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Late Cenozoic Climates of Alaska and Yukon: A Joint U.S. Geological Survey–Geological Survey of Canada Global Change Research Project

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This interdisciplinary paleoclimate research project involves scientists from the USGS, Geological Survey of Canada (GSC), Agriculture Canada, and several universities in Canada and the United States. Its objectives are (1) to improve understanding of the history of climate and environments in Alaska and Yukon during the past 17 million years; and (2) to improve late Cenozoic biostratigraphic and chronologic frameworks needed to interpret the surficial and subsurface geology of Alaska and northwest Canada. The research specialties involved in the project include sedimentology, stratigraphy, isotope geology, paleomagnetism, palynology, paleobotany, paleoentomology, and paleopedology.

The project began with a joint USGS-GSC planning workshop held in Menlo Park, Calif., in November 1989. The first joint field season was carried out in August 1990, when a team of nine scientists studied and sampled Miocene fossil-bearing deposits exposed along the valley walls of the Porcupine River in northeastern Alaska. Preliminary results indicate that between about 17 to 15 million years ago the climate of interior Alaska was far more temperate and substantially less continental than is today's rigorous subarctic climate. During middle Miocene time, forest vegetation included taxa such as *Pinus, Tsuga, Metasequoia, Abies, Ulmus, Pterocarya, Carya, Ilex,* and *Diervilla.*

None of those taxa grow in interior Alaska today. The second field season will be held in June–July 1991 in interior Alaska and northern and central Yukon. The 1991 field season will involve a team of 12 scientists, and field objectives include examination and sampling of deposits of Miocene, Pliocene and early Quaternary age. In 1992 the project will attempt to obtain a ca. 350 m sediment core from Yukon Flats in interior Alaska. If successful, the drilling effort will provide a rare opportunity to obtain a nearly continuous record of late Cenozoic climate and environmental changes in interior Alaska. The information derived from this project will contribute significantly to understanding how past global climate changes have behaved at high latitudes in the Northern Hemisphere. General circulation models suggest that global warming is most dramatic in those regions.

Using Spatial Statistics to Improve Estimates of Regional Methane Emissions From Tundra Ecosystems

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G.P. Livingston and R.E. Rossi, TGS Technology, Inc.

Spatial statistical methods, in particular geostatistics, are used to estimate quantities when data are not regularly sampled and to estimate the errors of interpolation for each point. Remote sensing technology, geostatistics, geographic information systems, and in situ approaches are integrated to modify estimates of midsummer methane emissions from tundra ecosystems on the North Slope of Alaska that are being made in a companion project sponsored by NASA. Based on ground coordinates of sampling sites and recorded methane emissions, geostatistical analysis has been used to test underlying sampling assumptions. Spatial interpolation and random simulation techniques are being used to generate methane emission and error surfaces. Using geographic information system analysis, the scientists will combine data on error surfaces with data on vegetation strata derived from Landsat multispectral scanner classifications, and with calculated strata emission means and variances, to produce flux estimates adjusted for sampling locations. Analysis is underway at three scales: Local—small areas about the size of a single multispectral scanner pixel (50 m^2); Meso—the land portions of the Beechey Point and Barrow 1:250,000-scale quadrangles; and Regional—the entire 196,000 km^2 of the North Slope. These analyses use tundra methane flux measurements from Prudhoe Bay, Point Barrow, and other Alaskan sites along the coastal plain and in the foothills of the Brooks Range.

Late Cenozoic Arctic Climatic Change

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This investigation began in fiscal year 1990 and initially was composed of two parts. The objective of Part I was to establish the character and chronology of major late Cenozoic climatic changes in northern Alaska. This part of the investigation was terminated after the first year of funding. Fortunately the research was founded on a solid base of geologic mapping and associated stratigraphic, geomorphic, geophysical, geochemical, and paleontological studies carried out over the past 15 years that facilitated several significant accomplishments from this single year of work: (1) Stratigraphic and paleomagnetic studies with J.W. Hillhouse (Branch of Western Regional Geology) determined an age of 2.48 million years ago for the Pliocene Bigbendian marine transgression of northern Alaska. Knowing the age of this high sea level event is important for the synoptic reconstruction of Pliocene warm intervals, which is an integral part of the National Global Change Research Plan. Also, determining the age of the Bigbendian transgression permitted calculation of a generalized ground temperature for the past 2.48 million years using measurements of the extent of amino acid diagenesis in the shells of Bigbendian mollusks. The calculated ground temperature is about $-15°C$, which suggests that permafrost has been present nearly continuously since the Bigbendian transgression. (2) Stratigraphic and palynological studies with R.E. Nelson (Colby College) determined that Arctic Slope vegetation during the Pliocene Colvillian marine transgression, which occurred sometime between 3.0 and 2.48 million years ago, was boreal forest or spruce-birch woodland with scattered pine and rare fir and hemlock. Climate was much warmer than at present and slightly warmer than during the succeeding Bigbendian transgression, which was characterized by an absence of permafrost and sea ice. (3) Results from oxygen-isotope analyses by J.F. Whelan (Branch of Isotope Geology) show that marine mollusk shells from deposits of the last two eustatic high sea level events along the Beaufort Sea coast, which include the last interglacial highstand (125,000 years ago), have higher $\delta^{18}O$ values than modern shells. Our initial interpretation is that this enrichment in part indicates less extensive summer sea ice than occurs during modern summers. Continuing this research could provide information regarding the response of the Arctic Ocean to warming during the last interglacial, which is one goal of the Earth System History element of the National Global Change Research Plan.

The objective of Part II, which began this fiscal year, is to determine the details of climatic change on the Alaskan arctic slope during the latest glacial-interglacial cycle through a multidisciplinary study of ancient eolian-dominated sedimentary systems. Emphasis will be placed on the warm period that peaked about 10 or 9 thousand years ago as a possible analog for a phase of the warming that is expected to result from the buildup of anthropogenic greenhouse gases in the atmosphere. Research will concentrate on eolian sand, interdunal lake sediments, and loess on the western part of the Arctic Coastal Plain, because studies have demonstrated that these now-stabilized eolian sediments and their intercalated paleosols are sensitive indicators of climatic change, and that they formed over the latest glacial-interglacial cycle. This research will include morphological and sedimentological studies that can provide information about wind directions, surface moisture conditions, and snow cover; studies of fossil lacustrine ostracodes by R.M. Forester (Branch of Paleontology and Stratigraphy) that will indicate water temperature-hydrochemistry-climate relations; measurements of oxygen isotopes in fossil and active ice wedges by D.E. Lawson (U.S. Army Cold Regions Research and Engineering Laboratory) that can provide paleotemperature information; and pollen analyses by R.E. Nelson that will show changes in vegetation through time. This research will link climatic change to physical processes on the Earth's surface in the climatically sensitive Arctic, which are goals of the Earth System History and the Solid Earth Processes elements of the National Global Change Research Plan.

Interrelations Between Gas Hydrates of Northern Alaska and Atmospheric Methane

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Atmospheric methane, a potential greenhouse gas, is increasing at such a rate that the current concentrations (≈1.7 ppm) will probably double in the next 50 years. Many researchers have suggested that destabilized gas hydrates may be contributing to this build-up in atmospheric methane. Little is known about the geologic or geochemical nature of gas hydrates, even though they are known to occur in numerous arctic sedimentary basins. Because gas hydrates occur close to the Earth's surface in arctic regions, they are affected by surficial changes in temperature; thus, destabilized gas hydrates may be sources of atmospheric methane. Under the present climate regime, the gas hydrates of the nearshore continental shelf may be the most vulnerable to change. Because of the abundance of available geologic data, our research has focused on assessing the distribution of gas hydrates within the onshore regions of northern Alaska. Our onshore gas hydrate studies are being used to develop geologic analogs for potential gas hydrate occurrences within unexplored areas, such as the thermally unstable nearshore continental shelf.

The primary goal of this project is to assess the relation between methane hydrate and global climate change. To reach this goal, the project has been divided into a series of three subprojects: (1) gas hydrate distribution, (2) gas hydrate composition, and (3) gas flux characterization. These subprojects have been designed so that deliverable products will be generated throughout the project. Each subproject has a distinct series of tasks and objectives. Within subproject 1, all available industry well-log and seismic data are being studied in order to determine the distribution of gas hydrates in the onshore and nearshore areas of northern Alaska. Subproject 2 deals with the characterization of the chemistry of the delineated gas hydrate occurrences. The primary source of data for this subproject has been our ongoing geochemical well sampling in the oil fields of the Prudhoe Bay area. *Subproject 3* will include onshore and offshore geochemical surveys, with the first onshore survey scheduled for the summer of 1991. Proposed work under subproject 3 will also include the establishment of gas-flux monitoring stations, which should enable us to directly measure the rate of gas flux from decomposing gas hydrates.

Assessing the Human Impact of Global Change in Western United States and Alaska

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Human populations and their occupation of the land are both a cause and an effect of global change. Three regions have been selected to study the dynamics of this relationship between man and nature: northern California, Colorado, and arctic Alaska. The present-day patterns of land use and land cover will be used as bases for mapping ecological and economic factors such as primary productivity, biomass, biological diversity, economic productivity, employment, and population. A model of the present-day state of land resources dynamics will be built. Variables in this model will be altered to test the impacts in these regions of various global change scenarios. Areas that are especially sensitive to these changes will be highlighted on resulting digital data maps and interactive displays. Policymakers will be able to distinguish critical areas and examine mitigation strategies before serious damage is done.

The Old Crow Tephra: A Stratigraphic Marker for the Last Interglaciation in Alaska?

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A recent fission-track age determination of 140,000 years ago, plus or minus 10,000 years, for the Old Crow tephra of Westgate and others (1983) (OCt) seems to indicate that it was deposited before the last interglacial maximum (oxygen-isotope substage 5e). The OCt has now been recognized at 11 sites in Alaska, and its stratigraphic placement at nine of these sites is well defined. The stratigraphic record at some sites seems to confirm deposition of the OCt before the last interglaciation, but data from other sites challenge this widely accepted age relationship.

At Birch Creek and Halfway House in central Alaska, the Old Crow tephra occurs within a paleosol that probably formed under forested conditions and that could represent substage 5e. At Fairbanks and at the Palisades of the Yukon on the other hand, the tephra occurs within silt that clearly underlies a conspicuous organic horizon that may have formed during substage 5e. Three sites in the Koyukuk Valley show comparable variations. At Ky-11, the tephra lies between the lower two of three horizons that exhibit spruce-pollen peaks; at Ky-12, peat with spruce wood occurs in loess 2 m above the tephra; at the Hogatza Mine the tephra overlies a peat rich in spruce pollen that indicates forest about as extensive as that of the present day.

The OCt also has been reported at two sites in western Alaska. At Imuruk Lake, it coincides with a minor spruce-pollen maximum 1.5 m below a major zone of spruce pollen that indicates forest limits beyond those at present. In the Holitna lowland, the tephra occurs below an extensive organic horizon that appears to represent interstadial rather than interglacial conditions.

At four of the sites discussed above (Palisades, Fairbanks, Ky-12, and Holitna lowland), the OCt clearly occurs below an organic horizon or spruce-pollen peak that represents a distinctive warm interval; but at three other sites (Birch Creek, Halfway House, and Hogatza Mine) it occurs within or just above an equally conspicuous paleosol. Multiple paleosols or spruce-pollen maxima at Birch Creek, Halfway House, Ky-11, and Imuruk Lake form complex records that make correlations with substage 5e uncertain. These multiple organic horizons suggest that no single buried forest bed or spruce-pollen peak at any site can be assumed to represent a unique "last interglacial maximum."

The varying stratigraphic positions of the OCt probably were not caused by multiple volcanic eruptions. No locality has yet been identified with more than one OCt, and geographic distribution and tephra geochemistry also are consistent with a single depositional episode. Alternatively, the OCt may have been deposited during an early warm phase of the last interglaciation when residual glaciers were still present, loess deposition was active locally, and soils and organic horizons formed elsewhere. High-resolution uranium-series ages show that the sea-level maximum associated with the last interglaciation lasted from about 132,000 to 120,000 years ago. An appropriate time for the diverse environments indicated by the OCt is just prior to this high sea-level event, perhaps about 135,000 years ago, plus or minus 5,000 years ago. This age estimate is consistent with the younger part of the time interval suggested by the recent fission-track age determination cited above.

REFERENCE

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Permafrost and Gas Hydrates as Possible Sources of Atmospheric Methane at High Latitudes

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The United Nations Intergovernmental Panel on Climate Change has identified permafrost and gas hydrates as important high-latitude methane sources on the basis of minimal quantitative information. Permafrost and gas hydrates are associated in two distinct high-latitude settings: (1) on shore, where the permafrost is continuous and the zone of gas-hydrate stability ranges in subsurface depth from about 200 to 1,200 m; and (2) on the nearshore Continental Shelf, where relict permafrost has persisted since times of lower sea level when the present inundated shelf was exposed to very cold subaerial temperatures. Three studies that consider methane occurrence in examples of these settings are reported here: (1) The current release of methane from gas hydrates on the Continental Shelf was estimated at about $3–5\times10^{12}$ g/yr, on the basis of the inferred distribution of methane in permafrost-associated gas hydrates and the transgression history of the Arctic Ocean during the Holocene. (2) Hydrocarbon-gas compositions were measured in 17 surface-sediment samples collected through the ice cover of Harrison Bay. This bay is offshore from an area of known gas-hydrate occurrence on the North Slope of Alaska. Geophysical surveys indicate the presence of offshore permafrost and of gas anomalies in the sediment. No major methane anomalies were detected in these surface sedimentary deposits, and deeper sampling is required to test more completely this nearshore region. (3) The gas composition of ground ice in permafrost was measured at two sites near Fairbanks, Alaska. In the air of a tunnel, where permafrost is subliming, methane concentrations were about 13 ppmv, whereas outside the tunnel, methane concentrations were only 1.7 ppmv. An ice sample from the tunnel contained 0.036 mL of methane per liter of melted ice. At the second site, near the University of Alaska campus, samples from a short core of permafrost contained as much as 6 mL of microbially derived methane ($\delta^{13}C$=L74 ‰) per liter of melted ice. These preliminary results indicate that (1) gas hydrates may currently contribute methane to the atmosphere and (2) shallow ground ice can contain varying amounts of methane at low concentrations and thus be a high-latitude source of methane.

Paleoclimate Reconstructions From Alaskan Ice Records: Teleconnections Between Pacific–North American (PNA), Reverse PNA, and El Niño–Southern Oscillation (ENSO) States

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We propose to reconstruct a detailed, high-resolution climate record from glacier ice recovered in southern Alaska that will emphasize the annual to most recent millennial time scale. Our results will be compared with records covering the same time span from lake varves of North-Central United States, coral records from central Florida, and the ENSO record both from the Quelccaya Ice Cap and sediment records from the Santa Barbara channel of southern California. While much is known from the continental ice sheets of Greenland and Antarctica, little comparable information is available from Alaska, where ice contains a climate record that is influenced by the northern Pacific Ocean. This same influence dominates all of North America. Volcanism in Alaska provides air circulation information through tephra layers of known source and age. We propose collection of ice core samples at a site(s) satisfying the following criteria: (1) location above the glacial equilibrium line (1,000–2,100 m), (2) presence in ice of an appropriate signal of annual cycles without frequent or major melting events, (3) existence of a polar to subpolar glacial regime, (4) confinement of ice by broad and simple bedrock topography to minimize complications from flow deformation, and (5) presence in ice of traceable horizons of volcanic products that also are suitable for age determinations. The proposed continental records from Alaska are critical to any global program of climate change.

Four complementary disciplines will be applied to the study of ice cores obtained. These include (1) study of the stratigraphic, structural, and petrofabric properties of the ice samples (J. Fitzpatrick), (2) study of occluded, adsorbed, and clathrated gas in ice and snow (firn gas) as indicators of changing greenhouse and other atmospheric gases (G. Landis), (3) study of metals as indicators of oceanic, continental, and volcanic exhalation materials in ice and snow samples (T. Hinkley), and (4) study of stable isotope variations in snow and ice samples as indicators of surface temperatures, climatic weather patterns, accumulation rates, and post accumulation modifications to ice (R. Rye). Evaluation of our proposed ice core site at Churchill—Bona in the Wrangell—St. Elias Range is planned for June of fiscal year 1991. Additional ice is available from GISP II (Greenland), Byrd core (Antarctica), Dunde (China), and Quelccaya (Peru) for correlation with Alaskan ice records obtained after fiscal year 1992.

Glacier Growth and Shrinkage Related to Climate Variations and Nonclimatic Factors in Alaska

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At a time when the effects of climate variations are the focus of global change research, it is important to separate the influences of climate on glaciers from those of other processes. Proxy climate signals in glacier behavior can be ambiguous because changes in either temperature or precipitation can produce growth or shrinkage, and such changes can be mixed with signals from geologic, hydrologic, and glaciologic processes. Glacier growth (volume increase) can result from either decreased melting or increased snowfall, or from non-climatic factors such as protection by landslide rock debris, reduction of water depth at glaciers ending in water, or recovery after a surge. A tidewater glacier, Hubbard Glacier for example, is growing and may continue its advance for another 60 km for a millennium as it moves a protective terminal moraine down Yakutat Bay. At the same time, Columbia Glacier is shrinking as it calves into deep water behind a moraine it recently abandoned, and retreats rapidly. We do not know if the total volume of these glaciers is changing because their advances and retreats are asynchronous and the rates are unequal. Glaciers on volcanoes and those carrying ash deposits from eruptions can also behave somewhat independently from climatic forcing.

Wolverine Glacier, 60.4°N latitude in Alaska, responds primarily to climate, and it experienced a period of growth from 1976 to 1988. Observations of the glacier show that variations in winter snowfall exert the primary control over its annual ice volume changes. When the glacier grows, the mountainous region experiences increases of air temperature and precipitation that generally take place at temperatures colder than −5°C at the altitude of the glacier in midwinter. Thus, the warming fails to convert snowfall at the glacier to rain. Summer temperatures and melting are relatively steady. Cold, dry winters have returned since 1989, and the glacier is again shrinking. Sea surface temperatures in the Gulf of Alaska and the position of the Aleutian Low have influenced these fluctuations. Thus, Wolverine Glacier currently tends to grow when its climate varies toward a warmer and wetter state. Several global climate models predict warming of winter temperatures and increases in precipitation at high latitudes with increasing concentrations of greenhouse gases.

These results support the hypothesis that high-latitude glaciers and polar icecaps could grow as climate warms, while low-latitude glaciers shrink; however, Wolverine Glacier is located about 200–600 km west of the primary glacierized region in North America (58–62°N), so our results may not apply to the behavior of these other glaciers. Studies of glaciers in this region are required to investigate the transfer of results from present research sites to the main mass of glacier ice in North America.

Oversimplified ideas of global climate change can produce ambiguous or incorrect predictions of glacier and ice sheet response; therefore, estimates of glacier behavior and runoff from climate model scenarios require that attention be given to seasonal patterns of both temperature and precipitation, as well as the altitude distribution of glacier ice in each geographic region. These interactions with climate can also be mixed with responses caused by variable boundary conditions, ice flow instabilities, and oceanic and geologic processes. This combination of processes explains why different glaciers in the same region are often observed to be both growing and shrinking.

Glacier Monitoring for Global Change—Three Case Studies

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The purpose of glacier monitoring is to document changes in glacier systems, focusing on changes in position, areal extent, and volume. Equally important is deciphering the recent history of the glacier system and documenting the chronology of change. Data for glacier monitoring come from the following: field observations, surface measurements, radio echo sounding (RES), remote-sensing (aerial photography, synthetic aperture radar (SAR) and satellite photography) and spectral imagery, published and manuscript maps and charts, and direct and proxy evidence of former glacier positions (trim lines, moraines, radiometric dating, lichenometry, and dendrochronology).

In 1984–1985, Mendenhall Glacier, which has retreated for more than two centuries, experienced a minor readvance. The advance triggered changes in the glacier's drainage, resulting in an order-of-magnitude increase in the glacier's rate of retreat. Annual field visits, combined with analysis of ground and aerial photography, were used to document the sequence of events involved in the accelerated retreat and to document that the retreat was not a manifestation of global warming.

Field observations, measurements of suspended-sediment-load, RES, and analysis of aerial photography, satellite imagery, and 80-year-old topographic maps were used to determine that Bering Glacier has retreated 8 km during this century. Retreat has formed a lake and resulted in the sediment starvation and rapid erosion of the beach separating the lake from the Gulf of Alaska. Continued beach erosion could result in Bering glacier icebergs entering the Gulf, where they could be a threat to shipping, including tanker traffic from Prince William Sound. RES determined that Bering Glacier occupies a fiord basin extending well below sea level and that several hundred cubic kilometers of the glacier could ultimately become icebergs.

SAR of the Malaspina Glacier reveal ice-surface morphological features that mimic bed morphology and provide insights into the glacier's Neoglacial history. Identification of the position of the end moraine of the adjacent Hubbard Glacier, under the Malaspina, provides constraints on when the Malaspina expanded to its present position. Photography, extending back to 1895, and satellite imagery document stagnation of the glacier's margin and surges. RES determined that Malaspina also occupies a fiord basin extending well below sea level.

Baseline Studies for Monitoring Global Climate Change in the Arctic Environment: A Remote Sensing-Spatial Data Base Approach

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In 1989 the U.S. Geological Survey's EROS Data Center Alaska Field Office established a 10-year monitoring program based on remote-sensed and other digital spatial Earth science data bases to support global climate change studies in arctic, subarctic, and boreal regions of Alaska. The monitoring program is designed to support studies and models of Earth system processes at landscape, ecosystem, and regional scales. These site and regional models will improve parameter estimates for circumpolar and global climate change models. A major component of the project focuses on research elements associated with the spatial integration of widely varying sources of Earth science data and multiplatform, multitemporal sources of remote-sensed data for land surface characterization. Site-specific information will be correlated through collaborative studies with regional and hemispheric level data bases for broad scale extrapolations and predictions.

Establishment of a monitoring program for the arctic and subarctic regions will be accomplished by addressing the following goals:

1. Establish eight study sites within Alaska that sample unique ecosystems with a high potential for change.
2. Compile a comprehensive archive of remote-sensed and automated Earth science data bases for designated sites.
3. Develop baseline data bases and maps from which to document change in the biological and physical components.
4. Identify and develop data analysis and data integration techniques for detecting and monitoring change.
5. Establish a program for acquisition and integration of new data from existing and future satellite systems.
6. Use geographic information system technology to develop parametric and nonparametric models to study and predict ecosystem change.
7. Correlate site and ecoregion level data with statewide and circumpolar data for broad scale modeling.

A key element of the project includes the development of an ecological regionalization map of the entire circumpolar arctic and subarctic regions through collaborative efforts with the Environmental Protection Agency and Environment Canada.

Some Anticipated and Measured Responses of Glaciers to Global Change in Alaska

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The linkage between glaciers and climate and the role that glaciers play in the hydrologic cycle are imperfectly known. Global temperature increases are expected to cause surface melting at higher elevations on glaciers worldwide. At first, most of the increased surface melt at high elevations will be refrozen within glaciers as internal accumulation. Runoff modelers need to recognize how the process of forming internal accumulation will decrease and delay the runoff derived from increased surface melting.

A small sea-level rise could cause several large glaciers in Alaska to begin drastic retreats. A rise that is inconsequential to most human activities could increase erosion along the narrow beaches that presently separate Malaspina, Bering, and other glaciers from attack by the waters of the Gulf of Alaska. Recent ice-penetrating radar measurements show that the potential retreat of Malaspina Glacier is 45 km and of Bering Glacier, 50 km. A small sea-level rise also increases the potential for retreat of a few actively calving glaciers. The threatened glaciers are sea-calving glaciers that are near their extended positions.

Long-term studies of glacier mass balance and runoff from Wolverine and Gulkana Basins, Alaska, show that recent increases in glacier ice storage are associated with increased basin runoff and increased total precipitation. This is contrary to the accepted relation in which ice storage increases are assumed to be withheld from unchanged total precipitation, which would reduce basin runoff. At Wolverine Glacier, a measured increase in the mean annual temperature has been associated with increases in both ice storage and basin runoff. The direct relation among mean annual temperature, ice storage, and runoff is not expected to hold for all glaciers, nor for these glaciers, as temperature continues to rise. Because the areal extent and temperature range over which the direct relation applies is undefined at this time, the sign of its effect on global sea level is undetermined. An important implication of this work is that in the absence of precipitation and ice storage change assessment, the reason for changes in basin runoff are ambiguous.

Our plans are to (1) extend the long-term records of glacier mass changes and climate data at existing study sites for use in empirical and theoretical assessment of the glacier/climate relation; (2) increase the mass balance and climate sampling density and coordinate the expanded effort with Canadian and other agency colleagues for use in improving and ground-truth checking GCM results; (3) improve understanding of relation between changing glacier mass and the hydrologic cycle; and (4) recognize uniquely glacier processes and bring them to the attention of the global circulation modeling community.