. I do intend them, however, to be broadly representative of the different dimensions of human well-being relevant to an integrated assessment of ecosystem changes in the Bering Sea region.

Linking Policies to Emerging Understanding

The National Academy Study of the Bering Sea Ecosystem recommended that we, "adopt an adaptive or experimental approach to management actions concerning the Bering Sea ecosystem" (NRC, 1996:4). The intent of this approach is to use actual interventions in the ecosystem on a modest scale to advance our understanding of ecosystem processes and the effects of alternative policies. Study members illustrated this approach by calling for experimentation with no-fishing zones of varying sizes around sea lion rookeries (NRC, 1996:255). Another example mentioned by the committee was to vary fishing pressure among selected areas (NRC, 1996:255). Critical to the success of an adaptive approach to management are the observations of effects of policies and feedback of this information to the development of policy.

Role of Native Knowledge and Expertise

Native hunters have a much longer and extensive history of observing ecosystem changes than do scientists. Native residents are better able to discern subtle changes in the ecosystem on a daily basis. They have ideas on possible relationships between observed changes in the ecosystem. They are in the best position to report changes in their own lives. It therefore makes sense to involve Natives in the design, conduct, and interpretation of research.

The scientists' ideal is a joint research effort by Native experts, scientists, and managers. Many Native experts, however, would prefer to mount a parallel, but separate effort. Their experience with joint research efforts has commonly been that their expertise is judged by scientific standards to be anecdotal.

Native leaders in the Bering Sea region have formed a coalition to understand changes in the health of the ecosystem and to identify what actions can be taken to improve the health of the ecosystem (Larry Merculief, personal communication). The Bering Sea Coalition of Native experts offers an opportunity to design separate but interactive efforts. We need an explicit, workable agreement on the process by which research priorities are set; policy alternatives developed; funding is arranged; hypothesis are generated; information is collected, organized, and shared; analyses are performed and interpretations made; results are discussed; and, how further actions are identified.

One of the impediments to interaction between the Native and scientific communities are communication links. Scientists now routinely exchange ideas and data electronically. We need to extend this technology to Native experts. An important component of the research agenda, then, is a jointly developed communications plan which: builds on ongoing communications initiatives; identifies funding to support equipment, software and connection charges; provides technical assistance; establishes a protocol for information sharing; and which identifies clear applications that are appropriate to each phase of the research and policy development process.

12.5 Next Steps in an Integrated Assessment

Native experts, along with natural, physical, and social scientists can initiate an integrated assessment by addressing the following questions:

- ***Human Implications:*** What are the most important potential outcomes of direct concern to people?
- ***Notes***: consider both people who live in the region and effects on larger populations at the state and national levels.
- Specifying human implications does not mean that all research needs to include a human component. Rather, we all need to be clear on how each research effort can ultimately be connected to a human concern.
- Natural and physical scientists are in the best position to identify the most important direct outcomes of human concern. An example would be a decline in a species known to have commercial or subsistence value. Social scientists are in the best position to trace out the implications of such a change. They may, for example, relate changes in resource harvests to changes in living conditions and to migration decisions.
- ***Drivers of Ecosystem Change***: What are the principal causes of ecosystem change?
- ***Notes:*** In your working group's area of interest, a driver of ecosystem change may be considered by another group to be an outcome of ecosystem change. Changes in ocean temperature, for example, may be considered an outcome by one group and may be a driver of ecosystem change by another group.
- ***Pathways***: What are the principal links between each driver of ecosystem change and each human implication?

- ***Notes***: The pathways shown in Figure 1 are no doubt gross simplifications of the pathways that can be drawn by experts in each area. The value of the simplified version of pathways is to establish a comprehensive framework for discussing research priorities and approaches.
- ***Polices***: What current and potential policies are most likely to influence either the drivers of ecosystem change or their effects?
- ***Notes***: Polices affecting the rate of increase of greenhouse gases may be considered beyond our area of expertise, but BESIS is a prime example of a regional study which is capable of illustrating the real world connections between international policies and human well-being.
- ***Time Scales:*** For each pathway, estimate whether people are likely to experience a significant impact in years, decades, or centuries.
- ***Uncertainties:*** Again for each pathway, highlight the pathway segments that are most uncertain.
- ***Notes***: It would be most helpful if you can differentiate between levels of uncertainty as follows:
- unsure that the relationship exists
- unsure about the direction of the relationship under varying conditions
- unsure about the magnitude of the relationship
- ***Research and Local Knowledge Potential***: Again for each segment, but focusing on those segments with greatest uncertainty, can research and/or local knowledge reduce our uncertainty?
- ***Notes:*** If research and/or local knowledge can reduce uncertainty:
- Who should be involved in designing the approach to reducing uncertainty?
- What are examples of potentially viable approaches?
- What, if any, policies might be tested in conjunction with the effort to reduce uncertainty?

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