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CHAPTER 10

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR ALASKA

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Acknowledgments

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CHAPTER SUMMARY

Regional Context

Spanning an area nearly a fifth the size of the entire lower 48 states,Alaska includes extreme physical, climatic,and ecological diversity in its rainforests, mountain glaciers,boreal spruce forest,tundra,peatlands,and meadows. Lightly populated and growing about 1.5% per year,Alaska has the nation's highest median household income,with an economy dominated by government and natural resources. In contrast to other regions,the most severe environmental stresses in Alaska at present are already climate-related. Recent warming has been accompanied by several decades of thawing in discontinuous permafrost,which is present in most of central and southern Alaska,causing increased ground subsidence,erosion,landslides,and disruption and damage to forests,buildings,and infrastructure. Sea ice off the Alaskan coast is retreating (by 14% since 1978) and thinning (by 40% since the 1960s),with widespread effects on marine ecosystems,coastal climate,human settlements,and subsistence activities.

Climate of the Past Century

- Alaska's climate has warmed about 4°F since the 1950s,7°F in the interior in winter, with much of this warming occurring in a sudden regime shift around 1977.
- Alaska's warming is part of a larger Arctic trend corroborated by many independent measurements of sea ice,glaciers,permafrost, vegetation, and snow cover.
- Most of the state has grown wetter, with a 30% average precipitation increase between 1968 and 1990.
- The growing season has lengthened by about 14 days.
- Dramatic reductions in sea ice and permafrost have accompanied the recent warming.

Climate of the Coming Century

- Models project continued strong warming in Alaska, reaching 1.5-5°F by 2030,and 5-18°F by 2100,strongest in the interior and north and in winter.
- Continued precipitation increases are projected, reaching 20-25% in the north and northwest, with areas of decrease along the south coast.
- Increased evaporation from warming is projected to more than offset increased precipitation,making soils drier in most of the state.

Key Findings

- As much as the top 30 feet of discontinuous permafrost is projected to thaw over the 21st century, causing increased ground subsidence, erosion, landslides, and disruption and damage to forests, buildings, and infrastructure.
- The melting of sea ice is projected to continue, with the Canadian climate model projecting a complete loss of summer Arctic sea ice by 2100. Loss of sea ice allows larger storm surges to develop, increasing the erosion and coastal inundation, and also threatens populations of marine mammals and polar bears that depend on ice, and the subsistence livelihoods that depend on them.
- Recent warming has been accompanied by unprecedented increases in forest disturbances, including insect attacks. A sustained infestation of spruce bark beetles, which in the past have been limited by cold, has caused widespread tree deaths over 2.3 million acres on the Kenai Peninsula since 1992, the largest loss to insects ever recorded in North America.
- Increases in blow-downs in forests due to intense windstorms, and in canopy breakage from the heavy snows typical of warm winters, have increased vulnerability of forests to insect attack. Projected further warming is likely to increase the risk of insect attack.
- Significant increases in fire frequency and intensity, both related to summer warming, have occurred. Simultaneously, the potential damage from forest fires has increased due to an increase in dispersed human settlement in forests. The projected further warming is likely to increase near-term risk of fire.
- In the longer term, large-scale transformation of landscapes is likely, including expansion of boreal forest into the tundra zone, shifts of forest types due to fire and moisture stress, northward expansion of some commercially valuable species, and the appearance of significant fire risk in the coastal forest for the first time since observations began.
- The Gulf of Alaska and Bering Sea support marine ecosystems of great diversity and productivity, and the nation's largest commercial fishery. The effect of projected climate change on these ecosystems could be large.
- Present climate change already poses drastic threats to subsistence livelihoods, practiced mainly by Native communities, as many populations of marine mammals, fish, and seabirds have been reduced or displaced due to retreat and thinning of sea ice and other changes. Projected climate changes are likely to intensify these impacts. In the longer term, projected ecosystem shifts are likely to displace or change the resources available for subsistence, requiring communities to change their practices or move.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR ALASKA

PHYSICAL SETTING AND UNIQUE ATTRIBUTES

Alaska spans 20 degrees of latitude and 42 of longitude,with a land area of 570,000 square miles - nearly a fifth of the lower 48 states - and a coastline of more than 34,000 miles,longer than those of the other 49 states combined.This enormous expanse embraces extreme physical, climatic,and ecological diversity. In the south,a series of mountain ranges parallel the coast,where intense precipitation produces lush cool rainforests and large mountain glaciers. These southern ranges culminate in the long arc of the Alaska Range,which includes McKinley (Denali),the highest peak in North America. Beyond,in the interior, lie the wide valleys of the Yukon River and its tributary the Tanana. Further north,the Brooks Range divides the interior from the cold and arid Arctic slopes. Alaska contains about 75% of US national parklands and 90% of national wildlife refuge lands (USGS BRD, 1999). It contains roughly 40% of the nation's surface water resources (Lamke,1986),63% of its wetlands (Hall et al.,1994),essentially all of its permafrost,and more glaciers and active volcanoes than all other states combined.

SOCIOECONOMIC CONTEXT

Alaska is lightly populated,with 614,000 people in 1998 distributed between the small cities of Anchorage (260,000), Fairbanks (84,000) and Juneau (30,000),a few smaller towns,and many villages and rural settlements. Average annual population growth was more than 3% per year in the 1980s declining to about 1.5% per year in the 1990s, where it is projected to remain, giving a projected total state population that reaches 885,000 by 2025 (US Census Bureau,2000). Native peoples comprise about 16% of Alaska's population. The state's median household income,nearly $52,800 in 1996,is the highest in the nation.[1] The economy is dominated by government and natural resources,with Federal civilian and military payrolls,and the State's Permanent Fund,contributing 44% of total incomes. The North Slope oil fields,which provide 19% of US crude oil production (8% of US consumption) provide a further 35% of the state's incomes,while fisheries provide an additional 7%. Other significant income shares include tourism (5%),timber (2%), and mining (2%),with the remainder miscellaneous (agriculture contributes 0.1%) (Goldsmith,1997). In addition,diverse forms of subsistence livelihood are practiced throughout the state,primarily but not exclusively by native communities. These activities depend on fish,marine mammals,and wildlife - including partly commercial reindeer herding - and play a social and cultural role vastly greater than their contribution to monetary incomes.

ECOLOGICAL CONTEXT

Alaska's ecosystem types encompass an extraordinary diversity, reflecting the state's vastness and extreme variety of climates. Ecosystem types include cool Sitka spruce and Western hemlock forest in the southeast and south-central coastal regions;boreal forest of white and black spruce with hardwoods on well-drained uplands through the south-central region and interior;Alpine tundra and meadows at higher elevations on interior mountain ranges;maritime tundra along the west coast from the Alaskan Peninsula and Aleutians to the Seward Peninsula,including vast coastal wetlands in the Yukon-Kuskokwim delta;and Arctic tundra and barrens on the northwest coast and north of the Brooks Range. Only about 30,000 acres is in agricultural production,principally in the Tanana and Matanuska valleys and on the Kenai Peninsula;larger areas are used for pasture (185,000 acres) and reindeer grazing (12 million acres,mostly on the Seward Peninsula).

The Alaskan terrestrial landscape has been altered less by direct human intervention than anywhere else in the United States. The most significant current environmental pressures in Alaska include heavy stress on fish stocks and marine ecosystems from large commercial fisheries,both Alaskan and international;local impacts from the mining and petroleum industries,including the aftermath of the Exxon Valdez spill and its cleanup,as well as smaller ongoing impacts from routine operations;and strain

[1] Median household money income,in 1996 dollars.US Census Bureau (2000).

on fragile ecosystems and communities from rapidly growing summer tourism throughout the state. In addition,like most of the Arctic, Alaska is already experiencing much more rapid climate warming than the lower 48 states,with major ecological and socioeconomic impacts and the early signs of climate-related landscape change increasingly evident. With the exception of direct fishing pressure on marine ecosystems,the greatest present environmental stresses in Alaska are climate-related. Experimental manipulations and model studies both suggest that present and future climate change is highly likely to profoundly alter the range,species mix and functioning of Alaskan ecosystems.

Major Ecological Regions of Alaska

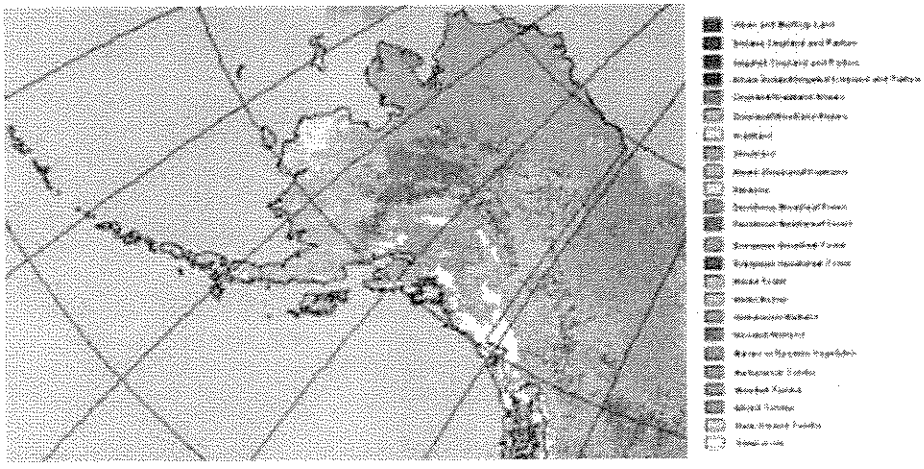

Figure 1: Major Ecological Regions of Alaska. Source: National Atlas of the United States. See Color Figure Appendix

CLIMATE VARIABILITY AND CHANGE

Alaska encompasses extreme climatic differences. The southern coastal margin,including the panhandle and Aleutians,has a maritime climate with cool summers, relatively mild winters,and heavy precipitation,up to 200 inches (500 cm) annually in parts of the southeast, forming large glaciers on the southern mountains. North of the Alaska Range the climate is continental,with moderate summers (July average 59°F or 15°C), very cold winters (January average -13°F or -25°C), rapid seasonal transitions, and annual precipitation of 8-16 inches (20-40 cm). The North Slope beyond the Brooks Range has an Arctic semi-arid climate,with annual precipitation less than 8 inches (20 cm), average July temperature around 39°F (3°C),and snow on the ground nine months of the year. Permafrost is present in all of the state except a narrow belt along the southern coast.

Alaska's climate shows significant interannual and interdecadal variability, associated with large-scale shifts in ocean temperature and salinity regimes,ice conditions,and marine ecosystems in the surrounding seas (Proshutinsky and Johnson,1997;Groisman and Easterling 1994;Serreze et al.,1995b;Thompson and Wallace,1998; Parker et al.,1994;Royer, 1993; Francis et al.,1998;Trenberth and Hurrell,1994; NRC,1996).

Observed Climate Trends

Alaska's recent climate has shown a strong warming trend. General Arctic warming began in the mid-19th century, but has accelerated in the past few decades (Overpeck et al.,1997). Alaska has warmed 4°F (2°C) since the 1950s on average,with the largest about 7°F (4°C) in the interior in winter (Chapman and Walsh,1993;Weller et al.,1998). Local weather records show that the growing season in Alaska lengthened by 13 days since 1950 (Keyser et al.,2000). Much of the recent warming, occurred suddenly around 1977,coincident with the most recent of the large-scale Arctic atmosphere and ocean regime shifts (Weller and Anderson, 1998).

Alaska: 20th Century Annual-average Temperature

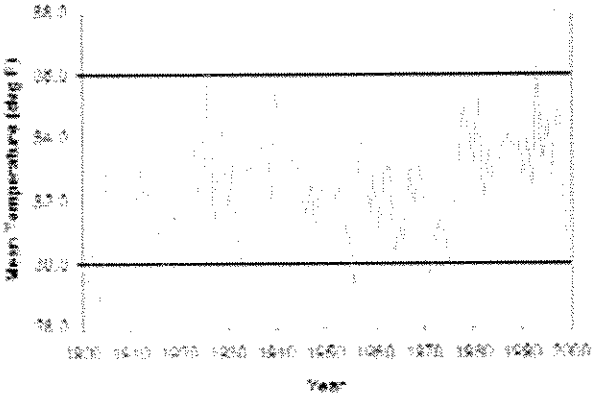

Figure 2: Average temperatures in Alaska have increased over the 20th century, with about 4°F warming since the 1950s. Source: Historical Climate Network, National Climate Data Center. See Color Figure Appendix.

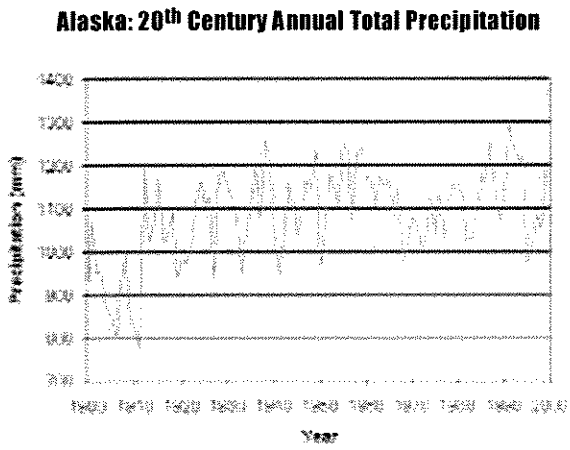

Figure 3: Over the 20th century, precipitation in Alaska has increased. Source: Historical Climate Network, National Climate Data Center. See Color Figure Appendix

Alaska has also grown substantially wetter over the 20th century. The sparse historical record since 1900 shows mixed precipitation trends,with increases of up to 30% in the south,southeast and interior, and smaller decreases in the northwest and over the Bering Sea. The trend to higher precipitation has been stronger recently, a 30% average increase over the region west of 141 degrees longitude (i.e.,all of Alaska except the panhandle) between 1968 and 1990 (Groisman and Easterling,1994).

Alaska's recent warming is part of a strong trend observed throughout the circumpolar Arctic, except for one large region of cooling over eastern Canada and Greenland. This broad Arctic warming has been accompanied and corroborated by extensive melting of glaciers, warming and thawing of permafrost,and retreat and thinning of sea ice (Echelmeyer et al., 1996;Sapiano et al.,1998;Lachenbruch and Marshall,1986;Osterkamp,1994;Osterkamp and Romanovsky, 1996;Wadhams 1990;Cavalieri et al., 1997;Serreze et al.,2000;Krabil et al.,1999; Dowdeswell et al.,2000). Paleoclimatic evidence suggests the Arctic is now warmer than at any time in the past 400 years (Overpeck et al.,1997). The start of Arctic warming in the mid-19th century indicates a contribution from natural factors (Overpeck et al.,1997). Of the stronger high-latitude warming of the past three decades, roughly half can be explained by changes in storm track patterns associated with natural patterns of climate variability, although it is possible that anthropogenic changes in radiative forcing may be shifting these patterns so they tend to favor high-latitude warming (Hurrell, 1995,1996). The remaining share of recent high-latitude warming, roughly half, is broadly consistent with model predictions of the consequences of anthropogenic greenhouse forcing (Serreze et al., 2000). Observations of vegetation and snowcover from satellites,and of the annual fluctuation of atmospheric CO_2 concentration,further corroborate the broad warming trend over northern mid to high latitudes. Mean annual snowcover of the Northern Hemisphere decreased 10% from 1972 to 1992 (Groisman and Easterling,1994),while the growing season over northern mid- to high latitudes increased by 7 to 14 days (Myneni et al.,1997).

Scenarios of Future Climate

All climate models project the largest warming to occur in the Arctic region,principally because of

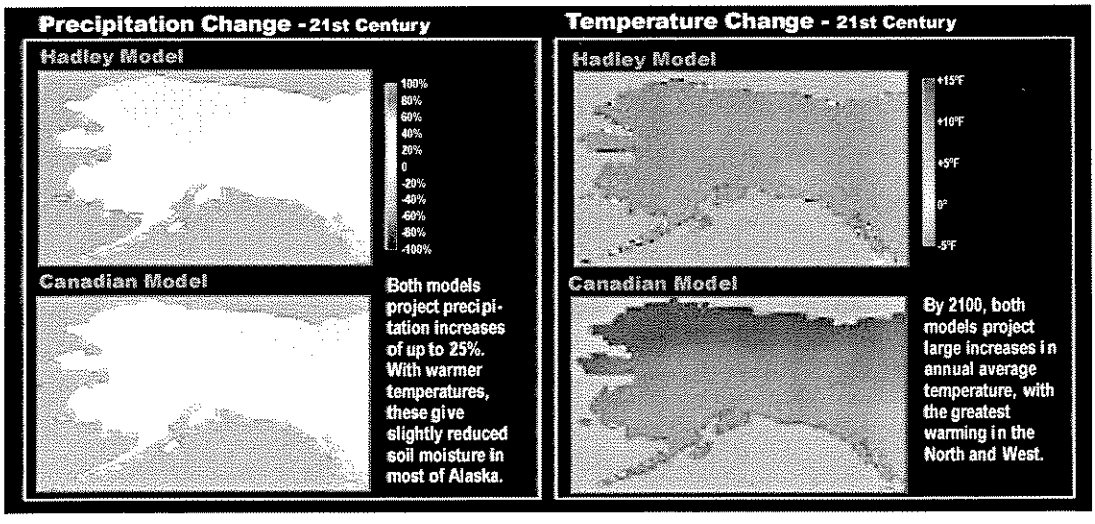

Figure 4: Precipitation and temperature change projected in the 21st century by two climate models. See Color Figure Appendix.

ice-albedo feedback (Kattenberg et al.,1996). Ice and snow are more reflective than the land or water they cover, so after melting,the exposed surface absorbs more solar radiation,accelerating further warming. In both the Canadian and Hadley scenarios (Boer et al.,1984;1999a,b,McFarlane et al.,1992;Flato et al.,1999;Mitchell et al.,1995; Mitchell and Johns,1997; Johns et al.,1997), warming in Alaska increases from the southeast to the northwest,and is strongest in winter. In the Canadian model,Alaskan warming ranges from 2 to 5°F (1.1 to 2.8°C) by 2030,and from 7 to 18°F (4 to 10°C) by 2100,accompanied by complete loss of summer Arctic sea ice. In the Hadley model, warming is 1.5 to 3.6°F (0.8 to 2°C) by 2030,5 to 12°F (3 to 6.5°C) by 2100,with smaller but still extensive loss of sea ice. Comparing these projected future changes to the 4°F (2°C) temperature change already experienced in the last few decades,they range from half as much again to a doubling by 2030,and from a doubling to a quadrupling by 2100.

The Hadley and Canadian scenarios also both project that annual precipitation will increase in most of Alaska,with the largest increases reaching 20-25% in the north and northwest,with some areas of up to 10% decrease along the south coast. The models differ more strongly in projecting seasonal patterns of precipitation changes,particularly in winter. Winters are wetter in the Hadley scenario except in the extreme west and the panhandle, while the Canadian scenario has drier winters everywhere except the Seward Peninsula and northwest coast. Summers have more precipitation in both scenarios except for regions along the south coast. In the Hadley scenario,this region of reduced summer precipitation is confined to the extreme southeast and part of the Alaska Peninsula, while in the Canadian scenario it covers a broad swath along the entire southern coast. Increased evaporation due to warmer summer temperatures exceeds projected precipitation increases,however, so both scenarios project soil moisture decreasing throughout the state, except for an interior region centered on Fairbanks in the Hadley scenario.

Winter Maximum Temperature Change

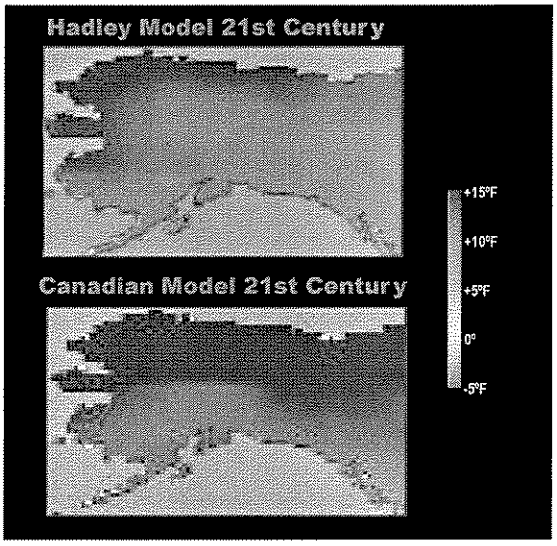

Figure 5: The largest projected warming is in winter, when both models show average daily-high temperatures increasing more than 15°F over the northern half of the state. Source: B.Felzer, UCAR. See Color Figure Appendix.

Summer Soil Moisture Change

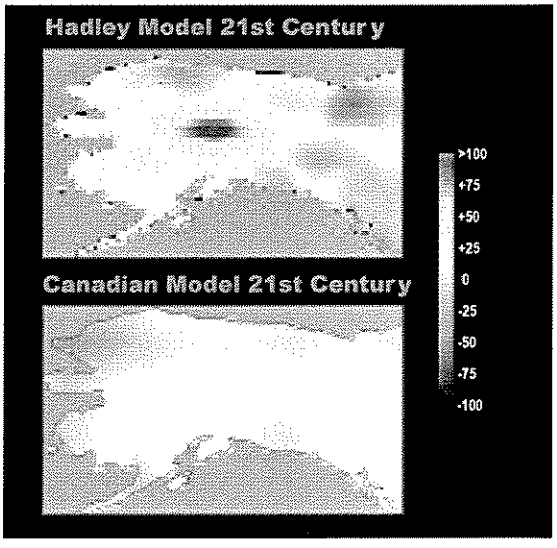

Figure 6: The Hadley model projects increased summer soil moisture in central Alaska and decreases in the north and south, while the Canadian model projects moderate decreases throughout the state. Source: B.Felzer, UCAR. See Color Figure Appendix

KEY ISSUES

The climate changes underway in Alaska have already had major impacts. This synthesis focuses on four key issues - thawing and melting of the cryosphere,particularly permafrost and sea ice; forest and tundra ecosystems;marine ecosystems and fisheries;and subsistence livelihoods. The approach combines reviewing projections of future impacts with describing impacts that are already occurring, which are likely to provide insights into the character of the larger projected future impacts.

Thawing and Melting:
Thawing of permafrost, retreat and thinning of sea ice,and reduction of the river and lake ice season are underway and are projected to continue. These changes are likely to bring widespread changes in ecosystems,increased erosion,harm to subsistence livelihoods,and damage to buildings, roads,and other infrastructure (including sanitary systems). In the longer term,longer ice-free seasons are likely to bring substantial benefits to marine transport and offshore operations in the petroleum industry, and will likely have major implications for trade and national defense.

Effects on Forests and Tundra Ecosystems:
Recent warming appears to have brought increased productivity in the boreal forest zone,offset to an uncertain degree by increases in summer moisture stress, fire and insect outbreaks. Future warming is likely to continue increasing both productivity and stresses,and eventually bring large-scale landscape transformation as boreal forest advances into present tundra and mixed forest into present boreal forest. Changes in these ecosystems will possibly have large effects on the global carbon cycle.

Marine Ecosystems and Fisheries:
Alaskan and Bering Sea marine ecosystems show strong signals of climate-driven variation,although their mechanisms are not known. Further climate change is likely to bring large changes in marine ecosystems including stocks important for both the commercial and subsistence catch,but knowledge of their specific character is very limited.

Subsistence Livelihoods:
Subsistence hunting and fishing have been significantly harmed by present climate changes,through stresses on fish,marine mammals,and wildlife driven by present thawing,sea ice retreat,and ecosystem shifts. While some specific subsistence resources are likely to grow more abundant (e.g., salmon near the northern limit of their range),these stresses are likely to grow more intense, even in the near term.

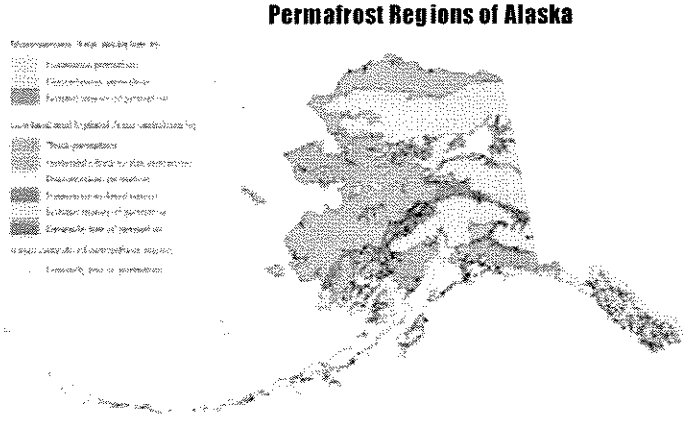

Figure 7: Permafrost regions of Alaska. Source: O.J. Ferrains, 1965. See Color Figure Appendix

1. Thawing of Permafrost and Melting of Sea Ice

Throughout Alaska,the landscape and human activities are fundamentally affected by the presence of ice,snow, and permafrost. Because annual average temperatures in much of the southern portion of the state are near 32°F (0°C) – e.g.,28°F (-2°C) in Fairbanks – a small warming can transform the landscape through thawing of permafrost,melting of ice,and reduction of snow cover. The ecological, hydrological,economic,and social effects of these changes to the cryosphere[2] will be large,and will profoundly affect every other domain of impact considered. All components of the cryosphere in the Arctic are experiencing change,including snow cover, mountain and continental glaciers,permafrost,sea ice,and lake and river ice. For example, glaciers in Alaska,as throughout the Arctic,have retreated through most of the 20th century. Estimated losses in Alaskan glaciers are of the order of 30 feet (10 meters) in thickness over the past 40 years,while some have gained thickness in their upper regions,consistent with recent increases in both temperature and precipitation (BESIS,1997). Melting of glaciers is contributing to rising sea levels worldwide (Meier, 1993),while melting of Alaskan glaciers may have pronounced regional effects through the contribution of their runoff to ocean currents and marine ecosystems in the Gulf of Alaska and Bering Sea,as discussed below. The discussion here concentrates on permafrost and sea ice,whose impacts on people and ecosystems were judged to be most direct and important. General warming would also reduce the ice season on lakes and rivers,impairing transport on ice roads (Cole et al.,1999).

Permafrost
Permafrost underlies about 85% of Alaska,the entire state except for a narrow belt along the southern coast. Its character varies widely, in depth,continuity, and ice content. In the interior and south of the state most permafrost is discontinuous and relatively shallow, reaching depths of 10 to 300 feet (3 to 100 meters). From the Brooks Range north and along the northern and northwestern coasts,it becomes

[2] The cryosphere consists of the frozen components of the Earth's surface:ice,snow, and permafrost.

thicker and continuous, reaching depths of 2,200 feet (670 meters) in some locations on the North Slope (Ferrians,1965;Osterkamp et al.,1985;Brown et al.,1997). Permafrost has profound effects on hydrology, erosion, vegetation,and human activities. It limits movement of ground water and the rooting depth of plants. On slopes,it allows characteristic fluid-like movement of surface soil and deposits. Seasonal thawing over continuous permafrost creates a saturated surface layer in which pools of meltwater accumulate,conducive to marsh and tundra ecosystems and peat formation. Building on permafrost requires that structures be stabilized in permanently frozen ground below the active layer, and that they limit their heat transfer to the ground, usually by elevating them on piles. For example,to prevent thawing of permafrost from transport of heated oil in the Trans-Alaska pipeline,400 miles of pipeline were constructed elevated on thermosyphons,at an additional cost of $800 million (Cole et al.,1999).

Permafrost in Alaska has been warming for more than a century. Continuous permafrost on the North slope of Alaska has warmed 4-7°F (2-4°C) over the last century (Lachenbruch and Marshall, 1986). Since temperatures at the upper surface of continuous permafrost are still low, typically below 23°F (-5°C),no significant loss of continuous permafrost is projected over the 21st century, although thickening of the active layer may cause active layer detachment,local subsidence,damage to structures, and hydrological changes (Osterkamp and Romanovsky, 1996). The discontinuous permafrost to the south is warmer, usually above 28°F (-2°C). Here,Osterkamp (1994) reported recently increased warming at multiple sites,1 to 3°F (0.5 to 1.5°C) since the late 1980s,and inferred from this and other evidence that much of the discontinuous permafrost south of the Yukon River and on the south side of the Seward Peninsula must already be thawing. Many reports of localized thawing and associated surface disruptions support this inference (Osterkamp,et al.,1998;Jorgenson et al.,2000; Osterkamp et al.,2000). In the central Canadian Arctic,a general northward retreat of the southernmost margin of discontinuous permafrost by about 60 miles (100 km) over the 20th century has been reported (Kwong and Gan,1994;French and Egorov, 1998). It is highly likely that recent climate changes have contributed to permafrost warming and thawing. The beginning of permafrost warming pre-dates the recent sharp increase in surface temperature,however, suggesting that other factors than warming – such as natural long-term variability or changes in snow depth and vegetation cover

Figure 8: For much of its length, the Trans-Alaska Pipeline is elevated on refrigerated pilings to prevent local thawing and ground instability. Source: ©David Marusek.

(which alter heat transfer from the surface to the ground) – have also contributed. Moreover, because much of the observed thawing is associated with human disturbance of the surface,and because systematic large-scale observations of changes in permafrost are lacking,the degree of contribution of surface warming to the observed thawing is not yet known.

Continued climate warming is highly likely to bring accelerated thawing of warm discontinuous permafrost. Over the 21st century the top 30 feet (10 meters) is likely to thaw throughout much of the ice-rich discontinuous permafrost zone,although complete thawing is likely to take centuries even in discontinuous permafrost (Osterkamp and Romanovsky, 1999). Canadian studies have projected that even present surface temperatures will cause an eventual further retreat of the southernmost permafrost fringe in the Canadian subarctic by 60 to 100 miles (100 to 160 km) (Dyke et al.,1997), with further retreat of 200 to 300 miles (300 to 500 km) under doubled-CO_2 equilibrium (Woo et al., 1992). The actual pattern of loss of permafrost will, of course,be more complex than a simple uniform retreat. Model studies using three transient climate-model scenarios have projected a 20 - 30% increase in depth of the active layer (Anisimov et al.,1997), and a 12 to 22% reduction in total Arctic permafrost area by 2100 (Anisimov and Nelson,1997).

Thawing is likely to benefit some activities (e.g., construction,transport,and agriculture) after it is completed,but the intervening transitional period of decades or longer is likely to bring many disrup-

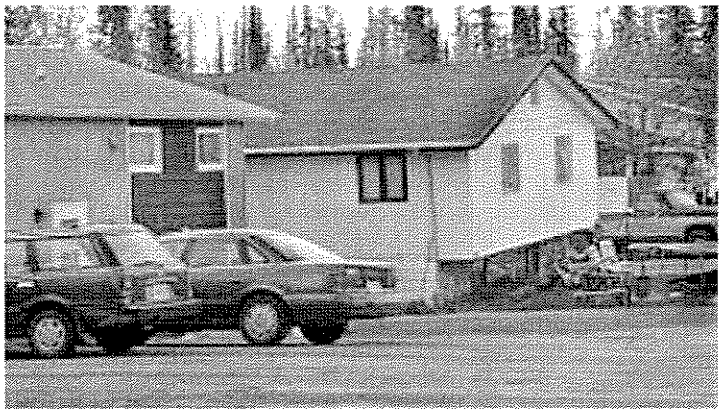

Figure 9: Houses near Fairbanks, Alaska use jacks for support as permafrost thawing causes uneven settling. Source: ©1999, Gary Braasch.

tions and few benefits. Thawing of any permafrost increases groundwater mobility, reduces soil bearing strength,increases susceptibility to erosion and landslides,and can affect soil storage of CO_2, thereby increasing release if the thawed soil drains and dries,or increasing storage if the soil remains flooded. Warming greatly reduces permafrost's bearing strength even if it remains below the freezing point, e.g., by 70% for a pile in permafrost that warms from 25 to 30°F (-4 to -1°C) (Nixon,1990;Cole et al.,1999). Where permafrost has a high ice content, typically in about half the area of discontinuous permafrost,thawing can induce severe,uneven subsidence of the surface,called thermokarst,observed in some cases to exceed 16 feet (5 m). Human-induced thawing of ice-rich discontinuous permafrost has already damaged houses, roads,airports, pipelines,and military installations; required costly road replacements and increased maintenance expenditures for pipelines and other infrastructure; and increased landscape erosion,slope instabilities and landslides.

Present costs of thaw-related damage to structures and infrastructure in Alaska have been estimated at about $35 million per year,[3] of which repair of permafrost-damaged roads is the largest component (Cole et al.,1999). Longer seasonal thaw of the active layer could disrupt petroleum exploration and extraction and increase associated environmental damage in the tundra, by shortening the season for minimal-impact operations on ice roads and pads. The near-term risk of disruption to operations of the Trans-Alaska pipeline is judged to be small, although costly increases in maintenance due to increased ground instability are likely. The pipeline's support structures are designed for specific ranges of ground temperatures,and are subject to heaving or collapse if the permafrost thaws. Replacing them,if required, would cost about $2 million per mile. Subsidence from thawing can also destroy the substrate of present ecosystems,destroying them or transforming them to other types of ecosystems, for example changing forests to grasslands or bogs (Jorgenson et al.,2000;Osterkamp et al.,2000). Where large-scale thawing of ground ice has occurred,the landscape has been transformed through mudslides, formation of flat-bottomed valleys,and formation of melt ponds,which can enlarge for decades to centuries (Everett and Fitzharris,1998,p.94).

Sea Ice

As permafrost is a prominent feature of the Alaskan landscape,sea ice is a prominent feature of its coasts and the adjoining marine ecosystems. Present for six months along the Bering Sea coast and ten months along most of the Chukchi and Beaufort Seas,sea ice strongly influences coastal climate,ecosystems,and human activities. The area of Arctic sea ice varies up to 50% seasonally, and also shows strong interannual variation. Large and statistically significant reductions in summer sea ice, which have been proposed as an early signal of global climate change (Walsh,1991),are evident in recent decades despite this variability (Cavalieri et al.,1997;Maslanik et al.,1996,1999;Wadhams, 1997). Recent reports show area declines of about 3% per decade since the late 1970s,with the largest declines 3.6% per decade in August and September (Serreze et al.,2000). The area of multi-year ice has declined by 14% since 1978 (Johannesen et al., 1999). Model calculations indicate that recent sea-ice trends are consistent with the estimated effects of present greenhouse warming,and are highly unlikely to be accounted for by natural climate variability (Vinnikov et al.,1999). Comparison of two satellite records suggests that the rate of area loss increased from 2.8% per decade in the 1980s to 4.5% per decade in the 1990s (Johannesen et al., 1995). Record low values of summer ice extent have been set repeatedly since 1980 (Chapman and Walsh,1993;Serreze et al.,1995a),while September 1998 ice area in the Beaufort and Chukchi seas (the western part of the Arctic Basin) was 25% below the prior minimum value over the 45-year record (Maslanik et al.,1999).

Arctic sea ice has also grown thinner over the past few decades. Local observations of sea ice thinning by 3.3 to 6.5 feet (1 to 2 meters) have been reported for several years (Wadhams 1990,1997;McPhee et al.,1998),but the limited spatial and temporal

[3] This sum represents about 1.4% of the State budget.

coverage of these measurements prevented drawing conclusions about Arctic-wide trends until recently. A recent analysis of submarine ice data,however, has provided the first persuasive evidence of large-scale thinning over the entire Arctic basin. Mean September ice draft[4] observed in six trans-Arctic submarine cruises from 1958 to 1976 was 10 feet (3.1 meters),while mean draft in three similar cruises between 1993 and 1997 was 5.9 feet (1.8 meters). In addition to the 4.1 feet (1.3 meters) of average thinning between the two sets of cruises,the recent cruises also found continued thinning at a rate of 4 inches per year (10 cm/year) from 1993 to 1997 (Rothrock et al.,1999). Evidence of widespread sea-ice melting is corroborated by substantial recent increase in freshwater content of the Arctic Ocean, from depth equivalent of 0.8 meters in 1975 and 2.4 meters in 1997 (McPhee et al.,1998).

Sea-ice retreat allows larger storm surges to develop in the increased open-water areas,increasing erosion,sedimentation,and the risk of inundation in coastal areas. Moreover, coastline where permafrost has thawed is made more vulnerable,which in combination with increased wave action can cause severe erosion (Brown and Solomon,2000; Forbes and Taylor, 1994;Shaw et al.,1998;Weller, 1998;Wolfe et al.,1998.). Local coastal losses to erosion of the order of 100 feet (40 meters) per year have been observed in some locations in both Siberia and Canada (Semiletov et al.,1999;Solomon and Covill, 1995). Aerial photo comparison has revealed total erosive losses up to 1,500 feet (600 meters) over the past few decades along some stretches of the Alaskan coast (Weller and Anderson,1998). Several villages on Alaska's west coast are sufficiently threatened by increased erosion and inundation that they must be protected or relocated. Present plans include constructing a $4-6 million sea wall in Shishmaref (a 10-15 year interim solution),and relocating Kivalina on higher ground at an estimated cost of $54 million (US Army Corps of Engineers,1998).

Under further climate change,further large reductions in sea ice are projected,although there is substantial variation in estimates of the magnitude and timing. Analysis with one transient climate-model scenario projected 60% loss of Arctic summer sea ice area by the time of CO_2 doubling,accompanied by an increase in the duration of the open-water season from 60 to 150 days. The same climate scenario also suggests an increase in the offshore distance of the ice pack from 90 to 125 miles (150 - 200 km) at present,to 300 - 500 miles (500 - 800 km) (Gordon and

[4] Ice draft is the depth of sea ice below the water line,equal to roughly 90% of total ice thickness.

Erosion on the Arctic Coast of Siberia

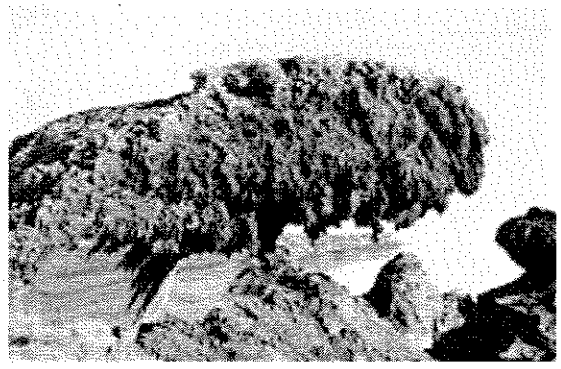

Figure 10: Coastal thawing and sea ice retreat have allowed extreme coastal erosion in both North America and Eurasia, with some local losses of up to 100 feet per year. Source: Igor Semiletov, Pacific Oceanological Institute, Vladivostok.

Projected Summer Sea Ice Change Canadian Model: An Ice-free Arctic Summer

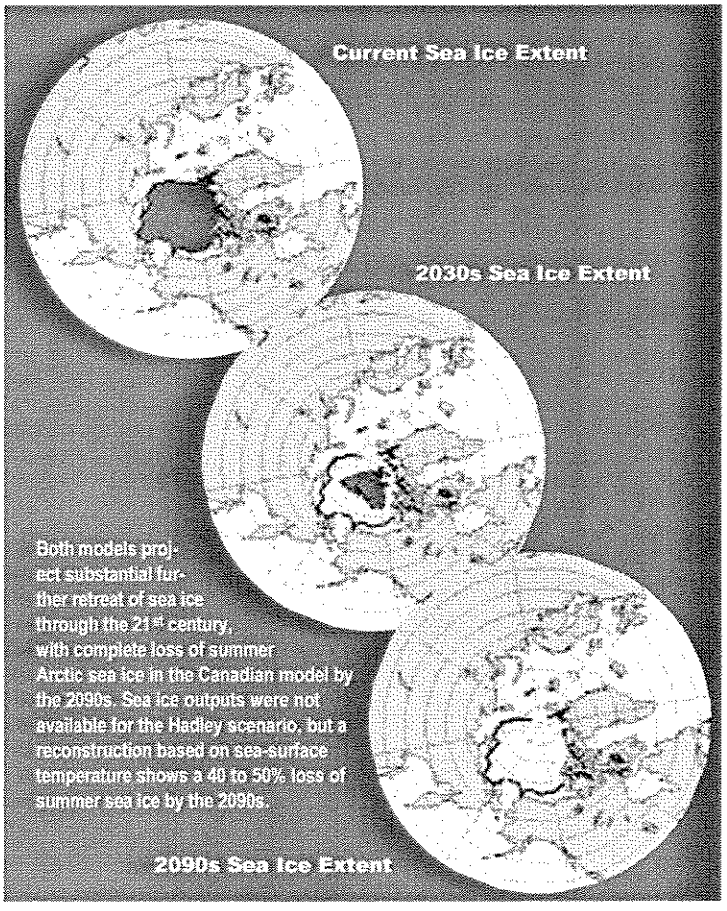

Figure 11: Canadian model projections of future Arctic sea-ice retreat. Source: B. Felzer, UCAR, 2000. See Color Figure Appendix

O'Farrell,1997). Both the Hadley and Canadian models project large reduction in summer sea ice by 2100. The Canadian model projects the more rapid loss,as shown in Figure 11,with complete disappearance of summer sea ice by 2100.

Loss of sea ice threatens large-scale change in marine ecosystems,threats to populations of marine mammals and polar bears that depend on the ice, and to the subsistence livelihoods that depend on them. Further retreat may also bring some benefits, principally by facilitating water transport and oil exploration and extraction. Expanded transport possibilities from greatly reduced Arctic sea ice extent and increased open-water season,including the possibility of routine summer navigation through both the Northeast and Northwest Passages (North of the Eurasian and North American continents),are likely to have major implications for both trade and national security.

Adaptation Options

Where sufficient information is available,vulnerability of structures to permafrost thawing can be reduced by careful site selection to avoid permafrost with high ice content and favor permafrost with high gravel content. Unfortunately, local information on permafrost characteristics is often unavailable or inaccurate,and many siting and development decisions fail to consider the information that is available,or the likely future development of the site and its surroundings (Smith and Johnson, 2000). When site or route modifications are not undertaken or not feasible,the effects of permafrost thawing on building and infrastructure can still be reduced,although at substantial cost and difficulty, through several approaches. Local contributions to thawing can be reduced by minimizing physical disturbance of the surface,and through insulation and heat transfer measures to reduce local thermal dis-

Betting on Spring Breakup: The Nenana Ice Classic

The town of Nenana is located about 65 miles southeast of Fairbanks on the Tanana river, a major tributary of the Yukon. In 1917,when Nenana was a construction base for the Alaska Railroad, railroad workers ran a betting pool on when the river ice would break up in the spring. Sufficiently popular to be repeated in subsequent years,the pool became a local tradition that now has been repeated every year for 84 years. Entry tickets cost two dollars,and represent a bet on a single one-minute interval. The jackpot,$800 in 1917, was more than $330,000 in 2000. The high stakes and long continuous history of this contest make it a unique local record of Alaska's 20th century climate history.

The same procedure is used to define the moment of breakup each year. In early March,a large log structure is frozen into the ice about 300 feet from shore,and later joined by a cable to a watchtower on the shore. A strong enough pull on the cable,which occurs when the ice has shifted enough to move the structure about 100 feet downriver, stops the clock.

Spring Breakup Dates in the Nenana Classic
(11-year moving average)

Figure 12: The average date of spring breakup of ice on the Tanana River at Nenana has advanced by eight days between the 1920s and the 1990s. Source: Historical data from Nenana Ice Classic, http://www.ptialaska.net/~tripod/breakup.times.html.

Over the contest's history the earliest breakup has been on April 20 (in 1940 and 1998),the latest on May 20 (in 1964). Although breakup dates vary greatly from year to year, the past few decades have seen a strong trend toward earlier breakup. Removing some of the year-to-year variation by calculating an 11-year average (for each year, the average of the eleven breakup dates from five years before to five years after) reveals an advance of eight days between the 1920s and the 1990s,from May 7 to April 29. Nenana is a major shipping center for summer barge traffic,so the earlier breakup brings significant local economic benefits. It is also a concrete local indicator of the strong warming trend that has occurred across Alaska over the past few decades.

turbance. Piles used to support structures can be sunk deeper in the permafrost or refrigerated,to maintain their bearing strength longer as the permafrost warms and active layer thickens. With enough advance planning,local thawing can be actively induced before construction, by stripping vegetation and surface soil from the site five years or more in advance (Osterkamp et al.,1998). Which of these types of measures is most promising will depend on site characteristics,the type of project, and its intended lifetime. For roads and runways, the consequences of thawing can be reduced by building with gravel rather than paved surfaces,as they can be more readily repaired after subsidence. Coastal settlements threatened by increased storm surge or erosion can be protected with sea walls or other fortification,or relocated further inland. No adaptation options are likely to be available for terrestrial ecosystems threatened by permafrost thawing,or marine ecosystems threatened by sea-ice retreat.

2. Effects on Forest and Tundra Ecosystems

Forests cover 129 million acres of Alaska, about one third of the state (Powell et al.,1993). Various forms of tundra cover another third,in mountainous and coastal regions and north and west of the Brooks Range. Of the forested land, about 10% is temperate coastal rainforest,the remainder interior boreal forest. About 21 million acres,or 16% of total forest,is classified as productive,capable of average growth of 20 cubic feet per acre per year. About 4 million acres,nearly all of it in the coastal forest,is outside protected areas and has the productivity of 50 cubic feet/acre-year necessary to support commercial harvest with road construction (Berman et al.,1999). The state's timber harvest increased from 600 to 1,100 million board feet from 1986 to 1990,and has since declined to about 500 million board feet. Employment and income in the industry followed the same pattern,peaking at 4,000 jobs and $200 million in 1990, declining to 2,500 jobs and $130 million by 1997. The decline of the 1990s principally reflects two economic causes:the closure of two pulp mills in southeast Alaska,and the depletion of Native Corporation timber inventories,which were exported in large quantities as round logs to convert assets to cash during a period of high world prices (Berman et al., 1999). In addition to their commercial value, Alaskan forests provide various ecosystem services and support subsistence livelihoods and recreation activities.

Recent warming in Alaska has increased average growing degree-days by about 20% over the state, bringing apparent increases in forest productivity on sites that are not moisture limited – principally in the southern coastal forest,but also including some regions of the boreal zone (Ciais et al.,1995; Myneni et al.,1997). At the northern margin of the boreal forest,the present climate already favors forest expansion into the tundra zone,particularly on the Seward Peninsula,with the potential for such expansion estimated as 35 miles per °F of climate warming (100 km per °C) (Weller and Lange,1999). On sites that are moisture-limited,which occur through much of the interior, recent warming has apparently increased moisture stress and reduced productivity (Barber et al.,2000). Near Fairbanks the average number of days exceeding 80°F (27°C) annually has tripled since 1950,imposing moisture stress on white spruce stands that can be observed in clear negative correlation of productivity with warm,dry summers (Juday et al.,1998, Fig.3.13). It has been suggested that the past 20 years have seen the greatest moisture stress and lowest productivity of the 20th century through much of the interior boreal forest (Juday and Barry, 1996) .

The 1990s Outbreak of Spruce Bark Beetles on the Kenai Peninsula

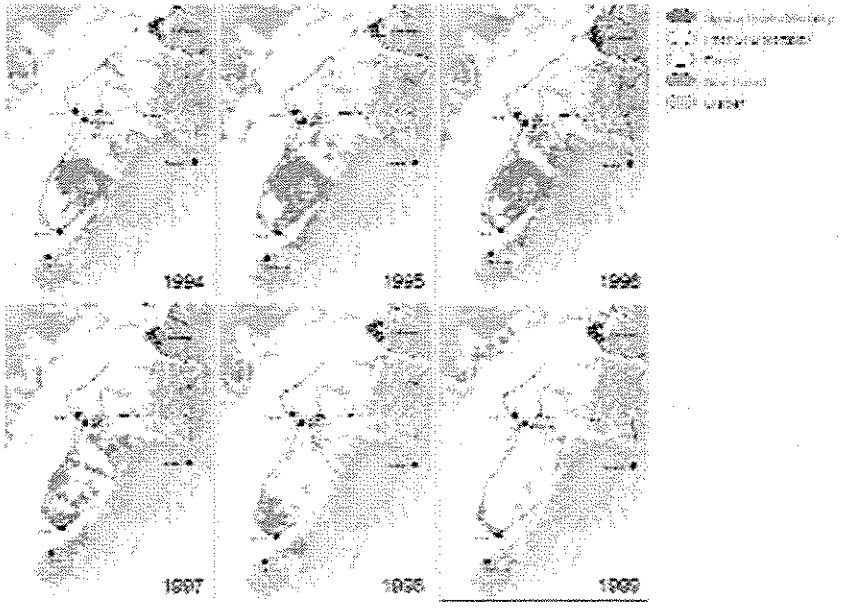

Figure 13: Since 1992, the largest outbreak of forest insects ever recorded in North America has caused widespread tree mortality over 2.3 million acres. Source: USDA Forest Service. See Color Figure Appendix

Substantial changes in patterns of forest disturbance,including insect outbreaks, blowdown,and fire,have also been observed in both the boreal and southeast coastal forest. Although systematic large-scale observations have not been made,localized observations appear to support the hypothesis that these changes are climate-driven. A sustained outbreak of spruce bark beetles since 1992 has caused over 2.3 million acres of tree mortality on the Kenai Peninsula,the largest loss from a single outbreak documented in the history of North America (Werner, 1996). The association of warmer temperatures with both accelerated beetle development times and increased tree vulnerability through moisture stress makes it likely that recent warming contributed to the outbreak (Juday et al.,1998). Outbreaks of defoliating insects in the boreal forest, including spruce budworm,coneworm,and larch sawfly, have also increased sharply in the 1990s, affecting a cumulative total of 800,000 acres (Holsten and Burnside,1997). Susceptibility of interior forests to insect attack may also have increased due to canopy breakage from the heavy snow loads typical of warmer winters.

In Southeast forests, warmer winters since the 1970s with more precipitation falling as rain have reduced the frequency of low and moderate-elevation avalanches,allowing mountain hemlock to colonize alpine tundra (Veblen and Alaback,1996). Reduced low-elevation snowpack has also likely

Annual Area of Northern Boreal Forest Burned in North America

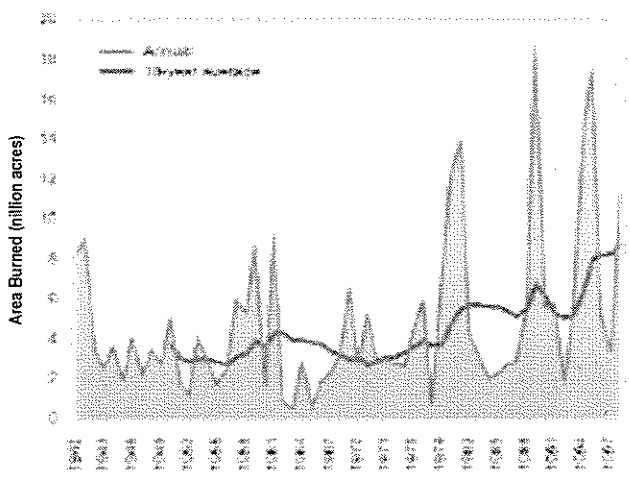

Figure 14: The Alaskan boreal forest is a small part of an enormous forest that extends continuously across the northern part of North America. The average area of this forest burned annually has more than doubled since 1970. Source: Kasischke andStocks, 2000. See Color Figure Appendix

contributed to the extensive decline of Yellow Cedar in the coastal forests,due to freezing of their shallow root systems during winter cold spells with no insulating snow cover (Hennon and Shaw, 1997). Over the same period,the southern coastal forests have also seen a marked increase in the frequency of gale-force winds,which are the primary disturbance agent in these forests (Veblen and Alaback, 1996),and outbreaks of the defoliating western black-headed budworm that appear to be triggered by warm dry summers (Holsten et al.,1985;Furniss and Carolyn,1977).

Forest fire frequency and intensity have also increased markedly since 1970. As Figure 14 shows, the 10-year average of boreal forest burned in North America,after several decades of around 2.5 million acres (1 million hectares),has increased steadily since 1970 to more than 7 million acres (3 M ha). Boreal forest fire reached extreme values in both Eurasia and North America in 1998,with over 27 million acres burned (11 M ha) in total,10 million (4.7 M ha) in North America (Kasischke et al.,1999). Analysis of historical Canadian fire data shows a strong association between area burned and anomalous patterns of mid-tropospheric circulation that tend to bring extended warm dry periods (Skinner et al.,1999).

A major change in Alaskan settlement geography since 1970,promoted by policies including large-scale private transfer of public lands and extensive road-building,has greatly increased dispersed settlement in forest land. At the same time,other policies to transform native villages into permanent communities created more than 60 communities with significant costly infrastructure surrounded by boreal forest (Leask,1985). These trends have greatly increased the vulnerability of people and settlements to forest fires. A single major fire in June 1996, for example,burned 37,000 acres of forest and peat,causing $80 million in direct losses and destroying 450 structures including 200 homes. As many as 200,000 Alaskan residents may now be at risk from such fires,with the number increasing further as outlying suburban development continues to expand (Nash and Duffy, 1997).

Continued increases in CO_2 concentrations and projected further climate warming are likely to bring continuing increases in forest productivity (Keyser et al.,2000),although these are likely to be limited by accompanying increases in summer moisture deficit, fire,and insect outbreaks (Fleming and Volney, 1995;Fleming and Candau,1997;Hogg and Schwarz,1997;Hogg,1999;Oechel et al.,1997b;

Sieben et al.,1997;Volney, 1996;Kasischke and Stocks,2000). Increased fire risk is likely, even in the near term. One study projecting fire risk under doubled-CO_2 equilibrium scenarios found a large increase in the area facing extreme fire risk in Canada and Siberia, very similar in both size and spatial pattern under four different climate models (Stocks et al.,1998). Substantial climate-related changes have also been conjectured for the coastal forest over several decades,including the appearance of new fungi and the appearance of significant fire risk for the first time in the observed record (Juday et al.,1998).

Over the longer term, climate change is likely to bring large landscape-level vegetation changes to both forest and tundra regions. Experimental studies in both boreal forest and tundra have shown that warming increases nitrogen availability (Van Cleve et al.,1990;Lukewille and Wright,1997). At one tundra site,a decade of experimental 6°F (3°C) warming brought major reorganization of the species mix,principally due to increased nutrient availability through changes in nitrogen mineralization (Chapin et al.,1995). Shrubs increased in dominance,while mosses, forbs and lichens were reduced or eliminated. Because shrubs transpire but the declining species do not,such a reorganization would increase evapotranspiration,with large impacts on surface water budgets at many sites likely, including reduced pond formation and runoff and drying of wetlands (Rouse et al.,1997). Moreover, the declining species include some that are critical for lactation and winter nutrition of caribou. Although there exist different views of how sensitive caribou are to such climate-driven changes,it is possible that they could greatly reduce herds,with serious consequences for native communities that depend on them (Gunn,1995;Callaghan et al., 1998).

Equilibrium studies using biogeochemistry and biogeography models have projected large increases in vegetation carbon under climate change in both boreal and tundra ecosystems (McGuire et al.,1995; McGuire and Hobbie,1997). These equilibrium studies exclude dynamics of ecosystem response and provide very limited treatment of disturbance,however, and may consequently either over or underestimate the effects of climate change on ecosystems.

Boreal forests and tundra ecosystems also contain large stores of carbon in their soils. Worldwide estimates of carbon content are about 50 gigatonnes (GtC) in tundra soils,and 200 - 500 GtC in boreal soils (McGuire et al.,1995;Melillo et al.,1995; McGuire and Hobbie,1997;Oechel et al.,1993; Post et al.,1982;Robinson and Moore,1999). These soils can act as either sources or sinks of greenhouse gases,depending on temperature and moisture conditions. As temperatures rise and soils thaw and dry, they become more susceptible to oxidation and release of CO_2. Where drainage is poor and the soil remains wet after thawing,emissions of methane

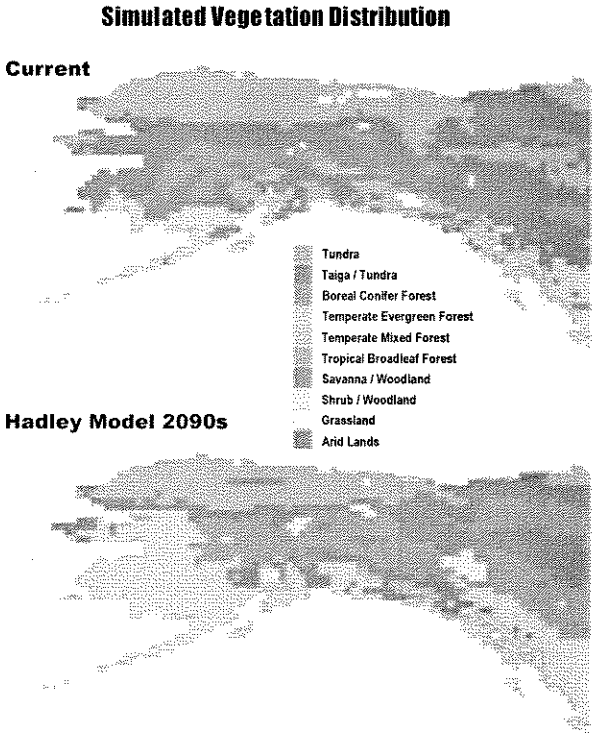

Figure 15: Under the Hadley scenario, the MAPSS biogeography model projects large-scale loss of tundra and taiga ecosystems as forests expand north and west. Likely consequences include disruption of wildlife migration and associated subsistence livelihoods, as well as the potential for large releases of soil carbon. Source: R. Neilson et al., 1998. See Color Figure Appendix

may increase (Gorham,1995;Rivkin,1998). Studies of both boreal forest and tundra have observed significant increases in soil carbon release following seasonal warming and thawing (Goulden et al., 1998). Growing-season observations of specific tundra sites have found them to operate as net CO_2 sinks in the cool, wet 1970s,net sources in the warmer, drier 1980s,and net sinks in the warm, wetter 1990s (Oechel et al.,1993,1995;Vourlitis and Oechel,1999). The seasonality and mechanism of carbon storage and release in tundra ecosystems have been called into question,however, by recent evidence that carbon release in winter may predominate (Oechel et al.,1997a).

In addition to increased carbon storage and changes in nutrient cycling,biogeography models consistently project large-scale transformation of Arctic landscapes,in which the northern edge of the boreal forest advances into the tundra (Melillo et al.,1996; Everett and Fitzharris,1998). In Alaska,northward forest advance is likely to be constrained by the Brooks Range,but substantial westward expansion on the Seward Peninsula is possible,as occurred during a warm climatic period 6,000 years ago (Chapin and Starfield,1997; Foley et al.,1994). Tundra,constrained by the coastline,is likely to both change in composition and shrink in area, by as much as two thirds, worldwide (Neilson et al., 1998;Everett and Fitzharris,1998).

In southern Alaska,temperate coniferous and mixed forests are likely to advance into the boreal zone. One model study found that an 8°F (4.5°C) warming imposed on the Seward Peninsula induced two landscape transformations over a century, from tundra to boreal spruce forest and subsequently - principally because of fire - to a mixed,deciduous-dominated forest (Rupp et al.,2000). Over one to two centuries,other possible landscape changes include expansion of the coastal forest westward on the Alaska Peninsula (Chapin and Starfield,1997);an expansion of forests to higher elevations,including colonization of some formerly glaciated lands;and a shift of interior regions with the greatest precipitation deficit to Aspen parkland.

Adaptation Options

Projected increases in forest productivity, including the possibility of northward expansion of commercially valuable species, would likely bring commercial benefits if not offset by increased moisture stress, fire,and insect outbreaks. Various adaptation measures could help to offset climate-induced increases in fire risk in commercially valuable forests or near settlements. These might include expanded road networks to increase fire-suppression capability and facilitate salvage and sanitation logging - assuming that subsequent increase in settlement in forested areas can be discouraged;periodic controlled burns around settled areas to create buffers;and increased investment and staffing in fire suppression. Any strategy based on expanded fire suppression,however, will carry its own ecological costs and also risks being ineffective in the long term,because by removing risk from property owners it would sustain incentives to build in fire-prone areas.

An alternative approach would create incentives to reduce private risk,e.g., by creating rural fire-protection districts in high-risk areas supported by special property taxes; requiring risk-adjusted assessment of fire insurance rates;or encouraging rural residents at risk to form volunteer fire and emergency-response cooperatives at their own expense. This approach would represent a radical departure from historical policies. A related strategy might reverse present policies that encourage dispersed development, by providing infrastructure only in present or designated densely settled areas.

For the projected larger-scale ecological and landscape transformations,no adaptation strategies are likely to be available.

3. Marine Ecosystems and Fisheries

The Gulf of Alaska and Bering Sea support marine ecosystems of great diversity and productivity. The Bering Sea supports at least 450 species of fish,crustaceans,and mollusks,and 25 species of marine mammals. The population of seabirds in Alaska is the largest and most diverse of any similar-sized region in the Northern Hemisphere,with 66 species present at some time of the year, and 38 species - over 50 million individuals - that breed there (Piatt and Anderson,1996;Meehan et al.,1999).

Roughly 25 species of fish,crustaceans,and mollusks are commercially exploited in the Alaskan fishery. In 1995,Alaska's fisheries landed 2.1 million tons with an ex-vessel value (the amount paid to fisherman) of $1.45 billion, representing 54% of the landings and 37% of the value of all US fisheries. Of this total,pollock were the largest share of volume (1.3 million tons,$297 million) while salmon were the largest share of value (497,000 tons,$490 million,of which sockeye contributed 175,000 tons for $321 million,and pink 218,000 tons for $80 million). A notable contributor to the value of the fishery is the Tanner crab or *Opilio*, for which the volume harvested was only 37,000 tons but the ex-vessel value was $175 million,more than any species except sockeye salmon and pollock. The Alaskan fishery employs about 20,000 people in harvesting and processing (Knapp et al.,1999,Table 1).

The Bering Sea and Gulf of Alaska have shown marked fluctuations in their physical and ecological characteristics over time. Observed ecological fluctuations have included large-scale shifts in the abundance and distribution of many important fish,invertebrates,and marine mammals. Many ecosystem components show clear association with interannual and interdecadal climate variability, with the influ-

ence of interdecadal variability apparently stronger than that of interannual variability (Royer, 1982; Parker et al.,1994;NRC,1996; Francis et al.,1998; Brodeur et al.,1996). While there is climate-driven variability at many different time scales,a few interdecadal climate variations during the 20th century have apparently caused rapid and extreme shifts in the organization of these marine ecosystems,most recently in 1977. Previous shifts occurred in 1924 and 1946 (NRC,1996,p.197),and some data suggest another may have occurred in the mid-1990s (Mantua et al.,1997;NOAA,1999).

The regime shift of 1977 brought warmer sea-surface temperatures and a sharp reduction in sea ice in the Bering Sea (NRC,1996;BESIS,1997). Salmon runs soared,and have largely remained high since then. The catches of 1997 and 1998 were of average volume but dropped sharply in value,principally because of large declines in the lucrative Bristol Bay sockeye run, roughly offset in volume but not in value by huge runs of Pink salmon (Kruse,1998). Groundfish species including pollock, Pacific cod, Arrowtooth flounder and Yellowfin sole dropped to low levels in 1977 and 1978,then began a sustained climb to record levels in the mid 1980s,after which they have stabilized or declined (Witherell,1999). Greenland turbot,the groundfish in the region most adapted to a cold climate,declined (NRC 1996, Fig 4.18). As pollock and other predators increased,several species of forage fish with high nutritional value,such as capelin and herring,declined sharply. Various marine mammals and seabirds that fed on these species changed their diets to other less fatty species,and have in turn declined sharply (NRC 1996, Fig.4.27).

Populations of many species of seabirds,including kittiwakes, murres,cormorants,larus gulls,guillemots,puffins,and murrelets,have declined by 50 to 90% since the 1970s (NRC 1996,pp.118-120). Marine mammals show similar signs of food stress. In the Gulf of Alaska,both Stellar Sea Lions and Harbor Seals have declined by more than 80%. The extreme decline of Stellar Sea Lions has prompted significant restrictions on the pollock fishery since 1998,to increase the sea lions' food supply. Northern Fur Seals declined by about 35% from 1970 to 1986,then rebounded somewhat through 1990. Sea otters have declined as much as 80% since 1990 over much of the west coast,but this decline has been attributed to predation rather than food shortage. Estes et al.(1998) suggest that a few *Orca* whales,perhaps only a single pod,could account for the observed decline if they began to prey on sea otters following a decline in their usual prey.

State of Bering Sea Ecosystem

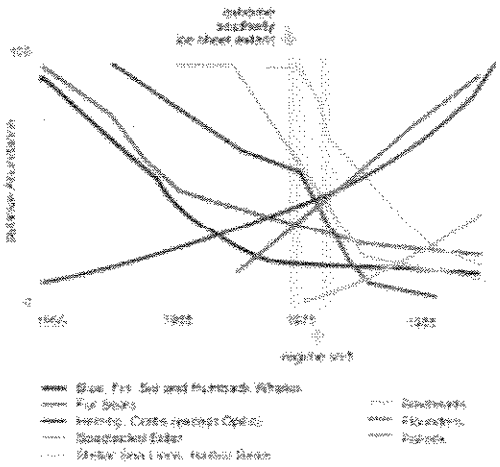

Figure 16: The climatic regime shift of the late 1970s caused large-scale reorganization of the Bering Sea ecosystem. Source: simplified from NRC (1996). See Color Figure Appendix

While climatic effects on larger-bodied,longer-lived species such as marine mammals through changes in food supply are most pronounced at longer time-scales,shorter-term changes can affect them in other ways,such as changes in the extent of sea ice that provides habitat for some species and excludes others (Fay, 1974). For example,the light ice year of 1979 brought unusually large overlap in the distributions of seals and walruses,and saw a high rate of walrus predation on seals (Lowry and Fay, 1984). Large changes in numbers and location of other commercially important fish species have been reported in other Arctic waters,in response to climate regional warmings or coolings of the order of 2°F (1°C) (Buch et al.,1994;Vilhjalmsson,1997).

These ecosystem changes reflect the joint effects of decadal-scale climate fluctuations and human harvesting of fish and marine mammals,but the complex time and space scales of both climate variation and human pressure prevents separating the contributions of each (NRC,1996). Moreover, the pathways of climatic influence on these systems are not known. They likely reflect combined effects of changes in streamflow, and the nutrient content, temperature,and vertical stability of coastal waters.

For the Bering Sea and Gulf of Alaska,one likely influence involves changes in the Alaskan coastal current. The intense storm systems generated by

the Aleutian Low drop as much as 30 feet (10 meters) of snow annually on the coastal mountains that ring the Gulf of Alaska, forming a large glacier system. The runoff from these glaciers is roughly 800,000 cubic feet per second,comparable to the mean annual discharge from the Mississippi,and contributes more than 40% of the freshwater input to the northeast Pacific. This runoff forms the swift narrow Alaska coastal current,whose low-salinity waters flow westward along the coast and through the Aleutian passes into the Bering Sea (Royer, 1981; Royer, 1982). Significant future changes in these coastal storm systems,which may be associated with either climate variability or anthropogenic climate change,could consequently cause large changes in the temperature,salinity and nutrient content of these waters,and hence in the organization of their ecosystems.

While it is possible that the responses of these ecosystems to future climate change will be large, their specific character is highly uncertain. Effects of stream warming on salmon can be projected with more confidence than any oceanic effects on any species:salmon are likely to benefit in the northern end of their range and be harmed in the south (Berman et al.,p.15). One preliminary study conjectured that 21st century climate change could increase or decrease particular Alaskan fisheries by as much as a factor of two (Knapp et al.,1999).

Adaptation Options

Any substantial change in the abundance, age-class distribution,or location of a commercially exploited species can bring large socioeconomic effects. Fisheries have tended to develop on stocks that are abundant,as the Alaskan pollock fishery has grown from minimal levels over the past 30 years. They have also tended to over-capitalize,leading to intense competition and rent-seeking when catches decline (Marasco and Arom,1991;NMFS,1996,p. 34). The effect of fluctuating catch on fishery revenue depends on the elasticity of demand. The Pacific halibut and salmon fisheries have been estimated to operate in the inelastic region of their demand curves:increases in catch reduce prices so much that revenue falls,as when much of the record 1991 Pink Salmon catch was dumped at sea (Knapp et al.,1999,p.12). Demand for pollock is presently estimated to be elastic,but would become inelastic with modest increases in catch (Criddle et al.,1998).

Figure 17: Diverse subsistence livelihoods based on fish, marine mammals and other wildlife, are practiced throughout Alaska. Source: D. Schmitz, National Park Service archive photo

In the face of such extreme uncertainty about the direction and magnitude of future climate effects on fisheries,the most useful adaptation options will be measures that increase the robustness of human activities and communities to shifts in the location and abundance of different species. The present system is quite vulnerable to climate change,because specialization of capital and the regulatory structure limit its robustness. Many communities specialize strongly in one or a few species (e.g.,Bristol Bay is highly dependent on sockeye salmon,while Dutch Harbor is highly dependent on pollock and crab). In extreme cases like the Bristol Bay salmon fleet, equipment is so specialized that it is only useful for one fishery in one location. Regulatory measures that favor Alaskan shore-based processors over offshore processing provide jobs and secondary economic benefits in Alaska,but reduce the ability of a fishery to respond efficiently to climate-driven shifts in the distribution of stocks (Huppert,1991). One important aspect of the present regulatory system that does promote robustness is the use of a limited-entry program. The ability of this program to respond to stock fluctuations could be further improved by allowing buyback of quotas,or by denominating allocations in terms of shares of a variable total harvest, rather than in terms of specific quantities of catch.

4. Subsistence Livelihoods

Subsistence makes an important contribution to livelihoods in many isolated rural communities in Alaska,especially but not exclusively for native peoples. While subsistence is practiced to gather food, subsistence resources and the activities associated with their harvest also make important contributions to health,culture,and identity (Callaway et al., 1999;Berkes,2000;Wenzel,1995).

Alaska's 117,000 rural residents are entitled to practice subsistence hunting and fishing on state, federal,and private lands and waters,while urban residents also quality for subsistence activities on state and private lands. The subsistence harvest by rural residents is about 43 million pounds of food annually (20 million kg),or about 375 pounds (170 kg) per rural resident. The subsistence harvest is largest in the most remote communities, about 500 - 800 pounds (225 - 350 kg) per person annually. Fish comprise 60% of total subsistence food,but there is substantial inter-regional variation: west coast communities rely predominantly on fish,interior ones on fish and land mammals,and northern communities principally on marine mammals (Wolfe and Bosworth,1994).

The links between subsistence harvest and commercial activity are complex. If subsistence food were not available,communities would have to substitute purchased food. With an assumed cost of $3 - 5 per pound of purchased food,a study of four rural communities with large wild food harvests (590 to 760 pounds,or 270 to 350 kg,per person) found that the cost of replacing the wild food harvest would be $1,800 to $3,800 per person,or 13% to 77% of community per capita income (Callaway et al.,1999, p.70). Moreover, practicing subsistence requires cash income to buy the required equipment,such as guns,boats,and snowmobiles. In one surveyed community (Unalakleet in 1982),the cost of practicing subsistence was about $10,000,nearly half of mean household income (Callaway et al.,1999,p. 65). Consequently, particularly for fishing in coastal communities,the subsistence and commercial harvests may be closely linked:profits from the commercial catch may help pay for required subsistence equipment,and subsistence fish may also be taken during commercial fishing.

Many aspects of the climate change already occurring,and its consequences for forests,marine ecosystems,permafrost,and sea ice discussed above, are already causing multiple serious harms to subsistence livelihoods. Many populations of marine mammals,wildlife,and seabirds have been reduced or displaced. Reduced snow cover, a shorter river ice season,and thawing of permafrost all obstruct travel to harvest wild food. Declines in some fish stocks have harmed subsistence as well as commercial harvesters (Weller and Lange,1999;Mulvaney, 1998).

The most extreme effects of recent changes on subsistence livelihoods have been from changes in sea ice,which have obstructed hunting of marine mammals. The ice is further from shore,thinner, and present for less of the year. These factors,and the rougher seas encountered in the larger open-water areas between the shore and the ice,have made hunting more difficult,more dangerous,and less productive. Retreat of the ice is also likely to directly harm some species on which subsistence hunters rely, including bearded seals and walrus. Walrus are particularly at risk because they need ice strong enough to hold their weight over water shallow enough that they can reach the bottom to feed (Callaway et al.,1999). Polar bears need sea ice to hunt seals,and recent ice reductions have been associated with declining health and birth rate. Projected further large reductions in ice duration and extent are likely to threaten them with extinction (Stirling et al.,1999).

Some subsistence harvests,such as salmon stocks near the northern end of their range,are likely to benefit from projected climate change. Still,most projected near-term climate changes are likely to intensify existing unfavorable impacts through further loss of sea ice, river ice, and permafrost. In addition,shifts in the composition of tundra vegetation may decrease nutrition available for caribou and reindeer, and invasion of tundra by boreal or mixed forest is likely to curtail the range of caribou and musk-ox (Gunn, 1995). As changes in the cryosphere and both terrestrial and marine ecosystems continue,continuing large changes or displacements of the resources available for subsistence are likely, requiring subsistence communities to make major changes in their practices,or move.

Adaptation Options

Subsistence cultures have historically exhibited substantial adaptability to year-to-year fluctuations in abundance of different species by shifting practices and target species,which likely implies some ability to adapt to effects of near-term climate change (Sabo,1991). Subsistence practices are now both extensively regulated and hotly contested,however, posing challenges to traditional means of adaptation. Moreover, for many subsistence-dependent communities,particularly northern coastal communities that rely on hunting marine mammals, few adaptation options are likely to be available. Consequently, it is possible that projected climate change will overwhelm the available responses. Some communities may be forced to reduce their dependence on the wild harvest,or relocate. General measures to increase the income and wealth of subsistence-dependent communities,and consequently their ability to adapt to large-scale

changes in the subsistence resources on which they depend, would likely mitigate the impacts of lost subsistence resources on nutrition,health,and incomes,but would likely have little effect in mitigating the associated social and cultural impacts (Nuttall,1998).

ADDITIONAL ISSUES

Due to limited time and resources in this first Assessment,the Alaskan regional study has focused principally on the four critical issues discussed above. The choice of these four reflected the judgments and concerns of participants in Alaskan workshops from 1997 to 1999,but does not imply that these are the *only* important areas of climate impacts in Alaska. Other areas of potentially significant impact include,e.g.,freshwater, agriculture, tourism, recreation,and human health. Very preliminary discussions are provided here of freshwater, agriculture,and tourism,based on contributions to workshops from 1997 to 1999,and the scientific literature.

Freshwater

Present and projected climate warming is likely to alter both seasonal and annual river flows in the Yukon and other Alaskan rivers,but the aggregate effects are quite uncertain. Over the entire Arctic basin,a recent analysis of runoff based on streamflow gauges found a significant increase in winter runoff with the largest increases in Alaska and Siberia,consistent with recent winter warming. The larger spring and summer flows show a complex spatial mix of increases and decreases,with significant decreases in Western Canada (both Hudson Bay and the McKenzie Basin) and small increases in Alaska (Lammers et al.,2000).

Model projections of future climate effects on Arctic river flows are also spatially mixed. Total Arctic basin runoff is projected to increase (Van Blarcum et al.,1995;Shiklomanov, 1997;Hagemann and Dumenil,1998;Walsh et al.,1998), by 10 - 20% annually and 50 - 100% in the small winter flows by the time of CO_2 doubling (Clair et al.,1998; Shiklomanov et al.,2000). One analysis of the Mackenzie basin projected a decrease in annual flow under climate change,however, consistent with the observed spatial distribution of recent flow changes (Kerr, 1997). Uncertainties in these projections for spring,summer, and annual flows are large, however.

Changes in total and seasonal river runoff are likely to interact with other changes in the oceans and cryosphere to yield complex patterns of ecological and socioeconomic impacts. Combined with increases in sea level and storm surge,they would alter the hydrology of coastal wetlands and deltas, possibly impairing seabird and shorebird breeding (Meehan et al.,1999). Spring flooding due to river ice jams is likely to reduce,bringing reduced flood risk to riverside communities but possibly drying out lakes and riparian and delta ecosystems that depend on periodic flooding (Beltaos and Prowse, 2000;Prowse and Conly, 1998). In contrast,smaller rivers and streams that presently freeze solid will likely retain some flowing water beneath the ice, enhancing fish habitat but also making these rivers liable to ice-jam flooding for the first time.

Agriculture

A lengthened growing season could possibly bring a substantial increase in Alaskan agricultural land and production,including the potential for introduction of new crops and animals. Permafrost thawing will likely impair agricultural potential in moisture-limited regions,however, by allowing drying of surface soils. Thawing can also exacerbate soil erosion and loss of organic materials,or obstruct agriculture in regions of ice-rich permafrost through thermokarst formation. Some of these effects could be mitigated through irrigation and soil conservation measures. In the long term,projected changes in tundra ecosystems are likely to seriously harm reindeer herding,through increased snow or ice cover of forage during warmer wetter winters, reduction of forage quality in dry summers,tundra fires,and expansion of forest into tundra. A climatic contribution to the large recent decline in Russia's domestic reindeer herds is possible (Weller and Lange,1999).

Tourism

Alaskan tourism has increased in recent decades,in parallel with climate warming,although it is not clear how much of the increase can be attributed to the warming climate. Continued warming could possibly bring significant further expansion of tourism,with associated economic benefits and increased risks to sensitive ecosystems and communities (Nuttall,1998;Weller and Lange,1999).

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Despite the strong evidence of present impacts of climate change in Alaska,there remain substantial uncertainties regarding all major domains of future impacts. Even for many impacts that are presently developing,there is insufficient systematic observation and continuing uncertainty about important causal processes. Many near-term research needs follow from this lack.

Cryosphere

Systematic observations of changes presently underway in permafrost are needed over a large scale,to specify the rate and character of present warming and thawing more accurately and to resolve present uncertainties regarding the contribution of climate warming to the observed thaw. Further understanding of the dynamics of permafrost are also needed,in order to identify likely rate and character of future loss under continued climate warming,and thereby to help identify the most appropriate responses.

Better understanding is needed of the interaction between thawing,thermokarst formation,surface hydrology, and ecosystem and site characteristics,in order to understand the effects of permafrost thawing on surface plant communities and carbon storage in vegetation and soils. For instance, recent observations in the Brooks Range foothills,where the observed depth of thawing on adjacent sites facing identical climates was strongly dependent on the acidity of the tundra,illustrate the importance of these investigations (Walker et al.,1998).

Continued monitoring of changes in Arctic sea ice is needed,both in area and thickness,and of coastal erosion and its relationship to both sea ice and storm conditions. In addition,better modeling of Arctic ice dynamics is needed to improve climate models,particularly as regards their projections in Arctic regions.

Forest and Tundra Ecosystems

More systematic large-scale observation of changes in the productivity, range,species mix,and disease and insect activity underway in the boreal and coastal forest are needed,as are studies (observational, experimental,and model-based) of potential interactions between climate change, forest productivity increase,species shift,and disturbances by fire, insects,and disease.

Better understanding is needed of how carbon storage in boreal and tundra ecosystems is controlled. It is possible that warming and thawing of boreal and tundra systems will release large quantities of CO_2 and CH_4 (Anisimov et al.,1997;Bockheim et al., 2000;Goulden et al.,1998;Lindroth et al.,1998; Chase et al.,2000),but the magnitude and even the sign of these fluxes will depend on accompanying hydrological changes and the rate of decomposition of exposed peat under warm temperatures (Oechel et al.,1993;McKane et al.,1997 a,b;Moore et al., 1998).

Models of potential future changes in these ecosystems under climate change should also consider the effect of increased surface ultraviolet (UV) radiation, which has increased 15 - 30% in Arctic regions over the past 20 years (Taalas et al.,1997). In initial experimental studies,enhanced UV has harmed several Arctic plant species with an apparent cumulative effect (Bjorn et al.,1997;Callaghan et al.,1998), and strongly stimulated the growth of one moss species (Gehrke et al.,1996).

Marine Ecosystems

While the history of major regime shifts in the Bering Sea and Gulf of Alaska ecosystems is increasingly well documented,the suite of factors causing them – and in particular, the extent of climatic influence in the shifts and the mechanisms by which they operate – are not yet understood. Further study is needed to understand both historical regime shifts,and the likely effects of future climate change.

One very likely consequence of global climate change will be significant changes in seasonal and annual runoff from the glaciers of Southeast Alaska. The potential effects of these runoff changes on the Gulf of Alaska and Bering Sea ecosystems is large but not well understood,and requires investigation.

Alaska's climate is strongly influenced by existing patterns of climate variability, but little is known about how these are likely to behave in a greenhouse-warmed world. Climate models are now beginning to reproduce ENSO, but do not reproduce observed patterns of interdecadal variability. If these patterns continue to behave as they did during the 20th century, then the changes projected from climate models must be modified by these observed patterns of variability. But whether these cycles will behave as they have in a greenhouse-warmed world,or will show coupled changes,is a critical unknown (Fyfe et al.,1999).

Human Dimensions

The possible interactions between climate-driven changes to natural systems and human responses are strong,diverse,and not well understood. Research is needed in the following areas:

- Develop and refine techniques to assess vulnerability of communities,what determines vulnerability, and strategies to reduce it;
- Investigate interactions between policy, fishing pressure,and the state of marine ecosystems,and how these are likely to adjust under climate change;
- Investigate how changes in economic conditions and forest management practices are likely to interact with climate-driven changes in forest ecosystems;
- Investigate response processes of subsistence-reliant communities to changes in the character of subsistence resources available;and
- Study the potential longer-term influence of climate change on aggregate prospects for Alaskan population and economic growth,including,e.g., large changes in the level and distribution of population,large-scale conversion of forested land to agriculture or settlement,or large shifts in the distribution of economic activity.

Arctic Feedbacks

The Arctic regions,including Alaska,are the site of several key uncertainties in modeling the global climate. These include the potential role of changes in the temperature,salinity, and flow regime of the Arctic Ocean,and of changes in Arctic sea ice,in changes in the global thermohaline circulation,possibly including large or rapid changes (Stocker and Schmittner, 1997;Manabe and Stouffer, 1993; Broecker et al.,1990). They also include a number of potentially important climate-change feedbacks, processes whereby climate change can cause more climate change,either by increasing absorption of solar radiation or by increasing emissions of the greenhouse gases that drive climate change. Gaining further understanding of these processes are key research priorities. While the influence of these processes on regional climate in the Arctic may be especially large,they are also of much wider importance for their contribution to driving climate at the global scale.

One major feedback,the ice-albedo feedback,is included in climate model projections. Present limitations in modeling sea-ice dynamics introduce substantial uncertainty to the representation of this feedback in climate models,however. A second feedback can change albedo through ecological processes,and is not presently represented in climate models. Since forests are darker than tundra, the expansion of boreal forest into the tundra zone as climate warms can reduce the reflectivity of the Earth's surface. It has been suggested that this process could amplify regional climate change by up to 50% (Foley et al.,1994). Both these processes need further study.

Other potential feedbacks would operate through climate change altering patterns of natural greenhouse gas emissions. Both boreal and tundra ecosystems are large carbon stores,particularly in their soils. As discussed above,the controls on carbon storage or release from these systems are not yet well understood,and it is possible that climate change could produce large increases in carbon sequestration,or large increases in release of either CO_2 or methane. Advancing understanding of these controls,and projecting future release under climate change,are key priorities.

A larger, though likely more remote uncertainty, concerns the possibility of methane release from hydrates. Hydrates are crystal structures,in which methane molecules are held at high density by being encased in an ice lattice at high pressure or low temperature. Methane hydrates occur worldwide in enormous quantity. Estimated world reserves are 400 million trillion cubic feet (TCF), versus 5,000 TCF of conventional gas reserves - in ocean sediments at high pressure or low temperature,and at substantial depths in continuous permafrost. Hydrates are of interest as a fuel source, although technical challenges to their exploitation are serious. They are also of interest in the long term for the risk of atmospheric release. While the prospect of significant releases over the next century is presently judged to be highly speculative (Kvenvolden,1999),long-term Arctic warming could eventually release methane by warming coastal waters to shift the depth at which hydrates become stable,or by thawing hydrate-rich permafrost.

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