FINAL REPORT

of the

WORKSHOP ON LONG-TERM MONITORING OF GLACIERS OF NORTH AMERICA AND NORTHWESTERN EUROPE

Richard S. Williams, Jr.,[1] and Jane G. Ferrigno,[2] Workshop Coordinators
U.S. Geological Survey
[1]Woods Hole Field Center-Quissett Campus
384 Woods Hole Road
Woods Hole, MA 02543-1598 U.S.A.

[2]955 National Center
Reston, VA 20192-0001 U.S.A.

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Workshop on Long-Term Monitoring of Glaciers of North America and Northwestern Europe

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(Convened at the University of Puget Sound, Tacoma, WA on 11-13 September 1996)

Workshop Coordinators: Richard S. Williams, Jr., and Jane G. Ferrigno, USGS

INSTITUTIONAL PARTICIPATION:

- Environment Canada
- Environmental Research Institute of Michigan
- Geological Survey of Canada
- Geological Survey of Denmark and Greenland
- International Glaciological Society
- National Aeronautics and Space Administration
- National Oceanic and Atmospheric Administration
- French Space Agency
- National Energy Authority (Iceland)
- Portland State University
- Swiss Federal Institute of Technology
- University of Alaska
- U.S. Department of the Interior
- University of Colorado
- University of Oslo (Norway)
- University of Wales (U.K.)
- University of Zürich-Irchel (Switzerland)

USGS
Woods Hole, MA 02543

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EXECUTIVE SUMMARY

The Geologic Division's Global Change and Climate History Program sponsored a Workshop on Long-Term Monitoring of Glaciers of North America and Northwestern Europe on 11-13 September 1996 hosted by the USGS (WRD) Ice and Climate Project at the University of Puget Sound, Tacoma, WA. The primary motivation for the Workshop was the recognition that airborne and satellite remote sensing of areal and volumetric changes in glaciers had reached the stage where quantitative scientific information could be derived from remotely-sensed data that had previously only been available from direct field measurements. In addition, many long-term national glacier-observation networks that had been established in the U.S. and Canada after World War II were being reduced or eliminated because of budgetary cutbacks. Institutional and programmatic reductions have caused the termination of many long-term datasets that are especially valuable in determining whether observed changes in key environmental parameters, such as glaciers, caused by changes in regional or local climate, are the result of natural variability, impact of human activity, or both. The Workshop provided the opportunity to develop a new strategy using satellite remote sensing, in conjunction with ground-based observations, to continue and possibly expand the existing ground-based network of glaciers being studied and monitored by various institutions in North America and Northwestern Europe. Such a plan would maximize the scientific results while utilizing available governmental funding in the most efficient and cost-effective way.

Thirty-two scientists with special knowledge of the glaciers of North America (Alaska, Canada, Western U.S., and Greenland) and Northwestern Europe (Iceland, Jan Mayen, Svalbard, Norway, Sweden, and the Russian Arctic Islands) participated; they represented 17 different institutions, including 7 U.S. and 10 foreign. The four science divisions of the USGS [Biological Resources Division (BRD), Geologic Division (GD), National Mapping Division (NMD), and the Water Resources Division (WRD)] and the U.S. National Park Service of the U.S. Department of the Interior were all represented.

Part I of the Workshop included presentations by glaciologists from North America and Northwestern Europe on "Existing Data Bases and Current Status of Monitoring Glaciers of North America and Northwestern Europe." Part II of the Workshop included presentations by glaciologists, other scientists, and engineers about "Current and Planned Remote Sensing Technology for Monitoring Glaciers." Part III of the Workshop was composed of presentations by glaciological-archive managers [for example; UNESCO's World Glacier Monitoring Service (Zürich, Switzerland); NOAA's National Snow and Ice Data Center/World Data Center - A for Glaciology (Boulder, CO); and the USGS EROS Data Center (Sioux Falls, SD), etc.] on "International Data Centers for Archiving Ground, Airborne and Satellite Data of Glaciers."

Following the presentations, round-table discussions were held. The general consensus reached was:

- Long-term monitoring of selected glaciers of North America and Northwestern Europe, as recommended in USGS Circular 1132 using a combination of traditional ground-based and airborne and satellite remote sensing methods, is of critical scientific value to understanding changes in glaciers, a climatically-sensitive element of the Earth's cryosphere and a keystone environmental parameter.

- Satellite remote-sensing technology represents the only feasible way of measuring and monitoring changes in the area and volume of the Earth's large glaciers (e.g., ice sheets, ice caps, and ice fields), but ground-based observations at selected locations are necessary to validate analysis of remotely-sensed data of glaciers.

- Because glaciers are part of the Earth System; they should be studied globally and systematically using a well planned and coordinated monitoring program carried out by the USGS and cooperating U.S. and foreign institutions.

- A better understanding of the role of glaciers in regional and global climate change is not just scientifically valuable, but is broadly relevant to governmental interests and responsibilities and to national and international programs, such as the U.S. Global Change Research Program and the International Geosphere-Biosphere Programme for the following reasons:

    - sea level change — the melting of about 400 km^3 of glacier ice will raise sea level 1 mm globally;

    - the hydrologic cycle — the cryosphere (glaciers; snow cover; sea, lake, and river ice; and permafrost or permanently frozen ground) is the frozen-water component of the hydrologic cycle; glaciers, for example "store" 2.15 percent of the Earth's water, the second largest reservoir of water, after the oceans (97.2 percent);

    - glacier-related hazards — e.g., glacier-outburst floods (jökulhlaups), surging glaciers, discharge of icebergs, etc.;

    - ecosystem changes — the increase or decrease in glacier area impacts high-mountain and high-latitude ecosystems (especially in National Parks and Monuments).

- The USGS glacier-studies program, while recognized as carrying out invaluable scientific studies and providing valuable scientific data on fluctuations and mass-balance of selected glaciers, could be more valuable if more focused and better coordinated internally [managed as a Bureau program (all four science divisions)] and if it had stronger external coordination, cooperation, and collaboration with USGS counterpart agencies in other nations involved in glacier monitoring (see table 1).

As a result of the discussions at the Workshop, the following recommendations are presented in the following two pages:

WORKSHOP RECOMMENDATIONS

1. The USGS should maintain its lengthy history of glacier studies with a revitalized and integrated bureau program based on a combination of ground-based, airborne, and satellite remote sensing methods as recommended in USGS Circular 1132. The program should be funded by the U.S. Global Change Research Program and other SIR funds, utilizing the respective scientific strengths of the four science divisions, in concert with strong collaboration with other agencies and institutions involved in glaciology, both domestic and foreign.

The USGS has been involved in glacier studies for 118 years and has the experience and current status as the principal Federal ecosystem agency to develop a strong integrated bureau-wide, glacier-monitoring program. It has been more than a decade since such a course of action was first recommended by various USGS scientists and later encouraged by Robert M. Hirsch, Chief Hydrologist. It is now time to take decisive action in light of the importance of long-term monitoring of glacier fluctuations to assessing regional climate change and the obvious source of sustained funding through the U.S. Global Change Research Program. **An integrated bureau program requires a strong leader with a national and international reputation in glaciology.**

The USGS should consider glacier studies as an integrated Bureau program involving all four science divisions, with programmatic funding and staffing derived primarily from the U.S. Global Change Research Program and secondarily from surveys, investigations, and research (SIR) and/or outside funding agreements (OFA) funding for glacier hydrology, cold-regions hydrology, impact of glacier recession on regional ecosystems (e.g., Glacier National Park, Montana), and other glaciological research programs traditionally supported by the divisions. Through an integrated Bureau program, in which planned fiscal-year budget submissions by each division would be coordinated, each science division would operate independent projects that draw from their respective scientific strengths and programmatic histories, including existing intra-divisional, inter-divisional, inter-agency, and non-USGS institutional (U.S. and foreign) cooperation and collaboration. Each USGS science division has the following glacier-studies strengths:

a. **Water Resources Division (WRD)** - Lead division in the continuation of long-term field studies of mass-balance, ice velocity, climate, runoff, and fluctuation of termini of selected glaciers in the conterminous U.S. and Alaska, field studies of glaciological hazards, glacier hydrology, and cold-regions hydrology. Close cooperation and collaboration with the other three USGS science divisions, collaboration with NASA Goddard Space Flight Center and several U.S. universities, National Park Service, and counterpart agencies in other nations (see following table: USGS and Counterpart Governmental Institutions in North America and Northwestern Europe Involved in Glacier Monitoring).

b. **Geologic Division (GD)** - Lead division in satellite remote sensing of glaciers of the Earth, with special reference to the glaciers of North America and Northwestern Europe. Currently completing an 11-volume Satellite Image Atlas of Glaciers of the World (USGS Professional Paper 1386) that involves more than 60 U.S. and foreign scientists in a baseline study, using Landsat images from the mid-1970's, to establish the areal extent of glaciers worldwide. Close cooperation and collaboration with the other three USGS science divisions, NASA, National Park Service, and glaciological institutions in other nations.

c. **National Mapping Division (NMD)** - Lead division for production of conventional topographic, planimetric, image, and specialized thematic maps of glaciers, including digital and paper formats. Principal archive (EROS Data Center) for airborne and satellite imagery [e.g., Landsat, EOS (Mission to Planet Earth), classified source material (including imagery derived products or IDP'S), aerial photographs and images, etc.]. Close cooperation with other international archives, cooperation with the other three USGS science divisions, NSF, NASA, and NOAA.

d. **Biological Resources Division (BRD)** - Lead division for field and airborne monitoring of glaciers in the National Parks of the conterminous U.S. and Alaska, especially impact of glacier recession on park ecosystems. Close cooperation with the National Park Service, the other three USGS science divisions, and Canada.

2. It is imperative that increased cooperation and collaboration, especially carrying out of joint (intra-or inter-national) field programs be a major objective of the USGS (see table 1). Because of the global nature of glacier studies, the importance of glacier studies to monitoring global environmental change, and reduced funding to and "downsizing" of staffs at U.S. and foreign scientific institutions involved in glacier monitoring, there is a need to continue and integrate acquisition and analysis of environmentally critical, long-term field-based data sets for historical perspective and to validate analysis of remotely sensed data and expand them geographically where warranted scientifically.

3. A cooperative program between scientists and their respective institutions needs to be established to share remotely-sensed data and to provide for easy exchange of data for independent or collaborative studies, because of the high cost of airborne and satellite images and other data (e.g., laser altimetry, radar, interferometry, etc.) and the need for a coordinated, systematic, and repetitive regional data-acquisition program for airborne and satellite data.

4. It is recommended that strong international support be given for maintenance of the glacier data archives, because of the value of these data archives for monitoring glaciers and determining historical changes of glaciers in North America, especially the Canadian glacier archive and the GeoData Center in Alaska. The Canadian archive includes important data of both Canadian and U.S. glacierized basins. Because of funding

cutbacks and other organizational changes in Canada, the data may no longer be fully accessible to glaciologists and could be lost if not properly archived. The GeoData Center of the University of Alaska's Geophysical Institute in Fairbanks, AK, is a major archive for remotely-sensed data of Alaskan glaciers, including the 60,000+ aerial negatives acquired by the USGS between 1960 and 1996 (see summary in Part I, Data Base and Geographical Perspective for Monitoring Glaciers of Alaska by Trabant and others).

In conclusion, a strong U.S. Federal program of glacier studies has been the responsibility of the USGS for more than a century. The USGS needs to have an equally strong presence in glacier studies for the 21st century, based on a well managed and revitalized glacier studies program within the USGS, and a close cooperative effort among the four science divisions of the USGS, in collaboration with the U.S. National Park Service, other agencies involved with the Department of the Interior in the U.S. Global Change Research Program, such as NASA and NOAA, academic institutions, and USGS counterpart institutions in other nations.

Table 1.—USGS and Counterpart Governmental Institutions in North America and Northwestern Europe Involved in Glacier Monitoring

Institution	Miscellaneous Glacier Monitoring (e.g., Radio-echosounding, Glacier Hydrology, Satellite Remote Sensing, etc.)	Monitoring of Termini Fluctuations	Monitoring of Mass Balance	Topographic Mapping of Glaciers	Data Archives (National/International)
United States					
USGS					
Biological Resources Division	X	X	—	—	—
Geologic Division	X	X	—	—	—
National Mapping Division	—	—	—	X	X (EROS Data Center)
Water Resources Division	X	X	X	X	X
U.S. National Park Service	X	X	X	—	—
NOAA	—	—	—	—	X* (NSIDC)
NASA	X	—	—	—	X (NSIDC)

*National Snow and Ice Data Center

Institution	Miscellaneous Glacier Monitoring (e.g., Radio-echosounding, Glacier Hydrology, Satellite Remote Sensing, etc.)	Monitoring of Termini Fluctuations	Monitoring of Mass Balance	Topographic Mapping of Glaciers	Data Archives (National/International)
Canada					
National Hydrology Research Institute	X	X	X	—	X
Geological Survey of Canada	X	—	—	—	—
Greenland (Denmark)					
Geological Survey of Denmark and Greenland	X	X	X	—	X
National Survey and Cadastre	—	—	—	X	—
Iceland					
National Energy Authority	X	X	X	—	X
Science Institute (University of Iceland)	X	—	—	—	—
National Land Survey of Iceland	—	—	—	X	X

Institution	Miscellaneous Glacier Monitoring (e.g., Radio-echosounding, Glacier Hydrology, Satellite Remote Sensing, etc.)	Monitoring of Termini Fluctuations	Monitoring of Mass Balance	Topographic Mapping of Glaciers	Data Archives (National/International)
Norway (including Svalbard and Jan Mayen)					
Norwegian Water and Energy Authority	X	X	X	X	X
Norwegian Polar Institute	X	X	X	X	X
Russia					
Institute of Geography (Russian Academy of Sciences)	X	—	—	X	X
United Kingdom					
Scott Polar Research Institute	X	—	—	—	—
Centre for Glaciology (University of Wales)	X	—	—	—	—
Switzerland					
World Glacier Monitoring Service	—	—	—	—	X

INTRODUCTION

History of USGS Involvement in Glacier Studies

The U.S. Geological Survey (USGS) was established by an Act of the U.S. Congress in 1879. The first Director of the USGS (1879-1881), Clarence R. King, had a special interest in glaciers dating from his education at Yale University and his participation in the field parties of the U.S. Geological Exploration of the Fortieth Parallel (1867-1872). King discovered Whitney Glacier on Mount Shasta on 11 September 1870 and three more glaciers on the north slope of the volcano. He published an article in the Atlantic Monthly (1871, v. 27, 8 March , p. 371-377) on "Active Glaciers within the United States." Israel C. Russell, a geologist with the USGS (1880-1892) and a founder of the National Geographic Society (NGS) in 1888, received the first research grant from the Society on 20 May 1890 to fund "The Mount St. Elias Expedition," the initial scientific study of one of the largest ice fields and associated outlet glaciers in North America. The NGS "had assembled contributions from 27 donors to help finance Russell's expedition......, where his team measured glaciers, gathered samples, and made sketches for National Geographic Magazine."* Russell published a report on "Existing Glaciers of the United States," in the 5th Annual Report 1883-84 of the USGS (1885) and on the "Glaciers of Mount Rainier" in the 18th Annual Report 1896-97 of the USGS (1898). Harry F. Reid, in the 16th Annual Report 1894-95 of the USGS (1896), published a report on "Glacier Bay and Its Glaciers."

Throughout the 118-year history of the USGS, the agency has supported research on glaciers, with each of the original three science divisions providing scientific leadership at different periods during that span of time. From the late 19th century to the present time, the Geologic Division supported a variety of glacier studies, initially as an adjunct to geologic mapping of high mountain areas in the western United States and Alaska and later as elements of other programs, such as the present Global Change and Climate History Program. From the late 1920's to the end of World War II, François E. Matthes of the National Mapping Division [Topographic Division], published annual reports on glaciers of the United States in the Transactions of the American Geophysical Union (1932-1945). By the mid-1950's, scientific leadership on glacier studies was provided by the Water Resources Division, with the hiring of Mark F. Meier, who eventually would become one of the preeminent glaciologists in the United States and the international glaciological scientific community. Meier established a strong scientific program in glaciology in Tacoma, WA, and staffed it with a fine group of scientists and support staff. During his long tenure, he and his staff established a long-term program of glacier monitoring, including mass-balance studies of selected glaciers (e.g., South Cascade Glacier, WA) and terminus fluctuations (e.g., systematic annual aerial surveys of glaciers by Austin Post and Robert M. Krimmel), fundamental studies of glacier dynamics and

*Pollack, Henry, Cox, Rob, and Komar, Paul, 1996, a bit of history: Israel C. Russell: Geoscience News (University of Michigan, July, p. 11

hazards, including the cyclical advance and retreat of tidewater glaciers (e.g., Hubbard Glacier and Columbia Glacier, AK, respectively), and jökulhlaup (glacier outburst floods) occurrences in Alaska (lacustrine and volcanic) and from volcanoes in the Cascade Mountains of Washington and Oregon (e.g., Mount Rainier). In the early 1960's another group of glaciologists in the Water Resources Division under the leadership of Lawrence C. Mayo in Fairbanks, Alaska began a long series of studies of Alaska's glaciers. The scientific productivity of the "Meier Group" and the "Mayo Group" was enormous, a conclusion confirmed by reference to the 1996 USGS Open-File Report 95-723, "Bibliography of Glacier Studies by the U.S. Geological Survey."

The retirement of Meier from the USGS in 1985 marked the beginning of major funding and staffing reductions by WRD for glacier studies. By 1997, 7 glaciologists of the staff of the glaciology group in Tacoma, WA, and Fairbanks, AK, had retired, resigned, or been transferred to other projects; this critical scientific and manpower loss has not been replaced. The late William J. Campbell, who was the head of the USGS-WRD Cryospheric Interaction Project, assumed leadership of a combined glaciology, sea ice, and snow group; the combined staff was called the Ice and Climate Project (ICP). Campbell's primary scientific interest was sea ice monitoring using passive microwave satellite remote sensing. Working with the NASA Goddard Space Flight Center and the French Space Agency, (Centre Nationale d'Études Spatiale (CNES)), he pioneered the use of microwave remote sensing of sea ice and used these techniques to determine long term trends in sea ice coverage. Under Campbell, the group continued the glacier-monitoring program and other snow and ice investigations despite severe budgetary restraints and the loss of additional staff that were also not replaced. In 1993, the year after the death of Campbell, the Ice and Climate Project moved from the administrative management of the WRD-National Research Program (NRP) to the Alaska District Office (ADO). The Fairbanks Glaciology Project and the Tacoma Ice and Climate Project are now considered part of the Alaska District Glacier and Snow Program. This combined group has continued strong programs in glacier mass balance of the three USGS benchmark glaciers, the relationship of mass balance with changes in global atmospheric circulation, glacier-climate interaction, tidewater glacier processes, microwave remote sensing of snow, and glacier-volcano and other glacier hazard analysis. However, Campbell was not replaced nor was a new leader appointed. The effect of the past 12 years of budgetary and staffing reductions has resulted in a greatly reduced glacier program in WRD without a clearly defined leader in glaciology for either WRD or the USGS.

Although the Alaska District Glacier and Snow Program (WRD) continues to be the principal focal point in the USGS for the scientific study of glaciers, the other three science divisions have also been active in glacier mapping, publication of a global inventory (baseline) of the areal extent of glaciers, and glacier monitoring. The National Mapping Division (NMD) compiles and publishes topographic, planimetric, and image maps of glaciers of the United States and Antarctica as part of its national topographic mapping responsibilities; Antarctic mapping is done as a cooperative endeavor with the National Science Foundation's Office of Polar Programs. NMD also operates the Advanced Systems Center in Reston, VA, to provide access to classified satellite imagery and other data useful for environmental monitoring by scientists who have appropriate security clearances. The Geologic Division, with funding from the Global Change and Climate History Program (a component of the multiagency U.S. Global Change Research Program), is publishing an 11-volume series of books that represents a global glacier inventory of the areal extent of glaciers using Landsat images from the mid-1970's: Satellite Image Atlas of Glaciers of the World (USGS Professional Paper 1386 A-K) [http://geochange.er.usgs.gov/pub/info/facts/atlas/index.html]. This long-term project involves more than 60 scientists, representing 25 nations and 45 different institutions; six volumes have been completed, including five published and a sixth to be printed in winter 1998 and a seventh in late 1998. Also, under the same project (Glacier Studies Project), satellite image maps and coastal-change and glaciological maps of Antarctica have been published* or are in preparation. In the mid-1970's, the Geologic Division began studying the glacial and sedimentation history of Alaskan coastal glaciers as part of the Outer Continental Shelf Environmental Assessment Project (OCSEAP) analysis of the Gulf of Alaska. This activity has evolved into the present decade-long study of the Malaspina and Bering Glaciers. From the late 1980's through the transfer of the collection in 1996 to the University of Alaska, this GD activity funded the USGS's airborne Alaskan glacier photo monitoring flights. More recently, arrangements have been made to systematically acquire classified data [e.g., National Technical Means (NTM)] of eight selected glaciers that are situated from the Brooks Range, AK to Nevada. The Biological Resources Division of the USGS and another Interior agency, the National Park Service, monitor the fluctuations of glaciers in selected national parks of the United States, with respect to impact on the ecosystem of changes in the areal extent of glaciers.

Climate Change and Variations in the Earth's Cryosphere

The cryosphere, one of the four components of the geosphere (lithosphere, hydrosphere, atmosphere, and cryosphere), is particularly sensitive to changes in regional and global climate. Glaciers, one of the four elements of the cryosphere [glaciers, floating ice, (sea, lake and river), snow, and permafrost (permanently frozen ground)] are excellent indicators of regional (and global) climate changes, because fluctuations in volume and area are linked to changes in winter and/or summer temperatures and/or in precipitation (amount and whether frozen or liquid). Glaciers are distributed on all continents, except Australia, at high elevations and/or high latitudes. Although 99 percent of the volume and 97 percent of the area of glacier ice on Earth is in the Greenland and Antarctic ice sheets, 1 percent of the volume and 3 percent of the area of glacier ice are represented by ice caps, ice fields, valley glaciers, etc., outside of Greenland and Antarctica, and it is these smaller glaciers that are especially sensitive to climate change and have been markedly reduced in volume and area since the end of the "Little Ice Age" during the latter part of the 19^{th} century. [Whether the Antarctic and Greenland ice sheets are increasing or decreasing in volume and area or are in equilibrium is not yet known.]

*Swithinbank, C.W.M., Williams, R.S., Jr., Ferrigno, J.G., Lucchitta, B.K., Seekins, B.A., and Rosanova, C.E., 1997, Coastal-change and glaciological map of the Bakutis Coast, Antarctica: 1972–1990. U.S. Geological Survey Miscellaneous Investigations Series Map, I-2600-F; scale: 1:1,000,000, with accompanying booklet, 12 p.

Reviews and Assessment of USGS Glaciology Programs

During the past 15 years, there have been repeated attempts by USGS glaciologists, scientific program managers, and non-USGS scientists to define the role of the USGS in a national glaciological research program and to determine how the USGS program can be effectively linked to other national and international scientific programs in glaciology. These periodic assessments, of which this Workshop is the latest, have been motivated by changes in program resources (e.g., changes in funding and/or staff) or in program rationale. Initially, the study of glaciers was driven by mostly scientific considerations, to gain new knowledge about glacier dynamics and how glaciers respond to variations in regional climate, especially the retreat of mountain glaciers in the Pacific Northwest and tidewater glaciers in Alaska during the past century. More practical concerns, such as glacier hazards (e.g., lacustrine and volcanic jökulhlaups, volcanic lahars, calving glaciers, surging glaciers, etc.) and glacier hydrology (e.g., contribution of glacier meltwater to the volume of surface and groundwater discharge from a glacierized hydrologic basin), of concern to reservoir mangers for irrigation and hydroelectric power generation, also played a role.

In October 1982, Lawrence R. Mayo, a glaciologist with WRD's Cold Regions Hydrology Project Office in Fairbanks, AK, wrote "A Plan for Snow and Ice Research in the Water Resources Division, USGS," and sent it to all USGS glaciologists for review and comment. The 41-page document was a comprehensive assessment recommending glaciological studies by four project offices in WRD [e.g., Precipitation-Runoff Modeling led by George H. Leavesley (Denver, CO); Glaciology, led by Mark F. Meier (Tacoma, WA); Sea-Ice Dynamics led by William J. Campbell (Tacoma, WA); and Cold Regions Hydrology, led by Lawrence R. Mayo (Fairbanks, AK)]; he also envisioned the establishment of a fifth office for technology transfer. Mayo also referred to a previous WRD research plan on glaciology prepared in 1973.

In October 1988, Richard S. Williams, Jr., a research geologist and coordinator for Global-Change Activities with the Geologic Division, recommended the establishment of a "Branch of Glaciology and Glacial Geology" in the Office of Regional Geology to Benjamin A. Morgan, Chief Geologist. Appended to the memorandum was a two-page review of "Glaciological Research in the USGS," and a four-page review of the USGS and global glaciology.

In December 1989, Raymond D. Watts, a geophysicist with the National Mapping Division (formerly, detailed by the USGS as Executive Director of the U.S. Global Change Research Program and later Acting Assistant Director for Research, USGS), prepared a draft (10-p.) of "Recommendations for a Glacier Research Program for the U.S. Geological Survey," and circulated it to 24 USGS scientists and managers for review and comment with a 3-p. cover memorandum. In the cover memorandum, Watts argued for a coordinated USGS glaciology effort and referred to a tri-divisional (GD, NMD, WRD) initiative for cold-regions research encouraged by Robert M. Hirsch, Chief Hydrologist (formerly, Hydrologist for Research and

External Coordination; Chief Scientist for WRD's contribution to the U.S. Global Change Research Program).

In 1989, Bruce F. Molnia, a glacial geologist with the Geologic Division, prepared a two-page pre-proposal "Inventory of North American Glaciers," to GD's Climate Change Program. Primarily directed at preparing a baseline for 30 selected glaciers from the Brooks Range to small glaciers in California and Colorado, Molnia relied heavily on the use of remote-sensing technology to carry out the work. His unsuccessful 1989 pre-proposal, Molnia's 1990 paper* arguing for a systematic monitoring of North American glaciers, and his 1993 ** paper on glacier monitoring for global change, however, provided early discussions of the importance of regional monitoring of glaciers with remote sensing technology.

In February 1991, the National Park Service , the U.S. Geological Survey, and the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory jointly sponsored a workshop on Glaciers and Monitoring held in Anchorage, Alaska. The goal was to promote cooperation and coordination between state, federal and other agencies in glacier research, especially for the understanding of global climate change.

In May 1994, several WRD glaciologists and glaciologists from other Federal agencies and academic institutions participated in a two-day "Glacier-Climate Relationships Workshop" at the University of Washington (Seattle, WA). This Workshop was a precursor to the 1996 Workshop and included some of the same participants.

In March 1996, John J. Conomos, Regional Hydrologist, Western Region (WRD), asked Thomas C. Winter, a WRD glaciologist, to lead a team of four USGS and two non-USGS scientists in a review of WRD's snow and ice projects. The 8-p report, "Hydrological Issues Related to Snow and Ice and the Need for Research and Basic Data on Snow and Ice in the Water Resources Division, USGS," was submitted by Winter to Conomos in April 1997.

Early in 1997, Robert A. Bindschadler, a glaciologist with NASA's Goddard Space Flight Center, sent a letter to Robert M. Hirsch, Chief Hydrologist (WRD), on the "Importance of Revitalization of the USGS Glaciology Program." An edited version of that letter is included as Appendix 6 of this Workshop report.

*Molnia, B.F., 1990, One glacier's retreat, a global warming does not make—An argument for systematic monitoring of North American glaciers [abs]: *in* Proc., International Conference on the Role of Polar Regions in Global Change, p. 25.

**Molnia, B.F., 1993, Glacier monitoring for global change; three case studies [abs.] *in* Kelmelis, J.A., and Snow, K.M., eds., Proc. of the U.S. Geological Survey Global Change Research Forum, Herndon, VA, March 18-20, 1991: U.S. Geological Survey Circular 1086, p. 99–100.

Two other reports related to glacier studies by the USGS and germane to the support of glacier monitoring by the USGS, and to the Workshop, were published by WRD in 1996, "Bibliography of Glacier Studies by the U.S. Geological Survey," USGS Open-File Report 95-723, by Elizabeth F. Snyder; and in 1997, "A Strategy for Monitoring Glaciers," USGS Circular 1132, by Andrew G. Fountain, Robert M. Krimmel and Dennis C. Trabant.

In late 1997, the Geologic Division's Strategic Science Team prepared a draft report, Geology for a Changing World, that addressed the importance of long-term monitoring of glaciers by the USGS under Science Goal 3, Anticipate the Environmental Hazards Posed by Climate Variability. In addition to noting the economic consequences of sea-level rise under climate warming, Number 2 of the 5 Strategic Actions recommended under Science Goal 3 is "2) In collaboration with other U.S. agencies and foreign institutions, initiate and expand long-term, baseline monitoring of key climate-change indicators such as glaciers, permafrost, and dune sand - (http://geology.usgs.gov/usgs/acgs/sst/draft.html)." Geology for a Changing World will be published in April 1998.

As noted, the Workshop on Long-Term Monitoring of Glaciers of North America and Northwestern Europe represents the latest in the attempt to define the scientific rationale for glacier research by the USGS that will be supported by USGS managers and funded by the U.S. Congress. It does so by making global environmental change the "raison d'être" and by involving other nations and institutions, especially USGS counterpart governmental institutions in North America and Northwestern Europe in an integrated bureau program dependent heavily on analysis of remotely-sensed data and close cooperation and collaboration with U.S. and foreign glaciologists and counterpart institutions.

Since the late 1980's, the increase in international scientific research on global environmental change and the development of the multiagency U.S. Global Change Research Program, the linkage between climate change, glacier fluctuation, and changes in eustatic sea level, has attracted growing attention. The Glacier Studies Project of the Geologic Division's Global Change and Climate History Program (Woods Hole, MA and Reston, VA), the Biological Research Division's glacier monitoring program in Glacier National Park (MT), some aspects of the National Mapping Division's glacier-mapping activities in Antarctica and the U.S. (Reston, VA), and part of the Water Resources Division Alaska District Glacier and Snow Program (Tacoma, WA; and Fairbanks, AK) are directed at addressing glacier-related global environmental change questions. It is clear that glacier studies by the USGS, in the context of the U.S. Global Change Research Program, must involve all four science divisions and should be treated as an integrated bureau-level research effort, with each division providing unique strengths through their individual programs and projects, with strong intra-divisional, inter-divisional, inter-agency, and other U.S. and international governmental and institutional collaboration, including exchange of data and information.

Objectives and Rationale for the Workshop

Richard Z. Poore, Program Coordinator for the Global Change and Climate History Program, through which the Glacier Studies Project is funded, suggested that a workshop be convened to address the feasibility of using satellite remote-sensing technology, complemented by existing ground-based observation networks and aerial monitoring, to monitor fluctuations (areal and volumetric) of glaciers of North America. He concluded that the baseline of the areal extent of glaciers established by the Satellite Image Atlas of Glaciers of the World (based on Landsat images from the mid-1970's) provided good control for regional studies, and that monitoring changes in the glaciers of North America in a long-term, systematic manner, would be the logical next step.

The two Workshop Coordinators, Richard S. Williams, Jr., and Jane G. Ferrigno, who are also the editors of the USGS Satellite Image Atlas of Glaciers of the World book series, agreed with Richard Z. Poore's suggestion, and began, during the early summer of 1996, the planning to convene such a workshop. We broadened the planned geographic area of the glaciers to be monitored from North America to include Northwestern Europe. This was done to include all of the major glacierized areas of the Northern Hemisphere, especially those influenced by the maritime climates of the North Pacific Ocean and the North Atlantic Ocean.

The Glaciers of Europe (1386-E; 1993) and Greenland (1386-C; 1995) volumes of the Satellite Image Atlas of Glaciers of the World had already been published. Editing for the Glaciers of North America (1386-J) has either been completed (Glaciers of México and Glaciers of the Western United States) or is in progress (Glaciers of Canada and Glaciers of Alaska) and writing for the Glaciers of Iceland (1386-D) is in progress. Therefore, a solid foundation of information, especially 1970's baseline data from satellite images, on the glaciers of North America and Northwestern Europe was already available and, most importantly, many of the authors of the Glacier Atlas volumes and other glaciologists knowledgeable about the geographic area agreed to participate in the Workshop.

Forty scientists, including several global-change research program managers, were invited to the Workshop. Thirty-two scientists attended the two-day workshop and one-day field trip to Mount Rainier on 11-13 September 1996. The Workshop was held at the University of Puget Sound, Tacoma, WA; local logistical and other support was provided by the Ice and Climate Project Office of the USGS's Water Resources Division. Several attendees participated in a post-Workshop field trip to selected glaciers of southeastern Alaska that was led by Bruce F. Molnia.

The primary motivation for the Workshop was the recognition that airborne and satellite remote sensing of areal and volumetric changes in glaciers had reached the stage where quantitative scientific information could be derived from such data that had previously only been available from direct field measurements. In addition, many long-term national glacier-observation networks that had been established after World War II were being reduced or eliminated because of budgetary cutbacks of scientific programs within institutions, resulting in the termination of long-term datasets that are especially valuable in determining whether observed changes in key environmental parameters caused by changes in regional or local climate, such as glaciers, are the result of natural variability (e.g., global warming during the past century following the end of the "Little Ice Age" in the mid-to-late-1800's), impact of human activity (e.g., increase in greenhouse gases in the atmosphere, especially carbon dioxide and methane), or both (fig. 1). Although not directly addressed in the Workshop, analysis of glacier-ice cores has proven that human activity is responsible for a 100 ppm increase in "normal" concentration of CO_2 in the atmosphere during an interglacial. Prior to industrialization, atmospheric concentration of CO_2 was 280 ppm, the same concentration attained during the previous interglacial about 130,000 years ago. During maximum cooling during a glacial, CO_2 concentration falls to 180 ppm. In less than 300 years, human activities have caused an increase in concentration of CO_2 in the Earth's atmosphere comparable to the late Pleistocene and preindustrial Holocene increase (+100 ppm) that required more than 20,000 years. Glacier ice, distributed on all the Earth's continents except Australia, contains records of the composition of past atmospheres, volcanic eruptions, dust content of the atmosphere, and other environmental "signals" that have high scientific value in assessing natural climate change for the past 200,000 years (ice cores from the Greenland and Antarctic ice sheets) and lesser periods of time for smaller glaciers (e.g., ice caps, ice fields, etc.).

It seemed a critical time to develop a new strategy using satellite remote sensing in conjunction with ground-based observations and compilation of data in a Geographic Information System (GIS) and to continue and possibly expand glacier monitoring by adding glaciers to the existing ground-based network of glaciers being studied and monitored by various institutions in North America and Northwestern Europe. Such a plan would maximize the scientific results while utilizing available funding in the most efficient and cost-effective way.

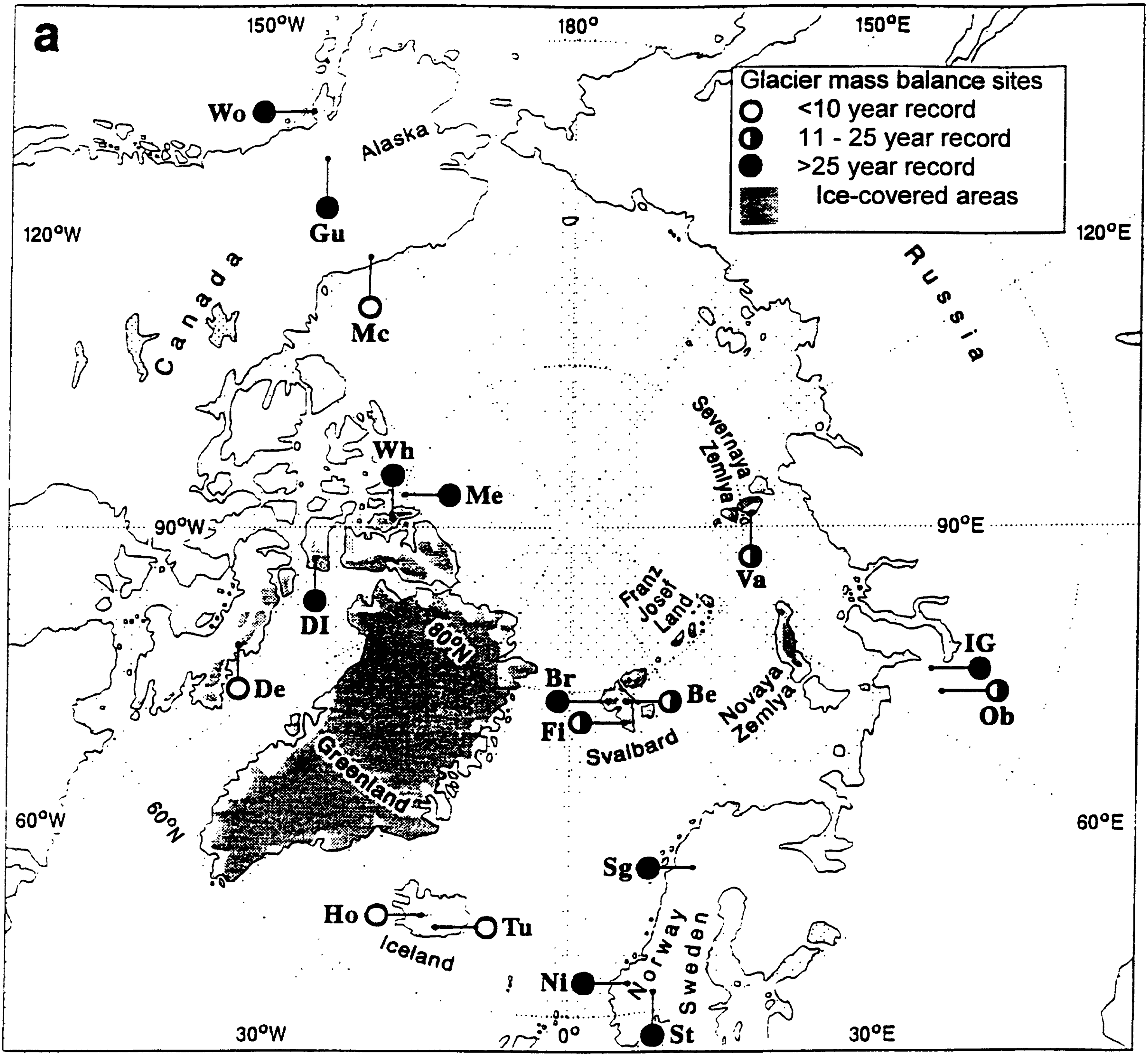

Figure 1.—Map showing the very small number of glacier mass-balance sites in current operation in North America and Northwestern Europe north of 60° N. lat. by length of record in years. Thousands of glaciers exist within the Arctic but only a few have been or are being studied and monitored scientifically. Map courtesy of Julian A. Dowdeswell, Centre of Glaciology, University of Wales.

Participating Institutions

Thirty-two scientists, from the 40 invited, participated in the two-day Workshop on Long-Term Monitoring of Glaciers of North America and Northwestern Europe, representing 17 institutions, seven U.S. and ten foreign. Glaciologists with special knowledge of the glaciers of North America (Alaska, Canada, Western U.S., and Greenland) and Northwestern Europe (Iceland, Jan Mayen, Svalbard, Norway, Sweden, and the Russian Arctic Islands) attended the Workshop (see the list of Attendees and other Invitees in Section V, Appendices. Names of participating institutions are as follows:

PARTICIPATING INSTITUTIONS

Environment Canada, National Hydrology Research Institute

Environmental Research Institute of Michigan

Geological Survey of Canada, Glaciology Section (Terrain Sciences Division)

Geological Survey of Denmark and Greenland (Denmark)
[Danmarks og Grønlands Geologiske Undersøgelse (GEUS)

International Glaciological Society (England, U.K.)

National Aeronautics and Space Administration, Goddard Space Flight Center

French Space Agency
[Centre National d'Études Spatiales (CNES)]

National Energy Authority (Iceland)
[Orkustofnun]

National Oceanic and Atmospheric Administration

Portland State University

Swiss Federal Institute of Technology
[Eidgenössische Technische Hochschule (ETH)]

U.S. Department of the Interior
- National Park Service
  - Denali National Park and Preserve (AK)
  - Glacier National Park (MT)
- USGS
  - Biological Resources Division
  - Geologic Division
  - National Mapping Division
  - Water Resources Division
  - Office of the Director

University of Alaska, Geophysical Institute

University of Colorado
- National Snow and Ice Data Center - World Data Center - A for Glaciology

University of Oslo (Norway), Department of Geography

University of Wales (U.K.)

University of Zürich-Irchel (Switzerland), Geographical Institute
- [Universität Zürich-Irchel, Geographisches Institut]

Structure of the Workshop

The two-day Workshop was organized around a series of presentations to bring all participants up to the same level of information. The presentations were followed by related and expanded discussions about the best way to cooperate in the use of currently available and existing and future planned technologies to carry out long-term ground, airborne, and satellite monitoring of fluctuations in glaciers of North America and Northwestern Europe. We also discussed existing glacier datasets (ground observations, airborne images and satellite images) archived in various data centers in different nations and in the major international archives such as the IAHS (ICSI)/UNEP/ UNESCO World Glacier Monitoring Service (Zürich, Switzerland), NOAA's National Snow and Ice Data Center/World Data Center - A for Glaciology (Boulder, CO), and the USGS EROS Data Center (Sioux Falls, SD), etc.

Part I of the two-day Workshop included presentations by glaciologists from Alaska, Canada, Conterminous United States, Denmark (for Greenland), Iceland, Norway (and Sweden), and Wales, U.K. (Russian Arctic Islands) on "Existing Data Bases and Current Status of Monitoring Glaciers of North America and Northwestern Europe." Part II of the Workshop included presentations by glaciologists, other scientists, and engineers about "Current and Planned Remote Sensing Technology for Monitoring Glaciers." Part III of the Workshop was composed of presentations by glaciological-archive managers on "International Data Centers for Archiving Ground, Airborne and Satellite Data of Glaciers."

All of the attendees (and non-attendees) were asked to provide an expanded abstract about their experience and perspective on glacier monitoring and related topics prior to the Workshop, so that the abstracts could be distributed to attendees. Selected background reading, was provided to each attendee.

On the afternoon of the second day of the Workshop glaciologists responsible for specific geographic areas or topics revised the original abstracts into brief comprehensive reviews with respect to the information presented and discussions held during the three sessions of the first 1 ½ days. Copies of these comprehensive reviews are arranged in the following sections according to the Workshop organization:

I. Existing Data Bases and Current Status for Monitoring Glaciers of North America and Northwestern Europe
II. Current and Planned Remote Sensing Technology for Monitoring Glaciers
III. International Data Centers for Archiving Ground, Airborne, and Satellite Data of Glaciers
IV. Monitoring of Various Glaciers in North America and Northwestern Europe. Miscellaneous Contributions
V. Appendices

Part I provides a geographic perspective, past and present. Part II gives a remote-sensing perspective, present and future. Part III provides a perspective on the major international data centers devoted, entirely or in part, to archiving of glaciological data. Part IV includes miscellaneous studies of glaciers in North America using a combination of technologies. Part V provides background information about the Workshop, attendees, non-attendees, selected reading, and other important information.

Acknowledgments

Convening a Workshop on Long-Term Monitoring of Glaciers of North America and Northwestern Europe and tending to the logistical and other needs of 32 U.S. and foreign glaciologists required substantial support from several dedicated individuals. From the Glacier Studies Project (Woods Hole, MA), the Workshop Coordinators are especially grateful to the outstanding support provided by Janice G. Goodell before, during, and after the Workshop. At the Water Resources Division (Ice and Climate Project Office in Tacoma, WA), Edward G. Josberger arranged much of the local logistics, including the conference room at the University of Puget Sound and myriad other details. We want to thank Ed for all his efforts and those of Jo Eggers (Tacoma, WA) for an exceptionally smooth operation; everything went off without a hitch. Bob and Birdie Krimmel hospitably opened their beautiful home on Vashon Island to all Workshop attendees for a cookout and informal evening session.

We also want to acknowledge the planning and leading of the post-Workshop field trip to Mount Rainier by Carolyn L. Driedger (Cascade Volcano Observatory, Vancouver, WA) to observe the effect of jökulhlaups/lahars on the landscape of Mount Rainier and environs and the potential hazards to life and property associated with a dormant volcano surmounted by an ice cap and many outlet/valley glaciers. Her scientific knowledge of Mount Rainier and its glaciological and volcanological hazards and her enthusiasm made for a most informative and enjoyable field trip.

We greatly appreciate the efforts of Bruce F. Molnia (Reston, VA) in planning and leading a post-Workshop field trip to the Bering Glacier and other glaciers in southeastern Alaska. The Alaska field trip was an option paid for by individual attendees.

We also appreciate the assistance of Clifford M. Nelson, USGS Historian, for providing and confirming information about the work on glaciers by the first director of the USGS.

Last, but not least, we are grateful for the programmatic and financial support from Richard Z. Poore, Program Manager, Global Change and Climate History Program, to convene the Workshop in Tacoma, WA, and to cover travel costs of the non-local attendees and other logistical costs.

LONG-TERM MONITORING OF GLACIERS
OF NORTH AMERICA AND NORTHWESTERN EUROPE —

WORKSHOP SUMMARIES AND ABSTRACTS

I.
EXISTING DATA BASES AND CURRENT STATUS FOR MONITORING GLACIERS OF NORTH AMERICA AND NORTHWESTERN EUROPE

ALASKA

Data Base and Geographical Perspective for Monitoring Glaciers of Alaska

by
Dennis C. Trabant, USGS
with contributions from workshop participants
Carl S. Benson, University of Alaska
Keith Echelmeyer, University of Alaska
Phil Brease, National Park Service
James Roush, National Park Service

The Alaska-Yukon glaciers cover about 100,000 km^2 in Alaska and adjacent parts of Canada. This is equal to the ice covered area of the Queen Elizabeth Islands of Arctic Canada; either of which is the third largest ice mass on earth after Antarctica (13.6×10^6 km^2) and Greenland (1.7×10^6 km^2). The Alaska-Yukon glaciers differ from the other large glacier covered areas because of their high rates of mass flux, large amounts of temperate ice, and their location in areas of vigorous and expanding human activity. The glaciers of Alaska feed every major river in the state except the Colville and play an important role in the oceanography of the North Pacific Ocean and in the climate of North America. Glacier runoff constitutes a line-source of fresh water along the south gulf coast of Alaska that produces a fresh-water stream equal in discharge to the Mississippi River. When seeking the tie between climate and these glaciers it is important to understand that some glacier changes are driven by mechanisms that are only indirectly linked to climate, or are completely independent of climate; these include: the calving-glacier cycle, surging, and glacier-volcano interactions. Furthermore, the gradient of climates from Maritime to continental, to Arctic polar basin across Alaska is the strongest of any on earth. Glaciers exist in each climate region and should be studied as a continuum from maritime to Arctic-desert types.

The glacier data base for Alaska includes glacial geologic reconstructions of Late Cenozoic glacier extents; 18th century terminus positions recorded by La Perouse, Cook, Vancouver, and others; and detailed studies of glaciers near the close of the 19th century by Reid, Gilbert, Tarr, and Martin (see T.D. Hamilton, 1994, for summary and references). Compilations of statewide glacier data have been published by Capps (1932), Pewe and others (1953), Karlstrom and others (1964), Coulter and others (1965), Pewe (1975), and Mayo (1984) (see T.D. Hamilton, 1994 for full references), and in Snyder (1996). The database also includes a large archive of aerial photographs and satellite images located at the GeoData Center of the University of Alaska's Geophysical Institute at Fairbanks, Alaska (see attached table, p. 35).

Seventy three glaciers in Alaska have baseline mass balance or detailed topology data that are important ground truth for the analysis and interpretation of satellite data (see attached table, p. 31, which includes glaciers in Canada and the Western United States). An additional number of glaciers have long series of terminus change measurements or have begun observations that are intended to produce long-term series (note especially those in Denali National Park and Preserve). In return, the surface-based data collection programs expect to benefit from new understanding of the relation between the measurement sites and regional glacier activity and guidance and backing in targeting effective expansion of the surface-based data collection efforts. The listed baseline glaciers are not uniformly distributed geographically but do include representatives for each of the recognized climate regions of Alaska. These data are products of several programmatic efforts: 1) Eight large-scale glacier maps produced by the International Geophysical Year (IGY) program in Alaska during the late 1950's. Many of the IGY glacier studies included some mass balance measurements; 2) Three International Hydrologic Decade (IHD) glacier mass balance programs operated during the 1960's (see accompanying table); 3) The U.S. Geological Survey benchmark glaciers (Gulkana and Wolverine), which have been sustained since beginning as IHD sites, include mass balance, climatological, and ice kinematics data; 4) Mass balance and longitudinal profiling of selected glaciers in Denali National Park and Preserve (DNP&P), Alaska, begun during 1991; a long-term commitment to continued surface-based measurements will be augmented by remote sensing information. The objective of the DNP&P work is regional characterization of glacier mass balance; 5) Airborne laser altitude profiles of 65 glaciers begun during 1992 under National Science Foundation funding to Echelmeyer and Harrison (written communication, 1996); 6) The long-term studies by the Geologic division of the Bering, Malaspina, and Mendenhall Galciers; 7) The late Williams O. Field's work on North American glaciers, especially his research on glaciers in Glacier Bay National Monument, AK, that he began in the 1920's; and 8) The recently completed contribution to the Glaciers of North America volume of the Satellite Image Atlas of Glaciers of the World by Bruce F. Molnia (GD) and Robert M. Krimmel (WRD) (in press) on the Glaciers of Alaska.

An important subset of the listed glaciers are those with the longest records and where surface-based and remote sensing monitoring programs continue to operate. The Gulkana and Wolverine Glaciers, the U.S. Geological Survey benchmark glaciers in Alaska, have the longest continuous time series of mass balance, and climatological measurements in Alaska. These records begin in the mid-1960's and are augmented by ice kinematics measurements that began during the early 1970's and, for some years, basin runoff was measured. Gulkana and Wolverine Glaciers have also been profiled by Echelmeyer and Harrison and are designated National Technical Means (NTM) fiducial sites. The next longest mass-balance and ice kinematics records are from McCall, Lemon Creek, and Black Rapids Glaciers. All of these glaciers have been profiled by Echelmeyer and Harrison. Mass balance at McCall Glacier was begun during the IGY, reinitiated during the IHD, and recently (1993 to present) by NSF grant to the University of Alaska Fairbanks (contact workshop participant Echelmeyer). There are both ice kinematics and some runoff data from McCall projects. Hydrologic balance measurements on Lemon Creek Glacier began during 1953 by the Juneau Icefield Research Project and basin runoff has been measured by the U.S. Geological Survey since 1951. The hydrologic balance data for Lemon Creek Glacier is discontinuous. Black Rapids Glacier mass balance and ice kinematics measurements began as a U.S. Geological Survey program during 1973 and are continuing at present by NSF grant to the University of Alaska Fairbanks (W.D.

Harrison). Because NSF programs can not be perpetually extended, the surface-based observations sets at McCall and Black Rapids Glaciers will be discontinued unless alternate programs are identified. The most geographically comprehensive recent data are the unpublished surface altitude profiles of Keith Echelmeyer (workshop participant) and W.D. Harrison (University of Alaska Fairbanks, written communication).

Recognized glacier monitoring deficiencies in Alaska include: 1) Need to quantify mass balances on the large glaciers along the Gulf of Alaska where the mass fluxes are among the highest on Earth and where the largest glaciers exist; 2) extrapolate glacier-climate relations from the long-term measurement sites to typify regions; 3) thereby, define regions in which glacier activity may be represented by the activity measured at a single glacier; 4) thereby also identify under-sampled glacier systems; and 5) improve understanding of the details of the linkage between climate and glacier response.

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No.	Glacier Names by Region	IGY	IHD	Mass Balance	Runoff	E&H Altitude Profiles	Terminus Change	Global Fiducial sites	North Latitude	min	West Long de	min
Western American Glaciers with Baseline Mass Balance or Detailed Topology												
Explanation:												
	"No." location plotted on attached map											
	* = unofficial name											
	^ = not plotted on attached map											
	IGY = International Geophysical Year, 1958-59											
	IHD = International Hydrologic Decade, 1965-74											
	"d" following mass balance beginning year denotes discontinuous record											
	"s" following mass balance year denotes simulated record reconstruction											
	E&H Altitude Profiles = Echelmeyer and Harrison GPS/laser altimeter glacier longitudinal profiles											
	yy.ddd = year and Julian day of first measurement											
	"LP" = longitudinal surface altitude profile											
	"TP" = transverse surface altitude profile											
	"DEM" = digital elevation models for recent years											
	Global fiducial sites = primary data collection sites for classified systems											
	Data to be released through the National Technical Means program											
	Alaska					yy.ddd						
1	Aialik					+			59	57	149	44
2	Arey					+			69	19	143	49
3	Baird					96.165			57	15	132	15
4	Bear					+			59	55	149	31
5	Bear Lake	+				94.148			60	11	149	18
6	Bering					95.161			60	10	143	50
7	Black Rapids			1973		92.134			63	30	145	53
A	Brady						+		58	21	136	37
8	Brady Icefield					95.155			58	40	136	47
9	Bravo					+			69	16	143	51
10	Burroughs			+					58	57	136	12
11	Cantwell					96.127			63	25	149	22
12	Chamberlin				+				69	17	144	54
13	Chernof					+			59	50	150	21
14	Chikuminuk	+				96.131			60	7	159	17
B	Cul de Sac						1996 & LP		62	25	152	45
15	Columbia			1974d		94.151			60	10	147	5
C	North Crillon						+		58	39	137	28
D	South Crillon						+		58	36	137	23
16	Demorest					93.241			58	36	134	8
17	Dinglestad					+			59	42	150	25
18	Double					96.136			60	42	152	38
19	East Fork					95.139			63	19	147	17
20	Esetuk					+			69	18	144	20
21	Exit					94.148			60	10	149	40
22	Flute				+				61	8	149	20
23	Gillam					96.116			63	40	147	17
E	Glacier Bay						1794-1986		58	22	136	0
24	Gooseneck					+			69	20	143	48
25	Grand Pacific					96.158			50	4	137	3
26	Gulkana		+	1965	d	92.204	LP & TP	+	63	16	145	25
F	Guyot						1900-1996		60	4	141	22
27	Hanging@McCall					+			69	18	143	50
28	Harding Icefield					94.149			60	0	150	0
29	Hidden					96.156			59	45	138	35
30	Holgate					96.139			59	51	149	52
31	Hubley North					+			69	17	143	44
32	Hubley South					+			69	17	143	44
33	Kachemak					+			59	43	150	38

34	Kahiltna			1991		94.212			62	29	151	15
35	Knik			see Mayo	and Trabant, 1982 via Mayo, 1984				61	24	148	34
36	Konamoxt					96.158			59	23	137	38
G	Hopkins						+					
37	LeConte					96.166			56	49	132	22
38	Lemon Creek	+		1953d	1951	93.246		+	58	21	134	21
39	Little Dinglestad					+			59	42	150	25
40	Little Jarvis	+				95.151			59	25	136	25
41	Malaspina					95.156			59	42	140	37
42	Matanuska								61	45	147	35
43	McCall	+	+	1958d	d	93.208		+	69	21	143	51
44	McCarthy					+			61	36	142	49
45	Mendenhall				+	95.154			58	25	134	33
46	Mt. Wrangell		see Benson & Motyka, 1978 via Mayo, 1984						62	0	144	0
H	Muir						+		59	0	136	0
47	Muldrow					94.215	+		63	24	150	33
48	Northwestern					+			59	47	150	3
49	Novatak					96.156			59	33	138	40
50	Nunatak					96.156			59	51	139	16
51	Okpilak East					93.223			69	9	144	12
52	Okpilak west					93.222			69	9	144	12
53	Polychrome	+				95.179			63	27	149	50
54	Portage		see Mayo, Zenone, & Trabant, 1977 via Mayo, 1984						60	46	148	48
55	Salmon					96.169			56	10	130	8
56	Shamrock					96.136			61	11	152	49
57	Sherman		see Bull & Marangunic, 1968 via Mayo, 1984						60	33	145	13
58	Skilak					+			60	19	150	2
59	Southwestern					+			59	48	149	55
60	Susitna					95.139			63	26	147	12
61	Taku					93.241			58	25	134	3
62	Tanaina					96.136			61	8	149	31
I	Tatina						1996 & LP		62	18	153	23
63	Tazlina					94.123			61	44	146	25
64	Toklat, east fork*			+		96.127	+		63	31	150	2
J	Toklat, middle fork *						1996		63	22	150	5
K	Toklat, west fork *						1996		63	22	150	9
L	Traleika			1994					63	13	150	42
65	Turquoise					96.136			60	47	152	57
66	Tustumena					+			60	3	150	34
67	Tuxedni					96.135			60	15	153	2
68	Variegated			1973d		95.156			60	0	139	22
69	West Gulkana	+				93.163			63	15	145	29
70	Wolverine		+	1966	d	94.147	LP & TP	+	60	22	148	30
71	Wolverine Crag					*			69	20	143	48
72	Worthington	+				94.151			61	10	145	42
73	Yakutat					96.156			59	28	138	54
******												
	Yukon, Canada											
M	Hazard					see Young, 1990			61	16	140	22
76	Kaskawulsh					95.141			60	46	138	35
N	Rusty			1968d					61	12	140	18
O	Steele					see Young, 1990			61	15	140	11
P	Trapridge					see Young, 1990			61	14	140	20
	B.C. coast mtns.											
Q	Alexander			1979d					57	6	130	49
R	Andrei			1978d					56	56	130	56
74	Berendon		+	1967d		96.169			56	15	130	10
S	Bridge			1976d					50	49	123	33
T	Cathedral			1971d					59	20	134	6
U	Forrest Kerr			1978d			1945d		56	54	130	6

75	Frank Mackie					96.169			56	20	130	10
V	Helm			1975			1945d		49	58	123	0
77	Melbern					96.158			59	15	137	38
79	Place		+	1965					50	30	122	40
W	Salmon	+				see Young, 1990			56	9	130	4
81	Sentinel		+	1965d			1945d		49	55	123	10
X	Sphinx			1976d			1945d		49	55	122	58
Y	Sykora			1976d					50	53	123	34
Z	Wedgemount						1947d		50	9	122	48
AA	Yuri			1978d					56	58	130	42
AB	Zavisha			1976d					50	48	123	25
	CA interior mtns.											
AC	Athabasca	+					1945d		51	12	117	15
AD	Drummond						1952d		51	36	116	2
78	Peyto		+				1942d	+	51	40	116	15
80	Ram River		+	1965d					51	50	116	20
AE	Saskatchewan						1945d		52	13	117	8
82	Triumph					96.165			57	30	132	14
83	Woolsey		+	1965d					51	10	118	5
	Canadian Arctic											
AF	Agassiz ^			1966d					80	25	70	0
AG	Baby ^		+	1959d					79	26	90	58
AH	Barns Ice Cap ^			1963d					70	10	73	30
AI	Boas ^			1970d					67	34	65	16
AJ	Decade ^			1965d					69	38	69	50
AK	Devon Ice Cap ^			1961					75	20	82	30
AL	East Ice Cap ^			1963d					75	39	114	28
AM	Gilman ^			1958d					82	6	70	37
AN	Laika ^			1974d					75	53	79	9
AO	Leopold ^			1963d					75	49	114	45
AP	Meighen Ice Cap ^			1959					79	57	99	8
AQ	Per Ardua ^			1964d					81	31	76	27
AR	South Ice Cap ^			1963d					75	25	115	1
AS	Thompson ^						1959d		79	28	90	30
AT	Unnamed ^			1966d					81	57	64	12
AU	Ward Hunt Ice Rise ^			1958d					83	7	74	10
AV	Ward Hunt Ice Shelf ^			1960d					83	7	73	30
AW	West Ice Cap ^			1963d					75	38	114	45
AX	White ^			1959					79	27	90	40
	California											
84	Maclure		+					+	37	45	119	17
	Colorado											
85	Andrews			+	see Outcalt, 1965 via Mayo, 1984				40	3	105	45
86	Arapaho			+	see Waldrop, 1964 via Mayo, 1984				40	3	105	45
87	Arikaree			+	see Muller, 1977 via Mayo, 1984				40	3	105	45
88	Fair			+	see Muller, 1977 via Mayo, 1984				40	3	105	45
89	Hendersen			+	see Muller, 1977 via Mayo, 1984				40	3	105	45
90	Isabelle			+	see Muller, 1977 via Mayo, 1984				40	3	105	45
91	Navahoe			+	see Muller, 1977 via Mayo, 1984				40	3	105	45
92	St. Vrain			+	see Muller, 1977 via Mayo, 1984				40	3	105	45
93	Front Range			+	see Johnson, 1979 via Mayo, 1984				40	3	105	45
	Montana											
94	Grasshopper			+	see Alford & Clark, 1968 via Mayo, 1984				45	7	109	40
95	Grinnell			+	see Johnson, 1980 via Mayo, 1984				48	15	114	0
96	Sperry			+	see Johnson, 1980 via Mayo, 1984				48	15	113	50
	Nevada											
N1	Wheeler			+					38	59	114	19

	Oregon											
O1	Eliot						+		45	20	121	35
	Washington											
97	Blue	+				96.172		+	47	49	123	42
98	Coleman			+					48	40	121	40
99	Columbia			1984					47	27	121	22
100	Daniels			1984					47	22	121	10
101	Foss			1984					47	22	121	14
102	Hoe					96.172			47	49	123	30
103	Ice Worm			1984					47	21	121	11
104	Lower Curtis			1984					48	46	121	38
105	Lynch			1984					47	23	121	11
106	Mt. Baker			+					48	40	121	40
107	Mt. St. Helens			+					46	12	121	10
108	Mt. Rainier			+					46	52	121	45
109	Nisqually			+			1931 & TP		46	40	121	44
110	Noisy					96.177			48	40	121	26
111	North Klawatti					96.177			48	32	121	2
112	Vesper			1974-75					45	0	121	30
113	Rainbow			1984					48	45	121	45
114	South Cascade		+	1957	+	96.177	DEM	+	48	22	121	3
115	Spider			1984					48	10	120	50
116	Thunder Creek			1884-1974s								
117	White					96.172			47	50	123	33
118	Yawning			1984					48	23	121	2
	Wyoming											
119	Dinwoody							+	43	10	109	38

Aerial Photography and Satellite Images held by
Geophysical Institute - GeoData Center
University of Alaska Fairbanks
http://www.asf.alaska.edu/daac_documents/avail_data.html#gdc

1938-1986 - Fairbanks Area Aerial Photography, miscellaneous photography.

1942-1950 - NARL Aerial Collection, black and white prints (no negs.). In process of being catalogued. Includes tri-camera photography. Mostly of North Slope, but some photos of Interior.

1948 - Wrangell Collection - Part 1: 1972-1974, 1981 Landsat - 157 images; Part II: 1948-1991 - Aerial photography - 2,057 prints and negatives.

1960-1996 - Approximately 60,000 aerial photographic negatives of glaciers of western North America; photographs from the U.S. Geological Survey's Ice and Climate Project collection acquired by Austin Post, Lawrence C. Mayo, and Robert M. Krimmel, other government agencies, and private contractors. All are large format, vertical and oblique aerial photographs, at various scales.

Miscellaneous Aerial Photography Collections:
- 1964 - 634 prints of Beluga Lake, Cordova and Turnagain Arm
- 1974, 1976, 1977 - 2,920 frames from several projects, including Susitna River Basin Cooperative Project, and Kenai Peninsula Project.

1968 - Amchitka/Rat Islands Aerial Photography - 930 black and white prints.

1972 - Kaltag/Point Hope Aerial Photography, 494 CIR transparencies.

1972 - NP-3 Photography - 2375 frames of natural color and CIR transparencies.

1972-84 - Low Altitude Village Aerial Photography - Transferred from Rasmuson Library, 1,600 black and white prints, with a few color prints.

1972-1990 - Landsat Imagery (CCT's and hard copy), (MSS) - 14,000 images.

1973-74 - Trading Bay Aerial Photography - 844 positive transparencies.

1974-1990 - NOAA /Advanced Very High Resolution Radiometer) - HRPT - (CCT's and hard copy).

1975, 1976 and 1984 - Airborne SAR flown in support of AIDJEX I, II and III, BESMEX, Microwave-76 and Winter-84 projects. Black and white strips (no negs.).

1976-1977 - National Ocean Service Aerial Photography- 1897 CIR and natural color transparencies.

1977 - APA Aerial Photography - 74 frames - CIR transparencies.

1977 - Denali Highway Project Aerial Photography - 60 CIR transparencies.

July, 1978 - March, 1992 - DMSP (positive black and white film).

1978 - Gas Line Aerial Photography - 121 CIR transparencies.

1978-1986 - Alaska High Altitude Aerial Photography Program (AHAP) - CIR transparencies and B&W negatives. Roughly 150,000 frames.

1982-85, 1987, and 1989 - AeroMap U.S. Browse Photography - more than 3,000 prints of local areas.

The Canadian Glacier Variations Monitoring and Assessment Network Status and Future Perspectives

by
Michael N. Demuth
National Hydrology Research Institute, Environment Canada

Introduction

Studies of glacier fluctuations (annual and seasonal mass balance, volume change and glacier margin variations) are a well recognized foundation for understanding changes in the energy and water fluxes at the surface of the earth (e.g., Haeberli 1994, Haeberli 1995). In general, mass balance fluctuations represent a direct response to climate forcing and shifting equilibrium line (limit of permanent glaciation) while the advance or retreat of the glacier margins represents a delayed/cumulative response. As such, glacier fluctuation records can provide both short and long-term perspectives on the nature of climate fluctuations and related influences on water resources (Appendix A).

Glaciers and other forms of perennial ice represent a significant portion of the world's freshwater resources (e.g., Meier and Roots 1982). Notably, the general past-century pattern of strong deglaciation has implications for global sea-level rise (Meier 1984, Dowdeswell 1995). Moreover, deglaciation and headwater extension will modulate the regulatory role of glaciers. Human activities in semi-arid lands contiguous to regions where glaciers are extensively found, rely heavily on the seasonality of glacier contributions to streamflow (e.g., reservoirs for water supply and electrical production needs) (Young 1985, Demuth 1996a); as do the fast-response biota which reproduce in low-order, base-flow dependent habitats (Ward 1994, Milner and Petts 1994).

Observations, Assessments and Reporting

The Canadian Glacier Variations Monitoring and Assessment Network (CGVMAN) resides at the National Hydrology Research Institute (NHRI), an Environment Canada research laboratory. CGVMAN is a new effort which hopes to revitalize glacier-related environmental monitoring and assessment in Canada. Currently, CGVMAN is a joint government-university effort centered around studies at four principle mass-balance network sites (remnants of the IHD network). The sites include: i) White Glacier (Axel Heiberg Island in the eastern high Arctic; see abstract by Koerner); ii) Peyto Glacier (Canadian Rockies-Eastern Slopes); iii) Place Glacier and Helm Glacier (Southern Coast Mountains of British Columbia) (Figure 1).

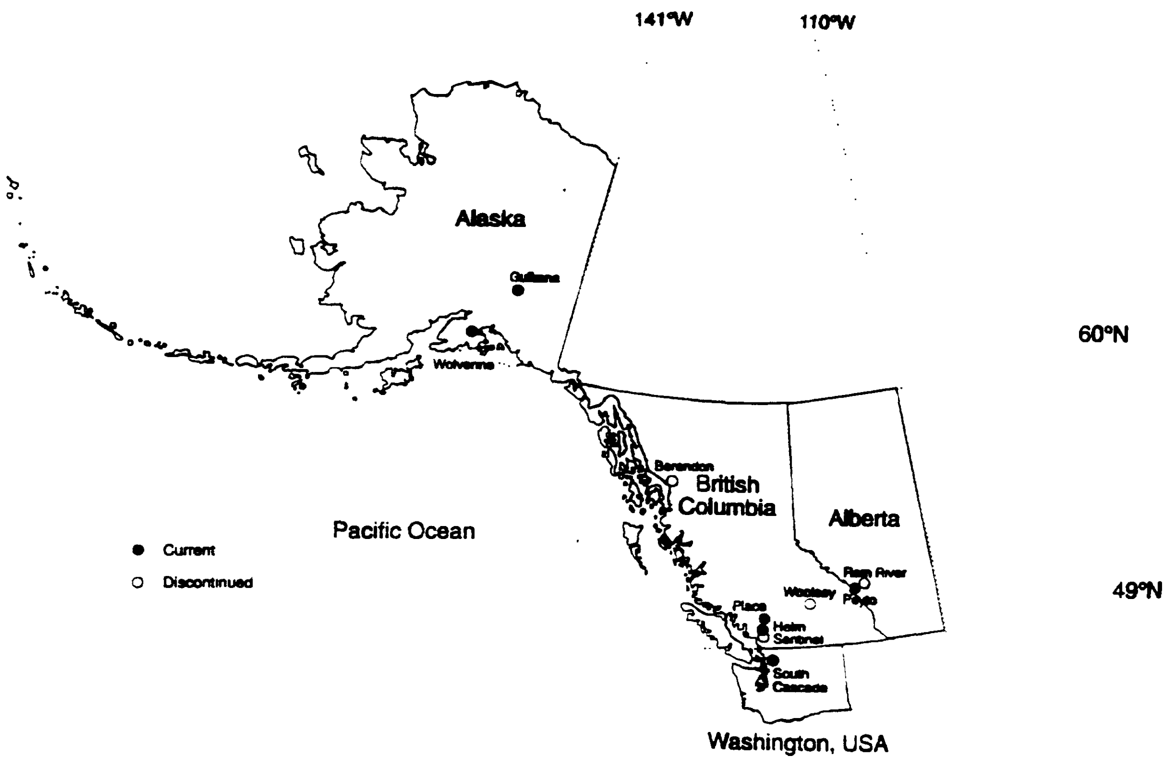

Figure 1 Benchmark glacier mass balance monitoring and assessment sites for western Canada, Alaska and the coterminous USA.

Operated by NHRI (Principle Investigator (PI) Demuth, except for Axel Heiberg area where PI Cogley and Adams), the current "benchmark" sites also provide infrastructure and support for university researchers and the opportunity for students to perform work towards their thesis project. In return, university staff assist NHRI in making routine mass balance observations. Current co-operation has been realized at Peyto Glacier between NHRI and Wilfrid Laurier University (PI Young) and the University of Toronto (PI Munro). Similarly, NHRI-CGVMAN and the NRCan - Polar Continental Shelf Project provides logistical support to Trent University for the White/Baby Glacier work. Similar partners are to be developed for operations at Place and Helm Glaciers. The applied methodology at these sites follows that of Õstrem and Brugman (1991) with the network safe-guarded by ablation tapes installed using a hot-water drilling apparatus. Data reduction is largely automated using an image analysis framework and pc-based water-equivalent mapping routines. The methodology is augmented by remote sensing (ERS-1 and RADARSAT SAR acquisition) at the close of summer-balance season.

While now a small fraction of a once more extensive network (e.g., Table 1a,b), CGVMAN represents a basic cross-section of mass balance gradient, equilibrium line altitude, mean annual air temperature and humidity as manifested by latitude and continentality (e.g., Figure 2). The discontinuation of an inner montane site (Woosley) and a humid central coastal site (Berendon) in the mid-70's, however, has been a significant setback. In 1995, work at Sentinel Glacier was minimized (terminus position only). Other work by Natural Resources Canada (NRCan) - Geological Survey of Canada, continues in the eastern Arctic (see abstract by Koerner). Notably, mass balance and mass balance-elevation band reporting had involved up to 22 glaciers nation-wide as recently as 1985 (e.g., Ommanney 1988). Reporting of data and assessments for the CGVMAN "benchmark" glaciers continues in the WGMS Glacier Mass Balance Bulletin (GMBB) through the WGMS Canadian Correspondent (White and Peyto will be new additions to GMBB#4).

Glacier variation observations (terminus position) and reporting had involved up to seventeen sites as recently as 1985 (e.g., Ommanney 1988). An unknown number of measurements continue (e.g., Ricker (personal communication 1996), has indicated that his efforts at Wedgemount Glacier are likely to come to a temporary hiatus). Some recent work by Brugman (personal communication 1994) has re-established quasi-regular measurements on Athabasca, Saskatchewan and Illecillewaet. Reporting these efforts and their resulting data through the WGMS Canadian Correspondent, however, has slowed considerably because of resource restrictions. With the departure of C.S.L. Ommanney, the entire WGMS reporting load has fallen on the shoulders of one individual (the current WGMS Canadian Correspondent). In the recent past, mass balance reporting to the GMBB was conducted by the principle investigator, while Ommanney would have provided the quadrennial reporting on variations, volume changes, hydro-meteorological observations and special events. The current WGMS Canadian Correspondent is investigating the possibility of again sharing the data reporting duties.

The need to co-operate, build partnerships and make wise use of diminishing research dollars, is illustrated by the observation that, for the numerous projects headed by Canadian glacier researchers, little consideration is given to operating process-based studies, for example, out of basins for which there are established facilities, geodetic benchmarks, baseline data, climate stations, accommodation, etcetera. Herein lies the basis for CGVMAN as described earlier; for re-establishing a critical mass and, moreover, for realizing network re-vitalization.

Appendix B provides a summary of recent CGVMAN activities and related contributions.

Table 1a Cordilleran glaciers in Canada having significant hydrological records (1940-1960's) (updated and modified from Young 1990).**

REGION/Glacier Name	*1940's*	*1950's*	*1960's*
YUKON			
Hazard 61°15.7'N 140°21.9'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Steele 61°14.6'N 140°10.6'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - z z z z
Trapridge 61°13.6'N 140°20.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - z z
Rusty 61°12.4'N 140°17.9'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - z o o
Kaskawulsh 60°45.0'N 139°06.0'W	- - - - - - - - - -	- - - - - - - - - -	- z z z z z z z z z
COAST MOUNTAINS B.C.			
Nadahini 59°44.0'N 136°41.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - x - x - x -
Cathedral 59°20.3N 134°08.3'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Alexander 57°06.4'N 130°49.1'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Yuri 56°58.0'N 130°42.2'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Andrei 56°55.7'N 130°55.6'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Forest Kerr 56°54.1'N 130°05.6'W	- - - - - x x x x -	- - - - - - - - - -	- - - - - - - - - -
Berendon+ 56°14.8'N 130°05.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - z - o o o
Salmon 56°08.6'N 130°04.0'W	- - - - - - - - - -	- - - - - - z z - z	- - - - - z - z z z
Sykora 50°52.7'N 123°33.8'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Bridge 50°49.4'N 123°33.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Zavisha 50°48.4'N 123°25.3'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Place+ 50°25.3'N 122°36.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - o o o o o
Wedgemount 50°09.2'N 122°47.8'W	- - - - - - - x - x	- x - - - - - - - -	- - - - x - - - - x
Helm 49°57.8'N 123°00.0'W	- - - - - x x x x x	x - x - x - x - x -	x - - - - - - - - -
Sphinx 49°55.0'N 122°57.5'W	- - - - - x x x x x	x - x - x - x - x -	x - - - x - x - x -
Sentinel+ 49°53.6'N 122°58.9'W	- - - - - x x x x x	x - x - x - x - x -	x - - - x o * o * o
INTERIOR RANGES			
Illecillewaet 51°16.0'N 117°20.0'W	- - - - - x x x x x	x x x - - - x x x x	x x x x x x x x x x
Woolsey+ 51°07.5'N 118°02.5'W	- - - - - - - - - -	- - - - - - - - - -	- - - - o o o o o o
Bugaboo 50°40.0'N 116°45.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - x - x - x -
Kokanee 49°45.0'N 117°08.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - x - x - x -
ROCKY MOUNTAINS			
Saskatchewan 52°12.5'N 117°08.2'W	- - - - - x x x x x	x - x - x - x - x -	x - x x x x x x x x
Athabasca 52°11.7'N 117°15.0'W	- - - - - x x x x x	x - x - x - x - x m	m m m m x x x x x x
Ram River+ 51°51.0'N 116°11.5'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - o o o o o
Peyto+ 51°40.6'N 116°32.8'W	- - x - - x x x x x	x - x - x - x - x -	x - x - o * o o o o
Drummond 51°35.5'N 116°02.0'W	- - - - - - - - - -	- - x - - - - - - -	- - * * * * x x - -

+ IHD Glaciers

x = variations
o = mass balance
* = variations and mass balance
z = other studies
s = other, some mass balance
m = other, some variations

** Illecillewaet, Nadahini, Bugaboo and Kokanee added.

Table 1b Cordilleran glaciers in Canada having significant hydrological records (1970-1990's) (updated and modified from Young 1990).**

REGION/Glacier Name	*1970's*	*1980's*	*1990's*
YUKON			
Hazard 61°15.7'N 140°21.9'W	- - - - - z z - - z	- - - - - - - - - -	- - - - - -
Steele 61°14.6'N 140°10.6'W	- - z z z z z - - z	- z - - - - - - - -	- - - - - -
Trapridge 61°13.6'N 140°20.0'W	z z z z z - z - - -	z z z z z z z z z z	z z z z z z
Rusty 61°12.4'N 140°17.9'W	z z z z z z z - - -	- - - - - - - - - -	- - - - - -
Kaskawulsh 60°45.0'N 139°08.0'W	z - - z z - - - - -	- - - - - z z z z -	- - - - - -
COAST MOUNTAINS B.C.			
Nadahini 59°44.0'N 136°41.0'W	x - x - x - x - x -	- - - - - - - - - -	- - - - - -
Cathedral 59°20.3N 134°08.3'W	- o o o - c - - - -	- - - - - - - - - -	- - - - - -
Alexander 57°08.4'N 130°49.1'W	- - - - - - - - - o	o o o o o - - - - o	o o - - - -
Yuri 56°58.0'N 130°42.2'W	- - - - - - - - o o	o o o o o - - - - o	o o - - - -
Andrei 56°55.7'N 130°55.6'W	- - - - - - - - o o	o o o o o - - - - o	o o - - - -
Forest Kerr 56°54.1'N 130°05.6'W	- - - - - - - - o o	o o o - - - - - - -	- - - - - -
Berendon+ 56°14.8'N 130°05.0'W	o o o o o o - - - -	- - - - - - - - - -	- - - - - -
Salmon 56°08.6'N 130°04.0'W	z - - - - - - - - -	- - - - - - - - - -	- - - - - -
Sykora 50°52.7'N 123°33.8'W	- - - - - - o o o o	o o o - - - - - - -	- - - - - -
Bridge 50°49.4'N 123°33.0'W	- - - - - - o o o o	o o o - - - - - - -	- - - - s s
Zavisha 50°48.4'N 123°25.3'W	- - - - - - o o o o	o o o - - - - - - -	- - - - - -
Place+ 50°25.3'N 122°36.0'W	o o o o o o o o o o	o o o o o o o o o o	o o o o o o
Wedgemount 50°09.2'N 122°47.8'W	- - x x - x z x x x	x * * * * x x x x x	x x x x x x
Helm 49°57.8'N 123°00.0'W	- - - - - o o o o o	o o o o o o o o o o	o o o o o o
Sphinx 49°55.0'N 122°57.5'W	x - x - - - o o * o	o o o - - - - - - -	- - - - - -
Sentinel+ 49°53.6'N 122°58.9'W	* o * o o o o o o o	o o o o o o o o o o	o o o o o x
INTERIOR RANGES			
Illecillewaet 51°16.0'N 117°20.0'W	x - - - x x x x x x	x x x x x x x x x x	x x x m m m
Woolsey+ 51°07.5'N 118°02.5'W	o o o o o o - - - -	- - - - - - - - - -	- - - m m -
Bugaboo 50°40.0'N 116°45.0'W	x - x - x - x - x -	- - - - - - - - - -	- - - - - -
Kokanee 49°45.0'N 117°08.0'W	x - x - - - - - - -	- - - - - - - - - -	- - - - - -
ROCKY MOUNTAINS			
Saskatchewan 52°12.5'N 117°08.2'W	x x x x x x x x x x	- - - - - - - - - -	- - m m m m
Athabasca 52°11.7'N 117°15.0'W	x x x x x x x x x x	- - - - - - - - - -	- - m m m m
Ram River+ 51°51.0'N 116°11.5'W	o o o o o o - - - -	- - - - - - - - - -	- - - - - -
Peyto+ 51°40.6'N 116°32.8'W	o o o o o o o o o o	o o o o o o o o o o	o o o o o o
Drummond 51°35.5'N 116°02.0'W	- - - - - - - - - -	- - - - - - - - - -	- - - - - -

+ IHD Glaciers

x = variations
o = mass balance
* = variations and mass balance
z = other studies
s = other, some mass balance
m = other, some variations

** Illecillewaet, Nadahini, Bugaboo and Kokanee added.

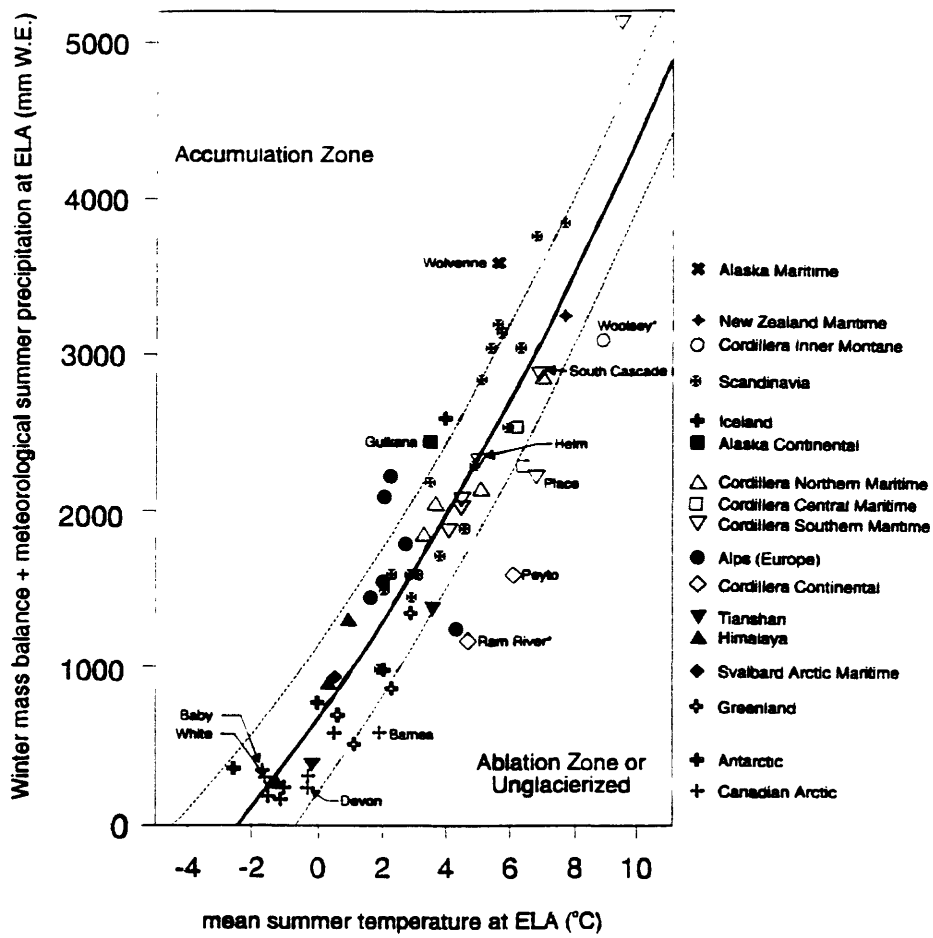

Figure 2 A precipitation-temperature representation of Global glaciation (after Ohmura *et al.* 1992) showing the current mass balance network in the Canadian/U.S.A. cordillera, Alaska and the Canadian Arctic (* represents discontinued IHD sites in western Canada).

Data Archive/Retrieval

A review of the status of cryospheric observing systems and data sets in Canada has been provided by Barry (1995) in which he summarizes "*The present status is considered to be unsatisfactory in a number of respects for the different cryospheric variables important for global change research.*". One of the recommendations coming out of recent reviews of glacier related activities in Canada (Munro 1995, Demuth and Munro 1995) was the need to improve access to data bases concerning themselves with glacier variations. Munro (1995) goes on to summarize that despite a general concurrence that the quality of glacier related work coming from Canada was high, the conduct and organization of such efforts was sporadic and improvements towards co-operation and inter-disciplinary study need to be made.

A recent proposal under CRYSYS has investigated the feasibility of augmenting a cryospheric data node with a "new" sub-node for glaciers. The feasibility study was centred around having the sub-node established at a university. The need for an effective cryospheric node to assist global change research has been demonstrated (e.g., Barry 1995) and is generally supported. While re-establishing the "glacier node" to another geographic location is an option, it is clear that what is required first and foremost is an infusion of capital and human resources to modernize the present node and improve access (the current node resides at the NHRI-Canadian Glacier Information Centre (CGIC).

One perspective on the current status of the CGIC is provided in the abstract by Ommanney. The results of the aforementioned CRYSYS feasibility study are not yet published. Appendix B describes several recent activities initiated by the author to improve (re-establish) the effectiveness of the CGIC.

Response and Future Perspective

In general, fiscal restraint continues to severely challenge the monitoring and assessment of freshwater resources in Canada. Moreover, ongoing efforts by Environment Canada (Canada's lead agency on surface water monitoring) to rationalize federal monitoring networks (e.g., Pilon *et al.* 1996), have not acknowledged the need to develop cooperative approaches with partners who are currently responsible for monitoring and assessing Canada's perennial snow and ice resources (NHRI and NRCan-GSC). When considering the utility of a national surface water data collection strategy for Canada, numerous observers feel that the data/analysis basis for assessing the impact of global change and being able to make informed water management decisions, is being acutely compromised by not considering the integration of programmes that monitor and assess the significant perennial snow/ice resource in Canada. Furthermore, while Canada must be able to address its own freshwater issues (e.g., those related to biological integrity, altered hydrological regimes and quality of life/human health), not having the ability to effectively assess the state of its perennial snow and ice resources will have a profound impact on Canada's contribution to the international study of global change (e.g., understanding historical and modern climate variations, global sea-level rise). Notably, Environment Canada made an announced commitment to UNESCO and the International Association of Hydrological Sciences/International Commission on Snow and Ice in 1965 (start of the International Hydrological Decade (IHD)) to monitor glacier variations as part of the global surveillance of glacier trends. This commitment was renewed in 1975 at the start of the International Hydrological Programme (IHP).

The general decline of support for glacier-related studies in Canada is complicated by eastern biases and the geographical isolation from the decision making table experienced by project scientists and science managers. Cuts in the budgets of numerous government departments, including those most active in scientific work (Environment, Fisheries and Oceans, Natural

Resources), have resulted in a troublesome deficit of expertise and mentorship (for glacier related work, the departure of numerous key contributors- Ommanney, Holdsworth, Alt, Perla). Currently, CGVMAN remains entirely funded by A-base dollars, however, at levels which barely sustain basic data collection and severely hamper efficient analysis/assessment, QA/QC and reporting activities. The increasing use of industrial-based 3rd party resources can further exacerbate the above situation. A recent runoff modelling study, supported by significant 3rd party hydro-authority money (e.g., Brugman *et al.* 1996), gave no consideration to co-lateral planning for the support of related national data collection and assessment activities- activities which, historically, established the regional data basis that ultimately provided relevance to the work.

To be effective and productive in contributing to related eco-system science and global change/water management research, CGVMAN may have to undergo additional transformations, beyond those related to efficiency and philosophical re-design. The operational aspects of CGVMAN and related management of the Canadian Glacier Information Centre may need to be aligned with other partners outside of NHRI and its confines as a research science institute. Koerner and others (1997), in a review of National Research Council and Environment of Canada glacier monitoring and research strongly recommended that the Federal Government Glacier Science Programme be an amalgamation in Ottawa at the Geological Survey of Canada of the two remaining Federal glacier science activities at the Geological Survey of Canada and the National Hydrology Research Institute. To ensure that CGVMAN's important contributions continue into the future, it must align itself with those elements in government, the universities and the private sector that have a broad philosophical interest in global change. It will then be pivotal for the sustainability of Canada's contribution to global environmental monitoring and assessment to: i) establish a foundation of short- and long-term, societal- and science-based issues; ii) recognize that, for geophysical and environmental systems undergoing unknown future change, monitoring, because it must remain flexible, is neither trivial nor routine; iii) broaden the relevance of glacier-related research and monitoring to other disciplines.

NHRI and CGVMAN hope to take a leadership role in bringing Canada's glacier and water resource community together to define a strategic direction for glacier-related work. Useful conceptual templates for such direction may be found in The Freshwater Imperative: A Research Agenda, (Naiman *et al.*, 1995). Here, traditional approaches to the monitoring and assessment of freshwater eco-systems are challenged to revitalize linkages between research and management; linkages that enable policy, politics and socioeconomics to be based on basic curiosity-driven research, sound freshwater science/modelling capabilities, and predictive understanding. Pivotal will be the re-affirmation of the role of science and the assurance of informed public input through integrated monitoring, information and research pathways (Figure 3).

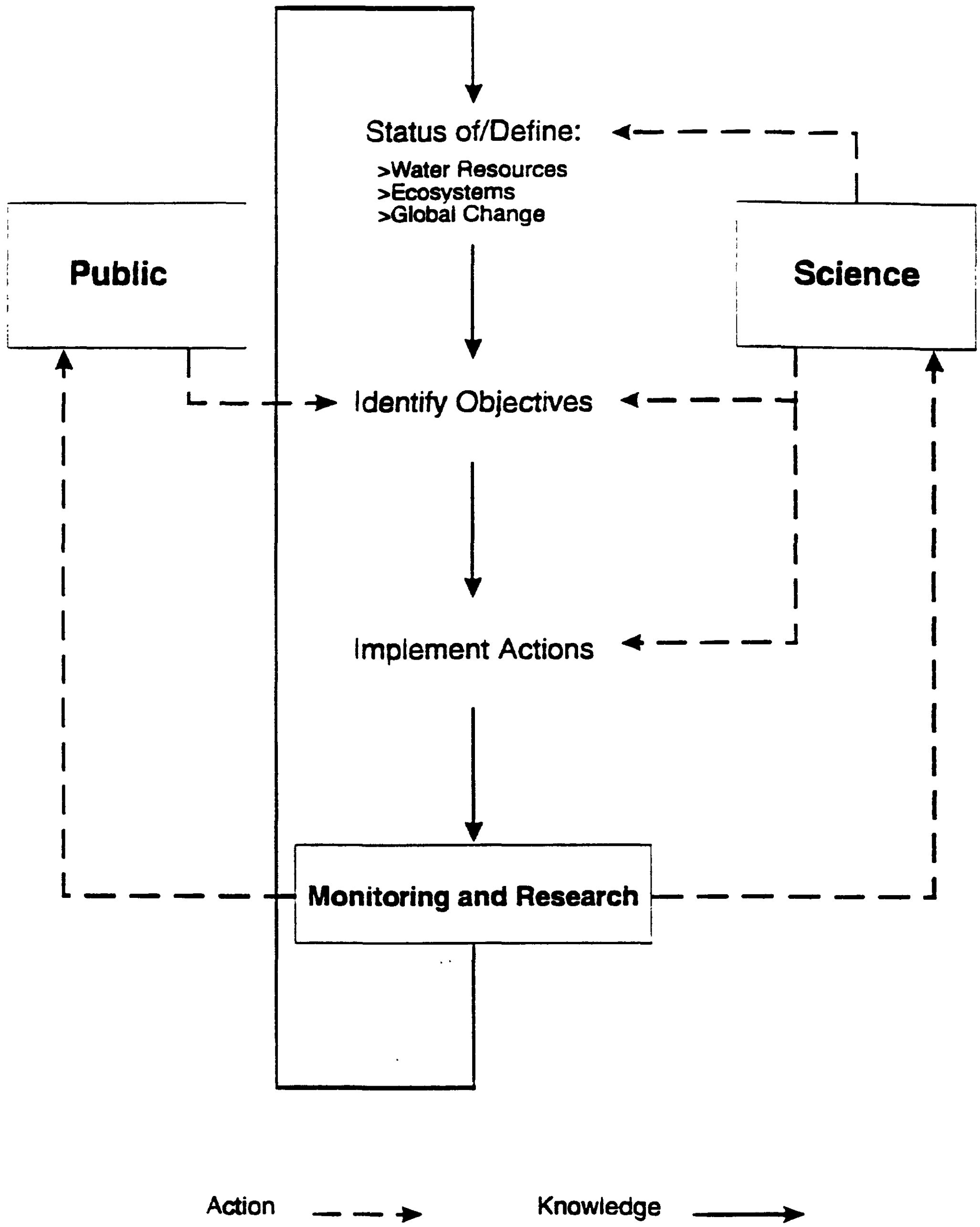

Figure 3 A basic framework whereby science and the public form a substantive component in the process of identifying and promoting sustainable water resource and ecosystem qualities. Monitoring and research activities serve as a foundation for the ability to deal with unknown future changes to environmental and geophysical systems (adapted from Stanford, personal communication, 1995).

On a final note, as commented in an article reviewing the study of natural evaporation by Philip (1987), "*... public research bodies are under increasing pressure to orient their research commercially. The politicians fail to grasp the consequent inefficiency for science and the loss to all mankind.*". For global change research in Canada, the same consequences will come true for those who orient such work around short-term flagship and 3rd party studies only, without consideration for the longevity and vitality of long-term monitoring and assessment programmes.

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Appendix A:

Glacier Mass Balance - A Foundation ....

- A measure of the integrated energy and water fluxes at the earth's surface; providing both instantaneous (mass balance) and delayed/cumulative (terminus fluctuation) signals:

  ... assessment of regional and synoptic-scale climate variations.

  ... understanding global change and the role of anthropogenic forcing.

- A tool with which to assess the state of a hydrological element and water resource which plays an important role in moderating streamflow:

  ... rivers which feed contiguous semi-arid regions.
  ... upper-catchment habitat.
  ... reservoir/irrigation infrastructure.

Appendix B: Recent CGVMAN and Related Contributions/Activities

1. An analysis of the mass balance record for White and Baby Glaciers (Cogley *et al.* 1995), is now available as an NHRI Science Report. The publication of this work was the turning point with respect to continued NRCan - Polar Continental Shelf Project logistical support for the CGVMAN-Trent University operation. The work in its own right will likely serve as a useful template for future reassessments and discussions of long-term glacier-related environmental time series.

2. On May 10-11, 1996, in Banff, Canada, the 100th anniversary of Peyto Glacier studies was celebrated at a workshop sponsored by NHRI and Wilfrid Laurier University - Cold Regions Research Centre. The workshop was held in conjunction with the Canadian Geophysical Union-Hydrology Section annual meeting. Invited speakers addressed a wide variety of topics related to Peyto as a glacier specifically and its broader context. Invited speakers including, Õstrem, Ohmuru, Young, Holdsworth, Collins, Morris, Luckman, Petts, Munro and Demuth are now in the midst of preparing written contributions towards a 100th anniversary publication to be edited by Young, Munro and Demuth.

3. A research team led by Professor Gordon Young at the Cold Regions Research Centre, Wilfrid Laurier University, is currently under contract to Alberta Environment to study the impact of glacier fluctuations on the flow regime of the Bow River.

4. CGVMAN has proposed to meld its efforts with ecological monitoring protocols in low order pro-glacial streams and lakes. These efforts will examine the nature of glacier fluctuation influences on habitat for keystone biota such as salmonids, the response of the zoobenthic community and its structure within the kryal and rhithral stream segments and associated riparian zones (e.g., Demuth 1996a, Milner and Petts 1995). This work will have ties with a European Union study (AASER) based out of the Environmental Studies programme at the University of Birmingham, UK.

5. The CGVMAN project is currently examining the contribution of glacier melt to the reservoir infra-structure of the Canadian portion of the eastern-slope montane eco-zone. Contributions to reservoir live storage and annual throughput are estimated at a scale larger than considered in most traditional investigations (Demuth 1996b). It is intended that these efforts, inpart, will generate support from Trans-Alta Utilities and Alberta Environment for CGVMAN activities.

6. A WWW site is being constructed from which information on facilities at CGVMAN sites, data view/retrieval services and links to CGVMAN partners will be provided. It is hoped that in the future, the CGVMAN WWW site will provide a destination for Canadian WGMS data describing glacier variations, volume changes, hydro-meteorological observations and special events.

7. At the NHRI - Canadian Glacier Information Centre, initiatives have begun to restore the GLADYS glacier inventory and PAPYRUS bibliographic data bases. NHRI and the USGS is co-operating to have the Glacier Atlas of Canada (GAC) reproduced in digital form. These initiatives, while moving forward, will likely progress slowly. Local funding for the work is currently limited to that remaining in the CGVMAN project budget after the annual logistical, observation and assessment tasks are completed. Notably, some significant support inkind for the GAC initiative has been discussed with USGS (Hugh Kieffer).

8. Brugman *et al.* (1996) have completed a comprehensive glacier runoff modelling study for the British Columbia Hydro and Power Authority. The study is centred around the historical and modern fluctuations of the Illecillewaet Glacier (Columbia River Basin). An algorithm simulating glacier melt is driven by coupling turbulent and radiation heat exchanges (measured *in-situ*), with glacier topographical and facies data derived from remote sensing imagery. Notably, the work has permitted the continuation of glacier variation observations for the Illecillewaet Glacier, supplementing a discontinuous, but never-the-less, substantial record dating back to the late 1800's.

CANADA

Status of Glacier Monitoring in the Canadian Arctic

by
Roy M. Koerner, Geological Survey of Canada

Presently three groups work on Canadian Arctic Glaciers:

1: Trent University, Geography Dept: continuing the mass balance work on White and Baby Glaciers on Axel Heiberg Islands (begun in 1960) and recently published as an NHRI report.
2: University of Edmonton, Geography Dept: various glaciological activities in Northern Ellesmere Island, no glacier monitoring program.
3: Geological Survey of Canada: Mass balance of Devon (1961-), Meighen (1960-), and Melville S. Ice Caps (1963-), and a glacier on Northern Ellesmere (1977-). Main program, however, is ice core and spatial snow studies for (paleo)climatic change and pollution studies. This program has been extended to Penny Ice Cap (southern Baffin) and is run in cooperation with the University of New Hampshire (USA), National Institute Snow and Ice Studies and National Institute Polar Research, both Japan. The paleoclimate aspect of this work is allowing broad-based extensions of present-day mass balance conditions back in time.

All mass balance programs under #1 and #3 use traditional, ground-based techniques. Under #3, a start has been made to incorporate automatic weather stations mainly for temperature and snow accumulation records. This approach will soon include the use of (hopefully) inexpensive automatic ablatometers in the ablation zones. NASA (Thomas) has completed a set of airborne radar/laser/GPS measurements, along tracks suggested by the GSC, over most of the ice caps and glaciers of the Canadian Arctic. These tracks, once repeated will give a wide-scale measurement of glacier change.

CANADA

Monitoring and Inventorying the Glaciers of Canada: An Historical Review and Personal Comments

by

C. Simon L. Ommanney, International Glaciological Society

Reflecting on the theme of the meeting and the current situation in Canada there are two observations I would make.

1. When considering the identification of a broader set of representative glaciers don't forget to consider previous discussions of this, as it may save some time.

When the International Hydrological Decade (IHD) program in Canada was established, apart from the representative glacier basins for the east-west and north-south profiles, a set of benchmark glaciers was also identified, to which the program would be extended as resources permitted, to fill in gaps in the principal observation network, This theme was revisited by the North American Committee on Climate and Glaciers and discussed in the full report of that meeting which was summarized in the article in EOS. Andrew Fountain should have a set of notes from that meeting. There was also the meeting convened by the Alaskans in Eagle River to discuss a more limited network in that State and published by Matt Sturm and others. I also summarized some of the mass-balance network information in the new Ostrem mass-balance manual. Mike Demuth should be able to get copies of any of my reports at National Hydrology Research Institute (NHRI) and could bring them with him.

2) Of very great concern is the current situation in Canada with regard to data already collected.

As various government programs shut down, records were consolidated and eventually transferred to the National Hydrology Research Institute in Saskatoon which seemed to have a strong program and represented a chance for security and continuity. With cutbacks there this information has now become inaccessible and indeed may be in the process of becoming irretrievably lost. Much of the information I managed when I was there has been taken off the computers where the data bases were maintained and the hard files sent to dead storage or piled in a corner of a locked room. I was in Saskatoon recently and tried to track down information I knew existed about records from a US Army Air Force Task Force in the High Arctic in the mid 1940s. The availability of photography from this mission had been noted in memos I had placed in about 6 separate files. All files had been sent to dead storage in Edmonton and probably been shredded under a 25 year disposal rule even though I had specified when I was in Saskatoon that these files contained historically important records and should never be destroyed. None of the files on Ellesmere Island included the memo that had been deposited in them in the mid 1970s. The flight lines for the photographs, the only copies in Canada as far as I know, have been removed from the map room to goodness knows where. A sorry tale that I would love to recount in person but I will have to settle for sending you these notes.

I think few people realize the extent of the collection that had been amassed in Saskatoon over the years and its vital importance to the glaciological and water-management community. The original collection goes back to the first glacier inventory that was started by Tuzo Wilson at the University of Toronto for the International Geophysical Year (IGY). This formed the basis of the IHD glacier inventory that was begun by George Falconer in the Geographical Branch that was subsequently transferred to the Glaciology Subdivision and came into my care as part of the Glacier Inventory Section in the late 1960s.

By the time this transfer took place the collection had been augmented by the acquisition of quite a large collection of historical photographs of Baffin and Bylot Islands, with material collected by the Geographical Branch expeditions there, with the trimetrogon photographs mentioned above which provided coast and inland passes coverage principally for Axel Heiberg and Ellesmere Islands. As a result of a visit from Bill Field we also acquired several thousand photographs from the phototop stations occupied during the International Boundary Survey around the turn of the century - an unique record of glaciers in the Coast Ranges. There were also other records of glaciological interest such as a card catalogue of ice observations in Canada derived from historical texts.

The objective of the Canadian Glacier Inventory was to identify and measure every perennial snow and ice body in Canada. The raw materials for this work were aerial photographs and maps. Over the years we acquired COMPLETE air photograph coverage of all the glacierized areas in Canada, several tens of thousands of photographs. These included the coverage obtained by the Alberta Provincial Government as well as the British Columbia Government. No one could afford to buy this coverage today yet the photographs are no longer properly cared for or organized. The map collection was also complete, at least two copies of the largest scale map of every glacierized area in the country. As far as I could tell the collection remains where it was though I have no idea what losses it might have sustained. Related information, such as the flight lines mentioned above, appear to have been removed, I hope not destroyed.

Once the Defence Research Board's glaciological program on Ellesmere Island, headed by Geoffrey Hatterslye-Smith, was shut down responsibility and the records were transferred to NHRI, including the original field notebooks.

The Water Survey of Canada had carried out glacier observations, and latterly terrestrial photogrammetry, on many glaciers in western Canada from the mid 1940s until 1980. The original survey notebooks were all transferred to NHRI when the principal investigator retired and the program was terminated.

Other records were also donated to NHRI in the expectation that they would be looked after. Records from everywhere from Baffin Island and Labrador to Vancouver Island.

At the centre of this collection was the Canadian Glacier Inventory with quantitative information on about 40,000 of Canada's approximately 100,000 glaciers, and annotated maps and photographs of many more. Special software, called GLADYS, had been developed to store and retrieve the basic inventory data, and a bibliography, with some 40,000 references to all aspects of snow and ice studies in Canada from 1975 onwards, including more specific coverage of glaciers to the start of observation in Canada in the 1880s, was stored in a PAPYRUS data base.

Requests to NHRI from a variety of sources in the last two to three years have met with the response that none of this information is available. If this were a public company the shareholders would likely deem this to be criminal neglect of a fundamental asset. Considering that the cost to the Canadian taxpayer of acquiring this information over the last 40 years would have been in the order of millions, rather than thousands, of dollars no one can afford to stand by and see it lost to future generations.

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CONTERMINOUS UNITED STATES

Status of Glacier Monitoring and the Remote Sensing Snow-and Ice-Data Base in the Conterminous USA

Robert Krimmel, USGS

More glaciers are presently monitored in the conterminous USA than ever before. Most glaciers are in National Parks, and since the early 1990's the National Park Service has begun a program to monitor glaciers in the National Parks. In 1996, 4 glaciers in North Cascades NP were monitored for the 4th year with seasonal balance measurements and annual vertical photography. Two of these glaciers will continue to be monitored indefinitely. In Olympic National Park, the Blue glacier has been continuously monitored since 1958, primarily by the University of Washington, and present efforts are to continue simple seasonal balance measurements, and to determine ice volume changes between several mapped dates. At Mt. Rainier National Park sequential vertical photography is done about every 5 years to measured ice surface levels and terminus changes. A program to measure altitudes along 3 transverse profiles of Nisqually Glacier, begun in the early 1930's, is continuing. In Glacier National Park, vertical photography of all the glaciers is obtained every 3 years, and a GIS data base including all available information about the changes is size of the glaciers has been developed. In Yosemite, McClure Glacier data from 1968-1974 has been assembled for publication, and a volunteer program is ongoing to monitor a nearby glacier. The US Geological Survey is continuing a program begun in 1958 to monitor South Cascade Glacier in Washington State with seasonal mass balance measurements combined with meteorological and hydrological measurements.

The glaciers within the conterminous USA are scattered over a large area, and tend to be small. Most glaciers taken individually are insignificant, but these small glaciers are very important hydrologically when taken as a whole, and should not be ignored in glacier inventories. Because of the small size of these glaciers, the present synoptic remote sensing data from Landsat and SPOT are of marginal use for glacier monitoring. Recent satellite sensors with less than 15 m resolution have potential utility, as does a plethora of still-to-be released classified intelligence data. Presently, the most informative glacier data base is the USGS 7.5 minute (1:24,000 scale) topographic map set. Many of these maps are now 30-40 years old, and show the glaciers as they were at that time. Despite the passage of time, these maps are often the most accurate portrayal of the snow and ice available. More recent mapping-quality photography is sometimes available through the National High Altitude Photography program, or within other agencies archives (such as state Department of Natural Resources, or the Forest Service), but are often difficult to locate. The USGS Ice and Climate Project also has acquired a collection of vertical and oblique photographs of glaciers of western North America, which are indexed by glacier name, and spans a time of 1960-1996. Only a small portion of this collection has been used to produce new glacier maps. Glacier inventories, which are a compilation of all the snow and ice areas within a specified geographic area, have only been completed for the North Cascades of Washington. We presently can not give an area of snow and ice cover within most geographic areas simply because the inventories have never been completed. The data base exists, that being the previously mentioned topographic map series, combined with more recent photography which is usually available. A potentially extremely useful outfall from the topographic map series is a compilation of all snow and ice masses into a digital data base. Each snow patch could be defined by a polygon around its perimeter, with a low density digital elevation model of its topography, and geo-referenced with name (if there is one), latitude and longitude, date of the photography from which the map was made, and other relevant data. This would become a "snapshot" of snow and ice from several decades ago, would allow changes between that time and more recent measurements (whether aerial photography, satellite, or other means), and would allow simple searches and statistics to be used to make general statements concerning regional glacier areas. The glacier areas in the accumulation zone, which may change dramatically year-to-year, independently of the long-term "glacier fluctuation" change, must be "locked" to a specific value so that only the terminal changes are monitored. Snow and ice identification algorithms must be developed so that small changes in end-of-balance-year snow albedo, or other conditions that may artificially change the apparent area of snow or ice do not dominate results derived by massive processing of remote sensing data.

Careful analysis of the dual data set of topographic maps and recent aerial photography or other remote sensing material will allow the interim change in glacier area to be measured, and will supply vital global change measurements.

GREENLAND

Status of Glacier Monitoring of Greenland

by
Anker Weidick, Geological Survey of Denmark and Greenland

Abstract

A review of basic requirements for monitoring Greenland glaciers is presented. The requirements of uniform and near-contemporaneous coverage by aerial photographs and map series have greatly improved over the past decade, and at the same time, satellite information has developed as an important tool for mapping Greenland glaciers and their changes.

"Conventional" inventory work has not kept up with this development. So far only ca. 5000 glacier units of West Greenland have been covered whereas there are an estimated minimum of ca. 15,000 glacier units in North and East Greenland still lacking. However, over the past decade a perusal of glaciers from the entire Greenland coastal area has been achieved. This was based on Landsat imagery, and shows the glacial characteristics from the different climatic regions of Greenland.*

From the work along these two lines of inventorying and from the current strong interest in local glaciers (due to their sensitivity to climatic change) it is clear that the paramount problem in Greenland is the determination of the total cover of local glaciers and hence, the delineation of the inland ice where it merges with local glaciers.

So far it is concluded that at least 10% of the total global coverage of local glaciers is to be found in Greenland, though this fact is often omitted from the literature.

First priority must therefore be to make an estimate of the local glacier coverage of Greenland on the basis of current 1:2.5 million map sheets, followed by a refinement of this figure by a detailed inventory of the lacking glaciers and supplying the individual glaciers with a proper address for filing of information and monitoring. The figure by the National Survey and Cadestre (KMS) is planned to be broken down into the glacier divisions suggested by the Geological Survey of Denmark and Greenland (GEUS).

*Wiedick, A., 1995, Greenland, with a section on Landsat images of Greenland, by Williams, R.S., Jr., and Ferrigno, J.G., Satellite image atlas of glaciers of the world (Williams, R.S., Jr., and Ferrigno, J.G., editors): U.S. Geological Survey Professional Paper 1386-C, 141. p.

ICELAND

Glacier Monitoring in Iceland: The Glacier Variation Data Set of the Iceland Glaciological Society

by
Oddur Sigurðsson, National Energy Authority

Historical Review

Information on the postglacial-variation history is being revealed by on-going geological interpretation. For the past 1,100 years (historical time in Iceland; settlement began in ca. 874) information can be derived from old manuscripts both directly and indirectly. Danish plane-table mapping (map scales of 1:50,000 and 1:100,000) was carried out during the years 1903-1938, giving reliable information on the position of termini of many outlet glaciers, especially in southeastern Iceland in 1903-1904.

In the year 1930, Jón Eyþórsson began a systematic program of monitoring the frontal variation of selected glaciers. The program started by him has been expanded since that time and now includes 41 glaciers and outlet glaciers at 55 different locations.

Oblique aerial photographs have been obtained since 1937 by geodetic institutes and private persons. Ground-based data and datable photographs are found in various private collections and archives, including the Iceland Glaciological Society.

The U.S. Army Air Force, in association with the U.S. Army Map Service (AMS) acquired almost complete coverage of Iceland with vertical overlapping (stereo) aerial photographs in 1945 and 1946; in 1956 and 1959-1961, the U.S. Air Force rephotographed most of Iceland in cooperation with the AMS and the Iceland Geodetic Institute (Landmælingar Íslands). Landmælingar Íslands has been taking vertical aerial photographs of various areas beginning in 1952. According to a coverage plan of LÍ, glaciers are supposed to be rephotographed every 10 years, but this is usually not the case. Information on the aerial photographic archive of Landmælingar Íslands can be obtained through their Remote Sensing Division.

Icelandic glaciers have been imaged by the Landsat (1-5) satellites since September 1972. Previous to that there may be existing classified satellite images, and photographs archived by intelligence agencies. Over time, additional spacecraft acquire data that are useful for glaciological information.

Mass balance of Icelandic glaciers was first carried out in the 1930's by the Swedish-Icelandic Expedition; it established a winter balance of 5 m water equivalent or more in the upper part of the accumulation area in the eastern part of the Vatnajökull ice cap. The summer balance at the terminus proved to be in some cases about -12 m water equivalent. Winter balance has been measured yearly by the Iceland Glaciological Society since 1954 in the Grímsvötn caldera in the west-central part of Vatnajökull.

Regular pit and stake mass-balance measurements have been carried out on the northern side of Hofsjökull since 1988 and likewise on the Þrándarjökull since 1991. Profiles of mass balance (pit and stake) have been established on the eastern and south-western side of Hofsjökull since 1989. Similar profiles have been assessed on the Tungnaárjökull, Dyngjujökull, Köldukvíslarjökull and Brúarjökull outlet glaciers of Vatnajökull since 1992 and the Eyjabakkajökull outlet glacier since 1991.

Interpretation of Glacier Fluctuations

Glacier variations in Iceland have been recorded systematically since the 1930's on 23 different outlet glaciers and other types of glaciers. Since that time, 18 more glaciers have been added to the monitoring system for Icelandic glaciers.

Twelve of the referenced glaciers are surge-type glaciers with virtually no indication of climatic control between surges. In the data set, 24 of the glaciers show little indication of surges and 4 are of uncertain or mixed character. The advance/retreat of some of the non-surging glaciers is intimately related to the climate with reaction at the terminus most of the time occurring well within five years from a postulated change in mass balance. The rise of the mean summer temperature by approximately 0.6°C from the first to the second quarter of the 20th century resulted in a rapid retreat of all measured glaciers in Iceland for the first 20 years of the measurement period, interrupted only in very few cases, mainly by surges. A turning point occurred around 1970 when most of the non-surging glaciers stopped retreating and many of them started to advance. Some of the glaciers have been advancing continuously since.

Since about 1970, the glaciers in the southernmost part of the country have regained about half of the ground lost since 1930, in the north about one third, in the west the recovery is about one quarter. In the southeast, some of the glaciers have been stationary for 30 years, while the easternmost ones have retreated slightly. Surge-type outlet glaciers with surge periods varying between 10 and 80 years are represented in the data set. In the period 1991-96 11 outlet glaciers have surged.

NORWAY AND SWEDEN

Status of Ground Based Glacier Monitoring in Scandinavia and Svalbard

by
Jon Ove Hagen, Department of Physical Geography, University of Oslo

Abstract

Mass-balance investigations have been conducted for longer and shorter periods in a transect from south Norway to Svalbard, from 61°N to 80°N. Systematic measurements of glaciers have a long tradition in Norway. Since the beginning of this century, frontal positions have been measured annually, with small time gaps, on about fifteen glaciers, and for shorter periods on several other glaciers. Mass-balance measurements were started in 1948 on Storbreen in Jotunheimen, southern Norway, by the Norwegian Polar Institute. The Hydrology Department of the Norwegian Water Resources and Energy Administration (NVE) initiated long-term mass balance studies on selected glaciers in southern Norway in 1962 and 1963. Glaciers regarded as representative for certain areas were selected.

Currently long time series are conducted on four glaciers in southern Norway (61°N - 62°N- maritime and continental), one in Svartisen area (~ 66-67° - maritime) and one (Storglaciären) in northern Sweden in the Kebnekaise area (68° N - continental). Storglaciären has been measured since 1946, and has the longest continuous series in the world, two years longer that Storbreen in southern Norway. Further north in Norway there are no ongoing measurements, although there are large glacier areas. However, for a five year period (1989-1993) one glacier at 70°N was measured.

In Svalbard, annual mass balance investigations were started in 1966 on Brøggerbreen (6.1 km^2) close to the research station Ny-Ålesund (79°N 12° E) on the northwest coast of Spitsbergen by the Norwegian Polar Institute. Observations on some other glaciers have been carried out by Russian and Polish scientists in shorter periods in other parts of the island. Currently there are three running mass balance series, Brøggerbreen (6.1 km2), Kongsvegen (105 km^2) and Hansbreen (60 km^2). The two latter are calving glaciers. Most of the glaciers in Svalbard are of surge type. It is therefore difficult to use the front position of a single glacier as a climate indicator, because the front will shrink and retreat in periods between surges. The front position therefore gives little information on whether the ice mass is growing or shrinking. Mass-balance measurements are therefore necessary to tell the true story about the volume change. Superimposed ice formation is important. Equilibrium-line altitude determination from aircraft or satellite is therefore difficult. On all investigated glaciers both accumulation and ablation have been measured by direct glaciological-stratigraphic method: snow-sounding profiles, density measurements, and stake readings. Most of the glaciers are fairly small (< 10 km^2) cirque glaciers or outlet glaciers from ice caps. In Scandinavia there is no existing program to monitor glaciers by remote sensing.

HIGH ARCTIC

Arctic Ice Masses, Recent Climate Change, and Implications for Global Sea Level

by
Julian A. Dowdeswell, Centre for Glaciology, University of Wales

The Arctic appears to be an area of the globe which is particularly sensitive to climate change. Several General Circulation Model (GCM) simulations of future climatic response to increasing proportions of "Greenhouse gases" in the atmosphere have predicted that Arctic regions will experience enhanced warming relative to lower latitudes. Ice-core records from Greenland have also indicated very abrupt past environmental responses to shifts in the linked ocean atmosphere system. The winter inputs and summer losses of mass from the glaciers, ice caps and ice sheets covering over 2 million km^2 of the Polar North vary in response to climate changes, and affect global sea level as increments of water are decanted to the oceans or stored in solid form. This area includes the 1.7 million km^2 Greenland Ice Sheet, together with the glaciers and ice caps which extend over 250,000 km^2 of the Arctic, on both the heavily glacierized archipelagos of the Canadian and Eurasian High arctic and the glaciers north of about 60°N within continental North America, Europe and Iceland.

High Arctic climate change over the last few hundred years includes the relatively cool Little Ice Age (LIA), followed by warming over the last hundred years or so, according to the oxygen isotopic and melt layer signals from ice cores and from the few long time series of direct meteorological observations available from the circum-polar North. Meteorological data from the Eurasian High Arctic (Svalbard, Franz Josef Land, Severnaya Zemlya) and Canadian High Arctic islands are scarce before the mid-Twentieth Century, but longer records from Svalbard and Greenland show warming from about 1910-20 (Dowdeswell, 1995). Other evidence of recent trends in High Arctic temperatures and precipitation is derived from ice cores, which show cooler temperatures (by 2-3°C) for several hundred years before 1900, with high interdecadal variability. The proportion of melt layers in ice cores has also risen over the last 70-130 years, indicating warming.

Two forms of observations have been made on recent trends in the mass balance of Arctic ice caps and the Greenland Ice Sheet: field and satellite measurements. There is widespread geological evidence of glacier retreat in the Arctic since about the turn of the century linked to the end of the LIA. An exception is the rapid advance of some surge-type ice masses. Field measurements of mass balance on ice caps in Arctic Canada, Svalbard and Severnaya Zemlya since 1950 show either negative or near-zero net balances, suggesting glacier thinning in response to recent climate warming (Dowdeswell, 1995). The total net input of melt from small glaciers and ice caps throughout the world is estimated at 0.4 ± 0.2 mm yr^{-1} of sea-level rise, averaged over the past 60-80 years (Meier, 1993). On the Greenland Ice Sheet, satellite radar altimetry is being used to measure whether the ice is thickening or thinning. The 18 km diameter footprint of the ERS-1 radar altimeter makes it unsuitable for making similar measurements of small ice caps (< 10,000 km^2), but laser ranging systems of high accuracy will be used in future to measure changing surface elevation on these ice caps. Repeat radar altimeter measurements for the southern 40% of the Greenland Ice Sheet (constrained by satellite orbital parameters) shows a thickening by 230 ± 70 mm yr^{-1}, equal to between 0.2 and 0.4 mm yr^{-1} of sea-level fall (Zwally and others, 1989; Wingham, 1995).

Predictions of ice-mass response to climate change have been modeled using two approaches: simple energy balance and more complex GCM experiments. A "greenhouse-induced" warming of 1°C in the High Arctic is predicted to produce a global sea-level rise of 0.063 mm yr^{-1} from melting of Arctic ice caps (excluding Greenland) based on simple energy balance calculations. By contrast, recent GCM results for the Greenland Ice Sheet using a high resolution grid (T106) to improve modeling of altitudinal effects, suggests an increase of ablation by about 200 mm yr^{-1} (water equivalent) for a doubling of atmospheric CO_2. (Ohmura, 1995). This is equivalent to a sea-level rise of 1.1 mm yr^{-1}. However, similar high-resolution modeling of the Antarctic Ice Sheet shows an increase in mass balance of 23 mm yr^{-1}, or a sea level fall of 0.9 mm yr^{-1}. According to these GCM experiments, the differing effects of doubling CO_2 on the mass balance of the two great ice sheet may cancel each other out.

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II.
CURRENT AND PLANNED REMOTE SENSING TECHNOLOGY FOR MONITORING GLACIERS

Monitoring Glaciers with Airborne and Spaceborne Laser Altimetry

by
James B. Garvin, NASA Goddard Space Flight Center

Abstract

As with all dynamic landscapes, glaciers display telltale morphologic features that provide quantitative evidence of their deformation rates and of the basic physics of their motion. High spatial and vertical resolution topographic information is of unquestionable value when the magnitudes and rates of surficial deformation on active glaciers must be inferred, but prior to the advent of advanced optical and microwave topographic remote sensing devices over the past decade, establishing a time series of topographic measurements for any glacier would have involved an unfathomable amount of effort. Furthermore, traditional topographic measurement techniques are frequently inadequate for describing the diverse suite of topographic elements that are found on the upper surface of a glacier. Measurement of longitudinal cross-sections of active temperate glaciers by means of geodetic airborne laser altimetry was first initiated by a joint team of NASA and USGS scientists in the late 1980's. An early version of the high pulse repetition rate Airborne Terrain Mapper (ATM) profiling laser altimeter was operated from a NASA P-3 aircraft in an effort to quantify the geometry of the terminus regions of several outlet glaciers in southern Iceland. Combining high precision aircraft attitude sensing equipment (laser ring gyros) with kinematic GPS tracking methods to facilitate sub-meter level removal of aircraft platform motions facilitated 15-20 cm RMS vertical accuracy observations of Breiðamerkurjökull (S. Iceland) with an along track sampling frequency of approximately 1 m. Direct detection of all major crevasses was achieved in this pathfinding demonstration of the possibilities associated with low-altitude geodetic airborne profiling laser altimetry. Advances in airborne laser altimeter instrumentation at NASA's Goddard Space Flight Center over the past seven years have provided a variety of approaches for monitoring glaciers on a routine basis. By developing cross-track scanning methods, as well as full echo recovery techniques, swaths of local glacier surface topography can be acquired with 1-5 m sampling scales. Swath widths currently exceed 100 m, and can be as large as 200 m. High altitude laser altimeter systems can synthesize footprints of various sizes (i.e., from 5 to 70 m in diameter), while measuring the complete echo resulting from transmitted laser pulses which interact with various features on glacier surfaces. Most recently, NASA deployed an array of three geodetic airborne laser altimeter sensors to Iceland, Jan Mayen, Svalbard, and Greenland. Included in this flight campaign was the SLICER large-footprint echo recovery lidar, the scanning ATM system, and a 2000 pulses per second ATM Profiler; in addition, the University of Kansas Ice Penetrating HF Radar was included. Both low and high altitude laser altimeter swaths were acquired for active outlet and icecap glaciers in Iceland and on Jan Mayen. Sub-meter accuracy topographic transects of the surging Sylgjujökull glacier (W. Vatnajökull, Iceland), of the Grímsvötn sub-glacial caldera, and of the ice cauldrons in the western portion of Vatnajökull were acquired between 27 May and 2 June, 1996. Laser altimeter profiles made up of footprints at the scale of those to be acquired as part of the

ICESAT component of NASA's orbiting Earth Observing System (EOS) were acquired; 30 m and 70 m diameter footprints were obtained in order to quantify how orbital laser altimeter echoes might be used to detect crevassed zones in glaciers at the margin of ice sheets or ice caps. Simultaneous acquisition of dense swaths of scanning laser altimetry will provide the ground truth (from the air). This Geoscience Laser Altimeter System (GLAS) emulation dataset will be released to the Earth Science community in a few months for detailed analysis.

NASA's strategy for monitoring important dynamic landscapes such as glaciers revolves around an array of passive imaging sensors (Landsat's ETM+, MODIS, ASTER, etc.), augmented by GLAS, which will orbit the Earth with the primary objective of sampling the polar icesheets and associated glaciers over a five year period in order to measure the mass balance of these important reservoirs. As presently designed, GLAS is a high vertical precision profiling system with a 70 m diameter footprint and with a sub-10 cm vertical precision. The GLAS sensor will be placed into a repeat orbit in ~ 2002, and in combination with the time series dataset of airborne laser altimeter observations of the Greenland ice sheet (i.e., under development since 1991 by R. Thomas and W. Krabill), it should provide the world glacier monitoring community with a potentially rich dataset of extremely precise profiles and spot elevation measurements for many high-latitude glaciers. With the apparent approval of the Shuttle Radar Topography Mission or SRTM, the prospects for 30 m per pixel digital elevation models of all continental glaciers lying between 60 N and 60 S latitudes are rapidly improving. As planned, the SRTM mission is to fly in late 1999 or early 2000, utilizing a novel C-band radar interferometry approach (InSAR) to produce nearly global DEM coverage of the Earth's land areas. While the vertical resolution of the InSAR DEM's will probably be ~ 10-15 m, the seamless 30 m gridding of this dataset could serve as an important foundation for future monitoring studies of temperate glaciers.

Further opportunities for spaceborne topographic remote sensing of glacier systems worldwide are emerging; NASA's fledgling Earth System Science Pathfinder (ESSP) program will solicit proposals for cost-constrained missions every two years, and the first selections were made in February 1997, with two missions to be launched around 2000. Polar orbiting satellite remote sensing systems are either in place or soon will be, some of which are ideally suited for glacier topographic and spatial monitoring. The Canadian RADARSAT system is a prime example. Indeed, Garvin, Williams and others will be utilizing monthly RADARSAT C-band SAR images of Iceland and Jan Mayen to track the spatial fluctuations of particularly dynamic glaciers in these regions over a three year period.

As a pathfinder to the next generation of orbital laser altimeter systems for Earth remote sensing, NASA recently flew the first of four Shuttle Laser Altimeter (SLA) experiments. In January of 1996, the SLA-01 experiment acquired over 80 hours of Earth surface observations during its week-long mission. While SLA-01 was restricted to an equatorial orbit (+28.5° N. and S. latitudes), orbital observations of ice covered surfaces in the Himalayas, at the summit of Mauna Kea volcano, and in other high relief mid-latitude localities suggests that future SLA spaceflight experiments could contribute to sub-arctic glacier topographic monitoring studies. Indeed, the SLA-02 experiment was successfully carried out as part of Space Transportation

System-85 (STS-85) in August 1997 in a 57° inclination orbit. SLA-02 was the first spaceflight demonstration of a 100 pulses per second (i.e., sub-100 m along track sampling) laser altimeter system in space, and will pave the way for future orbital scanning laser altimeter sensors. Designs are also underway at NASA for a wide-swath airborne laser altimeter system to be known as the Laser Vegetation Imaging Sensor (LVIS) (c.f. chief engineer J. Bryan Blair), which will be able to achieve 0.5 to 1.0 km wide swaths of sub-meter precision topography from moderate to high altitude aircraft platforms. The LVIS system could be utilized to develop baseline topographic reference maps (DEM's) of climatically important glacier systems in North America, Iceland, Greenland etc. over the next few years.

Finally, NASA is presently supporting a pathfinder study of the changing ice volume at the Mt. Rainier stratovolcano. This investigation, under the leadership of J.B. Garvin, involves the combination of geodetic airborne laser altimetry with airborne InSAR on an annual basis in order to quantify and model the volume changes in ice and snow deposits in the summit region of the edifice. A successful 1995 field season resulted in a laser altimeter model of the volume of the summit of Rainier (Sept. 1995), and airborne InSAR DEM's from August of 1995 are now in hand. Early evidence suggests that volumetric changes from 1994 to 1995 are insignificant. At the conclusion of this 3-year study, a geodetic database of annual laser altimeter measurements of the summit of Rainier will be available, as well as mathematical models of the summit topology and volume.

NASA has a profound interest in developing new remote sensing tools for monitoring dynamic landscapes and especially those that are coupled to short term climate change.

Satellite Remote Sensing (Imaging)

by
Dorothy K. Hall, NASA Goddard Space Flight Center

It is now feasible to infer regional mass balance of glaciers on each continent using satellite data from the early 1970s to the present. Measurements of synchronous and non-synchronous changes in glacier mass balance worldwide will allow us to relate those changes to sea level change, and to regional and global climate.

Utilizing regularly-acquired Landsat and SAR image data, one can gain a global perspective on glacier changes over almost a quarter of a century. Glaciers monitored for variations in glacier-terminus position probably account for less than 1 percent of the total number and area of glaciers worldwide, and the number of glaciers monitored for mass balance is only about one-tenth of the total number monitored for terminus variations (Wood, 1988). Thus, in order to study glacier changes worldwide, remote sensing must be employed (UNESCO, in press). Long-term studies of glacier-terminus position change can be accomplished using satellite data (Williams et al., 1997). Sustained change in glacier-terminus position is usually indicative of a mass balance change (Haeberli and Hoelzle, 1995). It is anticipated that, in the future, glacier-facies boundaries can be studied to detect changes that can be related to mass balance using a combination of Landsat and SAR data.

The primary imaging sensors for use in monitoring small glaciers in the world are the visible and near-infrared sensors on the Landsat satellites, since 1972, and the C-band synthetic aperture radar (SAR) sensors on the European Earth Resources Satellite (ERS)-1, -2, on Canada's RADARSAT, and the L-band SAR on the Japanese Earth Resources Satellite-1 (JERS-1). The SAR satellite data have been available continuously since 1991.

Visible and near-infrared Landsat data have been useful for mapping glaciers and ice sheets, and specifically, mapping glacier area, glacier-terminus position, glacier velocity, and snowline position. Dynamic events such as glacier surges and jökulhlaups have also been recorded by Landsat.

Prominent glaciological features that may be detected using SAR data include: detection of melt onset, glacier-terminus position and transient snowline (Fahnestock and others, 1993; Hall and others, 1995). The glacier facies (Benson, 1962) can also be studied. Some of the radar backscatter zones detected by SAR sensors may be, but are not necessarily, related to the glacier facies (Smith and others, in press).

In addition to the use of satellite-derived imagery for glacier mass balance studies, SAR data may be useful for determining streamflow and discharge from glacier-fed streams (Smith and others, 1995; in press)

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Use of Upcoming Satellite Technology

by
Hugh H. Kieffer, USGS

Satellite remote sensing can now allow a globally-uniform inventory of land ice. Although some regional inventories now exist, major regions have little or irregular coverage. No substantial Geographic Information System (GIS) inventories exist, even for the best-studied regions, such as Scandinavia and the Alps. Analog maps, even if of high resolution, do not support quantitative assessment of change without intense human labor. A digital geographic database incorporating detailed location of glacier boundaries is required for practical quantitative determination of change among glaciers. Considering the importance of glaciers as an indicator of climate, and the value that a global baseline would have to future studies of climate change, it is imperative that an image-based global GIS of glaciers (e.g., small mountain glaciers, ice fields, ice caps, ice sheets, outlet glaciers from the latter three types) be created as soon as practical, with Digital Terrain models (DTM's) where possible. This can be augmented by historical data of lower resolution or less complete coverage.

Both high-resolution optical (15m) and radar (~25m) imaging will be available in the next few years. Their combined capabilities can be used to map the more difficult situations, including mapping of debris-laden termini. The potential of combining these with precision altimetry surveys will allow remote mapping of ice volume changes.

Global Land Ice Monitoring from Space (GLIMS) is a specific program that has been established to use the EOS ASTER instrument (15m, along-track stereo, plus multiband imaging) to map the areal extent of all land ice and the annual motion of large glaciers. The image data will be archived at EDC, and derived products related to glaciers curated by NSIDC. The data acquisition required for 3 to 5 image attempts each year for the periphery of Greenland and Antarctica, and all other land ice, has been considered in the design of ASTER and in its mission planning and data-processing requirements; the GLIMS data requirements represent less than 1% of the total ASTER capability. The GLIMS concept includes involvement of "Regional Centers" with expertise on the typical weather/climate and specific glacier conditions of each area; the overall activity would be coordinated by the USGS. The GLIMS data base will be cross-indexed to World Glacier Monitoring Service (WGMS), which maintains an archive of scalar data for ~100,000 glaciers.

The GLIMS concept is distinctly different than, and complementary to, detailed observations on a small number of "benchmark" glaciers. It also complements the comprehensive overview of the Earth's glaciers from 1970's Landsat MSS images that are discussed in U.S. Geological Survey Professional Paper 1386 A-K, Satellite Image Atlas of Glaciers of the World.

Glacier Monitoring Using Classified National Systems

by
Edward G. Josberger
U.S. Geological Survey

Abstract

In 1992, the United States government established a program to evaluate the utility of classified U.S. remote sensing capabilities for addressing environmental issues. These sensors provide unique capabilities such as global coverage, high resolution, timely revisits, along with a four decade long archive of observations. Under this program, there are on going efforts to evaluate the capability of classified national systems for obtaining fundamental glacier observations, such as extent, surface velocities, firn-line position, and volume change. Robert A. Bindschadler, a glaciologist with NASA's Goddard Space Flight Center and a member of the Environmental Task Force (ETF), conceived of a glacier mass-balance feasibility study using data from classified systems and, with the author, is leading a joint MEDEA/USGS Project to critically assess the value of classified data sources to support glaciological investigations. Preliminary results indicate that classified systems can provide information not presently attainable from civil systems.

Although the imagery used in these studies remains classified at the present time, a process has been established for the generation and release of imagery derived products (IDP'S)—unclassified information derived from classified systems. A policy signed in October 1996 allows for the generation and distribution of unclassified information from classified systems. The process for declassifying products is still young, the number of products being approved for release is increasing and expected to become even greater. The USGS glacier program will significantly benefit from this capability through the generation of: (1) terminus-movement maps; (2) flow-rate measurements; (3) firn- line maps; and (4) high resolution glacier digital elevation models for volumetric change determinations.

A program is also being established for obtaining and archiving classified imagery to create a legacy of high quality imagery for the future. Under this program, imagery will be collected at appropriate intervals at a number of environmentally significant sites (termed fiducials) worldwide and archived at the Advanced Systems Center in Reston, VA. Civil agency users with the necessary clearances will have immediate access to the data as it is collected. The USGS has already recommended a number of glacier sites to be included in this program.

Classified systems can play an important role in the future monitoring of glaciers. The fiducials program is a first step in ensuring that a quality record of glacier imagery is available. With the approval of the derived-products policy, all federal agency personnel, with or without clearances can utilize information from classified systems. It is important that any long-term plans for glacier monitoring take advantage of the information provided by these systems.

An Overview of LightSAR; A Proposed Radar Satellite

by
James W. Schoonmaker, Jr., USGS

Abstract

The use of radar to map temperate glaciers and monitor their changing conditions has some advantages over traditional aerial photographs (Schoonmaker et al., 1989). Radar, being an active sensor in the microwave part of the electromagnetic spectrum, is capable of day or night imaging in almost all weather conditions. Radar, especially synthetic aperture radar (SAR), can also be used as a complementary data source with photography and multispectral imagery (Montgomery, 1996).

In August 1996, the National Aeronautics and Space Administration (NASA) held a workshop at the EROS Data Center (EDC), Sioux Falls, SD, on a proposed synthetic aperture radar satellite designed by the Jet Propulsion Laboratory (JPL) and dubbed LightSAR. Due to the possible applicability of LightSAR data to glaciology, a brief overview of the system was presented. Briefing materials were obtained from JPL's handout (Anon., 1996).

LightSAR as proposed will build upon experience gained from previous radar satellites: Seasat, ERS-1, JERS-1, SIR-C, and Radarsat. It will be low cost with a planned launch in September 1999 for a 3 year mission. The payload will be L-band synthetic aperture radar, multi-resolution/swath, multi-polarization, repeat path interferometry (stereo). Resolution will vary with swath; from spotlight (3 m, 15x20 km) to broad scan (100 m, 280 km). Orbit characteristics are: sun synchronous, near polar, 600 km, 10 day repeat cycle, with near global coverage (small gap around poles only).

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Monitoring of Glaciers: The NASA Pathfinder Program

by
David A. Kirtland, USGS

Abstract

The recent IPCC report discussion of the cryosphere noted medium confidence among experts in the belief that as much as one quarter of the world's mountain glacier mass would disappear if climate projections for 2050 were realized. Current trends show little change in some mountain glaciers and significant change in others. The report goes on to describe possible impacts associated with this and other cryosphere-related changes to include changes in seasonal water availability, altered landscapes, and changes in carbon dioxide and methane released to the atmosphere. Internationally coordinated glacier monitoring has been going on for over a century, and during the last several decades satellites have greatly improved monitoring capabilities (Fitzharris, 1996). To improve confidence in the understanding of the dynamic nature of glaciers and the impacts of changes in them, the NASA Pathfinder Program is using existing satellite-based data sets to study global change. Scientists studying glaciers have been directly involved in the levels and types of processing and end-to-end management needed to generate consistent products from satellite data for the user community. Examples of Pathfinder data sets include those generated by the Advanced Very High Resolution Radiometer (AVHRR) aboard NOAA weather satellites and the Thematic Mapper (TM) and Multispectral Scanner (MSS) instruments carried on the Landsat series of satellites. Data gathered by several instruments planned for the Earth Observing System component of Mission to Planet Earth in addition to synthetic aperture radar (SAR) data can also be used to monitor glaciers. Careful reprocessing of existing data from these instruments is paramount to ensure the greatest accuracy possible for comparison of changes in glaciers over time. Landsat images have been used to measure ice flow rates, as well as glacier advance and retreat. SAR data enables monitoring unencumbered by cloud cover and solar illumination conditions. Understanding the spatial and temporal variations in the responses of glaciers to changes in climate is critical to understanding their sensitivity to climate. The advantages of using remote sensing technology to monitor glaciers are evident in the ability to monitor hard-to-access or inaccessible glaciers and the ability to expand the spatial and temporal coverage required to compile sufficient empirical evidence of glacier dynamics. Data sets documenting these changes are valuable to climate modelers and researchers investigating the consequences of global change.

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Measurement of Changes in the Area and Volume of the Earth's Large Glaciers with Satellite Sensors

by
Richard S. Williams, Jr., USGS,
James B. Garvin, NASA, Goddard Space Flight Center
Oddur Sigurðsson, National Energy Authority (Iceland)
Dorothy K. Hall, NASA, Goddard Space Flight Center
Jane G. Ferrigno, USGS

Abstract

The global observation and measurement of changes in glaciers has been the long-term goal of glaciologists. Although several selected small glaciers have been surveyed and monitored for long periods, more than 100 years in the case of termini fluctuations and more than 50 years in the case of mass-balance measurements, most of the world's glaciers, large and small, have never been studied scientifically. Satellite remote-sensing technology has become an increasingly important tool to glaciologists in the measurement of changes in the areal extent of the Earth's large glaciers (e.g., Antarctic ice sheet, Greenland ice sheet, ice caps, and ice fields) on a global basis (Williams, 1986a; Williams and Ferrigno, 1994). Techniques have also been developed to measure changes in surface topography with radar altimeters (Zwally and others, 1983; Bindschadler and others, 1989) and with laser altimeters (Garvin and Williams, 1993; Krabill and others, 1995a,b; Thomas and others, 1995, Garvin and others, in press) and to determine volumetric change of glaciers. The Antarctic and Greenland ice sheets make up an estimated 99.3 percent of the volume of glacier ice on the planet, and ice caps and ice fields make up most of the remaining volume. Satellite remote-sensing technology represents the only feasible way of measuring and monitoring changes in the area and volume of these large ice masses (Williams, 1985; Williams and others, 1995; Williams and Hall, 1993, in press) .

Calculation of change in area for a large glacier can be accomplished from maps, vertical aerial photographs, and satellite images (Williams, 1986b; Williams, 1987; Hall and others, 1992; Williams and others, 1997). Calculation of change in volume for a large glacier can also be accomplished, if the elevation of the surface can be determined at two time periods. Haakensen (1986) compared sequential maps of two Norwegian glaciers, Hellstugubreen and Gråsubreen, that were compiled by stereophotogrammetric methods, to calculate changes in area and in volume and compare the volumetric changes to ground-based mass-balance measurements. With either airborne (Garvin and Williams, 1993; Garvin and others, in press) or satellite laser altimetry, the surface elevation of a large glacier can be determined from a series of profiles. If the profile grid spacing is sufficient to accurately represent the surface then calculations of elevation changes can be made at the same network of grid points.

The development and deployment of satellite-borne laser altimeters will soon provide glaciologists with a tool to accurately measure (± 1 m) the topographic surface of large ice

masses and, more importantly, permit the calculation of changes in surface elevation and surface configuration of large glaciers over time. For example, the January 1996 Space Shuttle Mission (STS-72) carried a Shuttle Laser Altimeter (SLA) instrument into Earth orbit (SLA-01 experiment) for meter-precision measurements of the Earth's surface topography and structure between 28.45° north and south latitudes. Vertical accuracy of these data is ~1 m, and 1 m RMS-quality data were achieved across the surface of the Red Sea and Lake Chad. An August 1997 Space Shuttle Mission (STS-85) carried an SLA instrument into Earth orbit (SLA-02 experiment) for meter-precision measurements of the Earth's surface between about 57° north and south latitudes. The orbital inclination of STS-85 passed over all of the Southern Hemisphere except for Antarctica and the Sub-Antarctic islands. Of particular glaciological interest in South America are its two largest glaciers, the Northern and Southern Patagonian Ice Fields situated in the southern part of the Andes Mountains on the border between Chile and Argentina. Future studies, including glaciological investigations, will utilize extensively laser data that is acquired from space on a repetitive and systematic basis.

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III.
INTERNATIONAL DATA CENTERS FOR ARCHIVING GROUND, AIRBORNE, AND SATELLITE DATA OF GLACIERS

Data Management for Long-Term Monitoring of Fluctuations of Glaciers of North America and Northwestern Europe

by

Greg Scharfen, National Snow and Ice Data Center/World Data Center-A for Glaciology
John L. Dwyer, Earth Resources Observations System (EROS) Data Center
Stephan Suter, World Glacier Monitoring Service/Swiss Federal Institute of Technology

Data management support for glacier-related data varies depending on the sponsoring agency and government. Principal data centers represented at this workshop that provide services to the international community are the National Snow and Ice Data Center/World Data Center-A for Glaciology (NSIDC/WDC-A), the Earth Resources Observations System (EROS) Data Center (EDC) and the World Glacier Monitoring Service (WGMS).

NSIDC/WDC-A supports the glaciological community with a variety of data management activities. These include: an extensive bibliographic collection of reports, reprints and periodicals; a microfilm copy and computer index of the USGS glacier photo collection to 1982; the American Geographical Society collection of approximately 10,000 glacier photos; a World Wide Web-based inventory of glacier information (This includes entries for more than 34,000 glaciers from the Former Soviet Union and China, each with up to 28 variables). Cooperative efforts with the WGMS are resulting in expansion of the inventory to include glaciers from New Zealand, the Alps, Norway and West Greenland); and the NSF-funded Arctic System Science (ARCSS) Data Coordination Center at NSIDC (including the archival of the Greenland Ice Sheet Program 2 (GISP2) data). Research activities include a Global Glacier Mass Balance Synthesis and a study of West Antarctic Ice Streams using various remote sensing data.

NSIDC is one of several NASA Earth Observation System Data and Information System (EOSDIS) Distributed Active Archives Centers (DAACs). The NSIDC DAAC is responsible for higher level cryospheric and polar products from the Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Microwave Scanning Radiometer (AMSR) and the Geoscience Laser Altimetry System (GLAS). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) will provide a global source of well calibrated, high resolution data for glaciological studies using visible, near infrared and thermal infrared data. The derivation of glaciological information from ASTER data is being coordinated by the USGS in Flagstaff, AZ, and is called Glacier Land Ice Monitoring System (GLIMS). NSIDC is participating in this cooperative effort with regional partners to assemble an extensive collection of ASTER images and to conduct regular surveys of representative glaciers using these images. NSIDC is planning to be the EOSDIS node for access to the derived glaciological data from GLIMS.

EDC has responsibility for the archive, management, and distribution of numerous collections of aerial photography, digital geospatial data, and airborne and spaceborne remotely sensed data, the latter of which comprises the National Satellite Land Remote Sensing Data Archive (NSLRSDA) that resides at EDC. The USGS data at EDC that are relevant to the glaciological research community include: black & white, color, and color-infrared aerial photography; Landsat multispectral scanner (MSS) and thematic mapper (TM) data; NOAA Advanced Very High Resolution Radiometer (AVHRR) data; digital elevation models (DEMs); and digital line graph (DLG) base cartographic data.

EDC supports NASA EOSDIS as the Land Processes DAAC. As part of the EDC EOSDIS Version 0 activities, numerous data sets have been acquired, processed, and archived for distribution in support of current global change research. These data include: Landsat Pathfinder data sets; NASA aircraft scanner data (NS001, thematic mapper simulator, and thermal infrared multispectral scanner); Shuttle Imaging Radar-C (SIR-C); and 1 km global digital elevation model data. The EDC DAAC will be responsible for the processing, archiving, and distribution of selected higher level data products from the MODIS and ASTER instruments (including ASTER data used in GLIMS analyses). The EDC will also have the primary U.S. responsibility for the reception, processing, archive, and distribution of Landsat 7 enhanced thematic mapper (ETM+) data.

The WGMS maintains glacier inventory data (spatial distribution of world surface ice), and glacier fluctuation data (changes in time of glacier parameters like mass balance, length changes, area/volume changes, ELA, AAR, etc.). Inventory data currently exist from 36 countries and about 70,000 glaciers; fluctuation data is archived from 33 countries and about 1,550 glaciers, including "high quality" mass-balance data from 58 glaciers in North and South America, Europe, Africa, and Asia. More information on types and availability of data are given in Appendices 8 and 9.

Other data centers important to the glaciological community include the National Hydrology Research Institute in Saskatoon, Canada, the Geophysical Institute's GeoData Center at the University of Alaska, Fairbanks, (see list attached to Trabant, and others, summary on Alaska on p. 35 of this report) and the Arctic and Antarctic Data Center in St. Petersburg, Russia.

NSIDC/WDC-A, EDC and the WGMS have the capability or are developing systems to support data archive and distribution, coordination of metadata, referral services, a user interface, and scientific stewardship of data sets. Increasingly, these centers coordinate their activities to provide a common basis for user services, cross-referral of information, and submission of metadata to international data dictionaries such as the Global Change Master Directory (GCMD), the Arctic Environmental Data Directory (AEDD) and the Antarctic Data Directory (ADD).

We encourage individual scientists to become familiar and utilize the services at these facilities and to coordinate published results and documented data sets with them. We also recommend the identification of other organizations and individuals responsible for glacier-related information in each country.

The World Glacier Monitoring Service

by
Wilfried Haeberli, University of Zürich-Irchel, and Martin Hoelzle and Stephan Suter,
Swiss Federal Institute of Technology, Zürich

Abstract

Since the beginning of internationally-coordinated, systematic observations on glacier variations in 1894, a valuable and increasingly important data basis on glacier changes has been built up. In 1986, the World Glacier Monitoring Service (WGMS) started to maintain and continue the collection of information on ongoing glacier changes, when the two former International Commission on Snow and Ice (ICSI) services Permanent Service on Fluctuations of Glaciers (PSFG) and Temporal Technical Secretary/World Glacier Inventory (TTS/WGI) were combined.

As a contribution to the Global Environment Monitoring System Global Terrestrial Observing System (GEMS/GTOS) of the United Nations Environment Programme (UNEP) and to the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organisation (UNESCO), the WGMS of the ICSI International Association of the Hydrological Sciences (IAHS) and the Federation of Astronomical and Geophysical Data Analysis Services (FAGS)/International Commission on Snow and Ice (ICSU) today collects and publishes worldwide standardized glacier data. At present, the WGMS gets important financial and logistic support from the University of Zürich and the Swiss Federal Institute of Technology, Zürich. The tasks of the WGMS are to continuously upgrade, collect and periodically publish glacier inventory and fluctuation data, as well as to include satellite observations of remote glaciers and to assess ongoing changes. The WGMS database stores two types of data: The World Glacier Inventory (WGI) contains glacier data describing the spatial variability, and the Fluctuations of Glaciers (FoG) contains data documenting changes over time. These data are stored at the ETH on the database system 'Oracle', which allows fast and selective data access. Glacier inventory data are an excellent tool in detecting regional climate-change effects. By applying a parameterization scheme on basic glacier inventory data, it is possible to assess and simulate regional aspects of past and future climate changes. Such a scheme was successfully applied to the European Alps. Long-term mass balance measurements for selected glaciers are a valuable regional climate signal and help with understanding the processes of energy- and mass exchange at the glacier-atmosphere interface. As only a few glaciers can be observed in detail, it is necessary to extend mass-balance information in space. Over time spans which match or exceed the characteristic dynamic response time it is possible to assess mass-balance information using glacier-termini changes. With this method not only secular mass-balance evolutions can be analysed but also information during the whole Holocene glacier-climate history be gained, which is certainly a key issue with respect to the present global-change discussion.

In a time with limited funding possibilities and observation networks being under increasing pressure, cost-saving technologies for long-term glacier observations must be developed and applied. Aerial photogrammetric and satellite imaging and laser-altimeter techniques must become more widely applied to observe glacier length, area changes, and changes in surface elevation at a global scale. It is of fundamental importance to maintain the current mass-balance programmes for assessing the representativity of results from remote sensing and modelling in view of potential acceleration of atmospheric warming.

A recently completed report from a WGMS Review Panel to the ICSI bureau recognizes the importance of a WGMS to the scientific community and notes a 'considerable interest'. The WGMS is expanding its efforts to serve the user community in getting high quality and easy accessible data. This will happen through data exchange with the World Data Center A for Glaciology (WDC-A) and the Global Resources Information Database (GRID) of GEMS as well as the WWW homepage, where the user will have the opportunity to directly access the database of the WGMS (http://www.geo.unizh.ch/wgms). An ICSI working group was established to help improve the funding for WGMS.

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IV.
MONITORING OF VARIOUS GLACIERS IN NORTH AMERICA AND NORTHWESTERN EUROPE: MISCELLANEOUS CONTRIBUTIONS

Determination of Changes in the Volume of Mountain Glaciers Using Airborne Laser Altimetry

by
Keith Echelmeyer, William D. Harrison, Joseph J. Sapiano, Guðfinna Aðalgeirsdóttir, Laurence Sombardier, Bernard T. Rabus, and Jeannette (DeMallie) Gorda
University of Alaska-Geophysical Institute

The changing volume of mountain glaciers in Alaska, Canada and the northwestern United States is believed to provide a significant contribution to the ongoing rise in sea level, and it is also a quality indicator of climatic change. In order to measure these changes, we have developed a compact, lightweight and relatively inexpensive laser profiling system which can be mounted in small aircraft capable of operating in mountain valleys. The system consists of a laser ranger for measuring the height of the aircraft above the glacier surface, a vertical axis gyroscope for determining the pointing direction of the laser, and Global Positioning System (GPS) receivers operated in kinematic mode for determining the position of the aircraft. Surface elevation profiles resulting from this system are accurate to about 0.3 m over a wide variety of surfaces and surface slopes (Echelmeyer and others, 1996).

Volume changes over decadal time scales can be obtained by comparison of these surface profiles with existing maps, while recent changes over shorter time scales can be obtained by repeat laser profiling. The accuracy of the longer-time scale volume changes is limited by the accuracy of the existing maps, which is on the order of 5 to 10 m.

Over the past 5 years we have profiled over 60 glaciers in Alaska, Canada and Washington. The broad spectrum of glaciers which we have profiled cover most of the climatic zones where glaciers occur in western North America, and cover many different sizes and types of mountain glaciers. They include small glaciers in the Brooks Range of arctic Alaska, which are very sensitive to the amplified climatic changes predicted in the Arctic; small glaciers in western Alaska, which are indicators of climatic change in the Bering Sea region; large glaciers along the Gulf of Alaska, which are thought to be major contributors to sea level rise; surging glaciers before and during surge; both terrestrial and tidewater glaciers along the coast of Alaska and British Columbia; and the smaller glaciers in the Cascades and Olympic Mountains of Washington.

Preliminary results show that regional trends in mass balance are complex, but most glaciers studied have undergone a loss of mass since the 1950's. It is interesting to note that not all termini have retreated over the same period.

Echelmeyer, K.A., Harrison, W.D., Larsen, C.F., Sapiano, J., Mitchell, J.E., DeMallie, J., Rabus, B., Aðalgeirsdóttir, G., and Sombardier, L., 1996, Airborne surface profiling of glaciers: a case-study in Alaska: Journal of Glaciology, v. 42, no. 142, p. 538–547.

The Mass of McCall Glacier. Its Regional Relevance and Climatological Implications for Climate Change in the Arctic

by
Bernard T. Rabus and Keith Echelmeyer
University of Alaska-Geophysical Institute

McCall Glacier has the only long-term mass balance record in Arctic Alaska. Mean annual balances over the periods 1958–71 and 1972–93 were -0.13 m and -0.33 m respectively; recent annual balances (1992–95) are around -0.6 m. For an arctic glacier with low mass exchange rate this marks a dramatically negative trend. Elevation profiles and terminus outlines, recently acquired with airborne and ground-based GPS methods on McCall and ten other glaciers of various sizes and aspects within a 30 km radius, were compared with topographic maps made several decades earlier. Comparison of the elevation changes of McCall and the other glaciers from 1956 to present show no major differences in the common parts of their elevation ranges. During this time span most glaciers have cumulative balances between -10 and -13 m (McCall: -12m). This indicates that McCall Glacier is representative for the region. Contrary to the cumulative balances which are similar for the different glaciers, the changes in terminus position vary markedly. This complicated regional pattern is dominated by effects of glacier geometry and flow dynamics in the terminus region. To estimate mass balance disturbances from fractional length changes is not possible in this area.

To show that the mass balance of McCall Glacier detects climate change on a larger synoptic scale we show results from a simple two parameter degree day/accumulation model. The model uses radiosonde temperature and ground precipitation data from coastal weather stations at Barrow (Alaska) or Inuvik (Canada) as input and is calibrated with a subset of the known annual mass balances of McCall Glacier. Positive degree days and accumulation calculated by the model show significantly different trends for Barrow and Inuvik; Inuvik data reproduce all measured annual mass balances of McCall Glacier within a 20% error band and also quantitatively reproduce the long-term trend towards negative balances. Barrow data on the other hand fail to reproduce either annual balances or the long term trend within reasonable error. Contrary to measurements, balances modeled from Barrow data are generally too negative except for a short period of positive balances in the 1970's. For their limited time range, 1948 to 1989, Kaktovik (Alaska) data gave results similar to those obtained with the Inuvik data. We speculate that the average location of the Arctic front in summer which separates Inuvik, Kaktovik and McCall Glacier from Barrow creates distinct climatic regions with non-identical climate change scenarios that explain the observed differences in modeled degree days and accumulation.

Given our results, we conclude that McCall Glacier is representative of a synoptic scale region and its mass balance record is an important measure of ongoing climate change in the Arctic.

Remote Sensing of Glacier Fluctuations Using Landsat Data: Lessons Learned

by
John L. Dwyer
Hughes STX Corp.[1], EROS Data Center, Sioux Falls, SD 57198

Abstract

Ten Landsat multispectral scanner (MSS) and thematic mapper (TM) images acquired between 1978 and 1991 were analyzed to map the positions of more than 75 ice fronts for tidewater and land-terminating glaciers in East Greenland. The images had different internal geometric characteristics due to variations among the individual satellite orbital geometrics and the types of processing applied by the satellite ground receiving stations. The images were coregistered to a single Landsat TM reference scene with a 30 meter by 30 meter pixel resolution, and error budgets associated with image registration were formulated. Scenes were individually contrast enhanced as false-color composites and integrated into a geographic information system (GIS). Softcopy digitizing tools within the GIS were used to compile maps of glacier basins and time-step overlays of ice front positions from which planimetric areal changes to glacier extents were calculated. The changes to glacier extent were then quantified to include uncertainties attributable to misregistration errors. Automated image cross-correlation techniques were applied to two Landsat TM images acquired in July and September of 1989 to derive surface velocity estimates for nine large glaciers in the study area.

The delineation and quantification of changes to land-terminating glacier extents were significantly compromised by the inability to consistently identify the boundary of ice fronts mantled with debris The spatial resolution of the images further precluded interpretation of surface morphological variations in the glacier terminus areas that might otherwise have aided inferences of the ice front positions. The lack of sufficient radiometric calibration data specific to the satellite sensors and ground processing systems also precluded attempts to spectrally discriminate changes in surface reflectance at the ice-moraine contacts. The contrast between highly reflective ice-snow and dark sediment often contributed to "memory effects" in the spectral response at the satellite sensors such that the discrimination of surface reflectance variations were "blurred". Increases in the extent of ice-snow cover were more readily discernible than states of regression or stagnation.

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Glacier Recession and Ecological Implications at Glacier National Park, Montana

by
Carl H. Key, Starr Johnson, and Daniel B. Fagre, USGS/Biological Resources Division
Richard K. Menicke, National Park Service

Glacier National Park contains 37 named glaciers that currently exist in various cirque, niche, ice apron, group and remnant forms. Thorough glacier surveys began with mapping the first USGS 30-minute quadrangles (1904-1914), and the work of Alden (1914). Only two glaciers, Sperry and Grinnell, have repeated assessment of surface profiles and movement to potentially reconstruct a history of mass balance (Johnson 1980). An additional nine glaciers have been mapped for terminus positions at varying intervals, extending back to the mid-1800's (Carrara and McGimsey 1981, 1988). Evidence for a general, regional recession is not new, but was recognized early this century (Dyson 1940). What is now known as the Little Ice Age (LIA) culminated here during the mid-19th century when Park glaciers were at their late-Neoglacial maxima (Carrara 1989). Since then, retreat has been consistent, with previous studies referencing conditions up to the late 1970's.

After nearly a 20-yr hiatus, we have begun to update the state of knowledge about glaciers of the region. Efforts to assemble and digitize historic maps and monitoring information proceed, adding new data to broaden spatial and temporal coverage. Work to digitize and assess 11 previously-mapped glaciers is complete, including delineation of 1993 perimeters on six of those. Recently digitized USGS 7.5-minute quadrangles exhibit about 83 ice and snow bodies larger than 10 ha (24.7 ac), at the time of aerial photography (1963-1966). This, the only comprehensive Park survey of perennial ice and snow to date, includes the named glaciers, separate pieces of former glaciers, and assorted patches (ice aprons, glacierets and snowfields) which may have not been true glaciers even during the LIA. The actual number of true glaciers (past and present), and the total extent of glacial recession since the LIA has yet to be determined empirically.

On six glaciers mapped from 1993 aerial photos, and two mapped through 1979, retreat from 1850 termini ranged from 818-1440 m and averaged 1244 m. Overall retreat rates varied between 6-17 m/yr. Those glaciers were reduced in area by 62-80%, for an average shrinkage to 27% of the estimated area in 1850. Retreat rates were not constant over time on any single glacier, but roughly correlated with warm-dry trends in climate. Agassiz and Jackson Glaciers, for example, lost between 3-117 m/yr through various periods from 1850-1979 (Carrara and McGimsey 1981). Pulses of recession occurred during the 1920's through the mid-1940's, and seem to be recurring now, as evidenced by change since 1979.

Of interest to ecosystem modeling and climate change research is how observed glacier changes might affect streams and surface characteristics across a mountain landscape. Using calculated retreat rates and the park-wide status of perennial ice and snow in 1966, regional conditions were projected for 1850 and 1993 on a drainage to drainage basis. Total area occupied by ice at the end of the LIA was estimated to be 99 km^2. Of 84 basins completely within the Park, 25 contained 1% or more perennial ice cover, and 19 contained 3% or more. Estimated quantities were reduced by 1993 to 26 km^2 total ice cover, 18 basins at 1% or more perennial ice, and only 4 basins with 3% or more. Decreased perennial ice within glacial basins, coupled with reduced number of glacial basins overall, likely reduced the moderating influence of glaciers on stream flow regimes throughout the year, and amplified biotically-stressful declines in run-off, particularly in late summer. On an ecosystem basis, such changes potentially represented significant alterations to lake and stream hydrology, and ultimately aquatic biota, in just the last 150 years.

Further work in the Glacier Park area is needed to complete regional assessment of glacial recession, and address climatological and ecological implications. Efforts continue to map the LIA maxima and the present status of glaciers throughout the park, and to build digital spatial models of recession. We hope to acquire new aerial photography in 1998. From guidelines for a comprehensive monitoring program (Fountain et al. 1997), a need exists for first-time, repeated mapping of accumulation and ablation zones to derive, if possible, time series of equilibrium line altitude and mass balance. Other primary field measurements are needed for monitoring at least one benchmark glacier. Also, stream gauging is needed to more precisely measure glacier contribution to hydrologic processes, which link in various ways to biological responses. Finally, future plans include development of new analytical approaches using satellite technologies to map margins and surface characteristics of small alpine glaciers.

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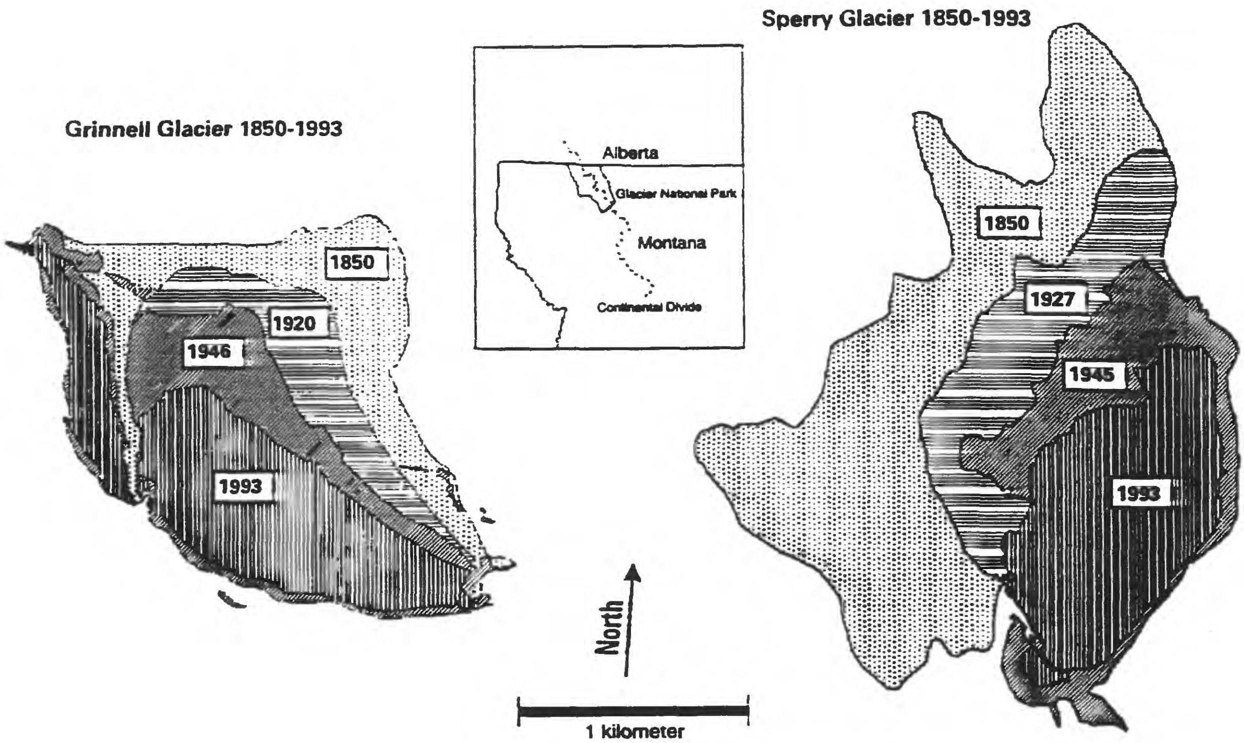
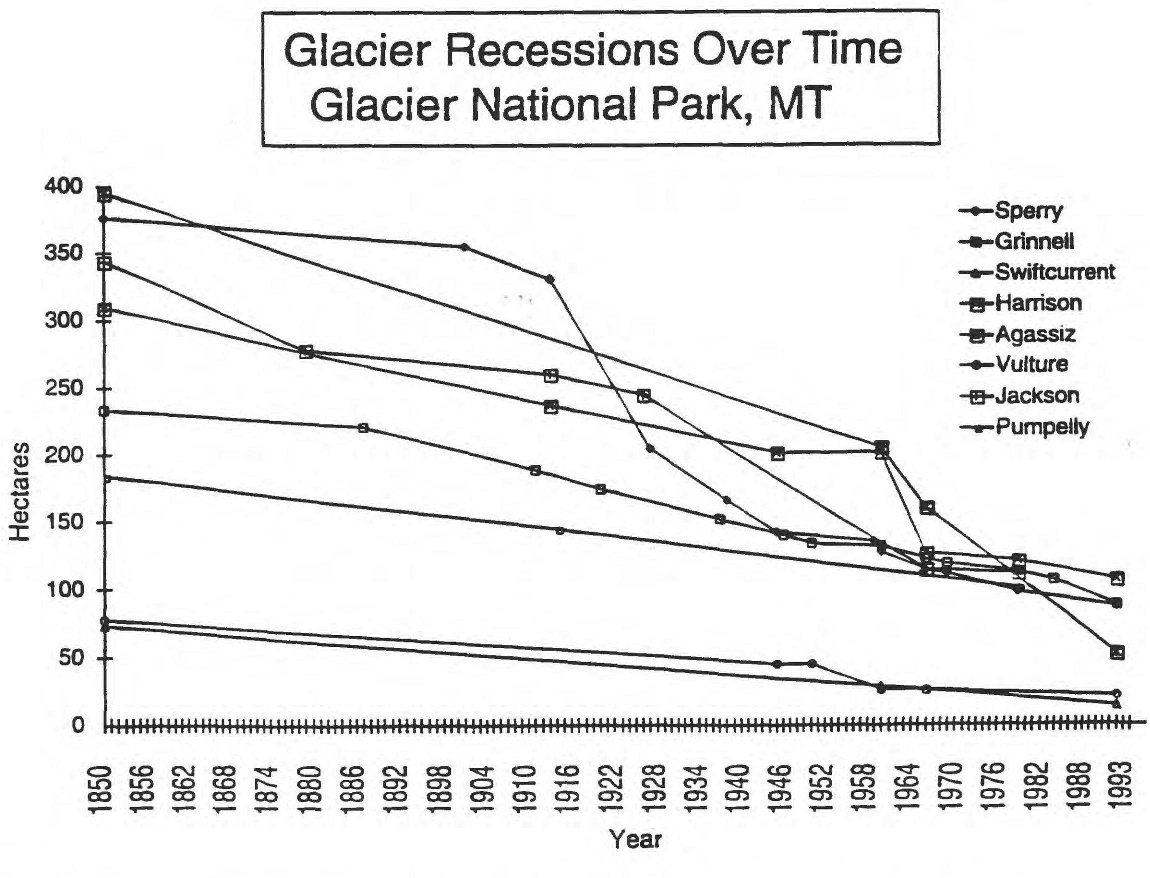
Following the Glacier Monitoring Workshop, Vice President Al Gore, having seen some of our figures in climate change documents, expressed a personal interest in learning more about the glacier research being conducted at Glacier National Park. On 9/2/97 the Vice President visited for a hike to Grinnell Glacier, accompanied by Montana Senator Max Baucus, former Congressman Pat Williams and the authors. Grinnell Glacier provided a dramatic setting in which to discuss climate change issues and the value of glacier investigations.





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Glacier Monitoring in Denali National Park and Preserve, Alaska: Integrating Field Study and Remote Sensing

by

James Roush and Phil Brease, National Park Service

The objective of glacier research in Denali National Park and Preserve is to develop a regional assessment and long-term monitoring program of glacier mass balance and flow. Glacier monitoring is carried out in Denali to meet the need for interpretation of Park resources, to support Park efforts at long-term ecological monitoring, and to fulfill the international responsibilities of Denali as a Biosphere Reserve. The latter requirement pertains specifically to the need to monitor indicators of global climate change. Glaciers may be among the most sensitive of Park resources to long-term trends in climatic conditions. Monitoring glacier mass balance and the resulting variations in geometry and flow may provide Denali with a measure of climate changes and their magnitude in south-central and interior Alaska. In this way, Denali may provide useful data on climatic trends which will be of interest to the international scientific community, and which will also meet the needs of the National Park Service.

Denali's glacier-monitoring program is currently under development. It is recognized that a major challenge to the goal of glacier assessment and monitoring on a regional (Park-wide) scale is the practical difficulty of glacier field study. In order to address this challenge, a variable scale study design is being implemented which will minimize difficult and costly field work by relying on remote sensing for regional assessments and long-term monitoring. Under this design, only one benchmark glacier is selected for field monitoring in each major climatic region of the Park. These glaciers need to be representative of glaciers in their region, be clearly visible in remotely sensed imagery, and be practical for field study (in terms of size, setting, and accessibility). First, an initial regional inventory of glacier conditions would be made with remote sensing imagery (most likely satellite synthetic aperture radar). The results of that inventory would be used to select suitable index glaciers. Detailed field study of the index glaciers would then be used as ground-truth data for remote sensing studies of glaciers throughout the Park. Finally, the ground-truthed remote sensing imagery would be used for long term monitoring of glaciers on a Park-wide scale.

If successful, Denali's glacier-monitoring efforts will not only support NPS managers and interpreters, but will also provide valuable information for the scientific community at large on the effects of global climate change in Alaska. The results of our research will be shared with those outside the NPS by publication in professional journals and by archiving in the appropriate locations.

An Integrated Approach for Monitoring Changes at Bering Glacier, Alaska

by
Bruce F. Molnia, U.S. Geological Survey, Reston, VA 22092
Austin Post, U.S. Geological Survey (Retired), Vashon, WA. 98070

Abstract

Monitoring changes at Bering Glacier, Alaska has been accomplished through a multi- faceted approach involving the collection and analysis of a variety of remotely-sensed data, field measurements and observations, and the analysis of historical maps and reports, leading to the development of a geographic information system (GIS). Integrating the results from these individual approaches has produced a detailed understanding of the twentieth century history of Bering Glacier and a comprehensive picture of the 1993-95 surge of the glacier.

Introduction

Bering Glacier, located in coastal southcentral Alaska, is the largest and longest glacier in continental North America (Molnia and Post, 1995). During the twentieth century, as much as 12 km of terminus retreat, accompanied by several hundred meters of glacier thinning, and as many as six major surges have occurred. Documenting this complex sequence of events and monitoring the resulting changes has been possible through a multi-faceted approach involving the collection and analysis of a variety of remotely-sensed data; field measurements and observations; and the analysis of historical maps and reports, some more than 150 years old. Much of these data are being incorporated into a developing geographic information system (GIS).

Monitoring changes at Bering Glacier, or for that matter any glacier, requires establishment of a baseline(s) or other reference standard(s). Later observations are then compared to this baseline(s) or standard(s), resulting in the determination of quantity and rate of change. For Bering Glacier, this baseline is complex and dynamic, consisting of multiple baseline data sets. For example, the position and elevation of the glacier's terminus was known from field observations and mapping since the first half-decade of the twentieth century. Additionally, much information about the glacier's geography was previously known from the nineteenth century (Molnia and Post, 1995). These observations provide a baseline against which to measure twentieth century retreat and thinning. Later observations have provided details about changes in terminus position in the early 1920s, late 1930s, late 1940s, early and late 1950s, and virtually every year since 1960. Since August 1993, the start of terminus displacement in the latest surge of Bering Glacier, field and remote-sensing observations have been made almost monthly.

One of the first steps necessary to monitor and record changes at Bering Glacier was the compilation and construction of a complete map base of the Bering's eastern piedmont lobe.

The base map is being used for depicting the many identified locations of the glacier's terminus since 1900 and for plotting the locations and values of measured parameters. The map is based on U.S. Geological Survey topographic data (1904 - 1906, 1957, 1972), GPS measurements (1990 - 1995), and vertical aerial photography (1990 - 1995).

This map presently is the basis for "analogue" or paper monitoring and change detection. This map is also being used as the base map for the development of a digital Bering Glacier Geographic Information System (GIS) currently being developed jointly with the U.S. Bureau of Land Management (BLM), an agency of the U.S. Department of the Interior. The GIS is being formulated for the integration, display, manipulation, and storage of the various geographically located data and information available for Bering Glacier.

During the 1993 - 1995 surge, airborne remotely-sensed data were collected approximately every 30 - 60 days. Combined with the quantity and variety of all of the other data collected during the surge, this may be the best documented surge event of any glacier.

Bering Glacier Data

Airborne and spaceborne remotely-sensed data of Bering Glacier include:

- 1) more than 75 vertical and oblique aerial photographic data sets, containing about ten thousand photographs (1938 - present);
- 2) more than 50 multispectral scanner and thematic mapper Landsat images (1972 - 1992);
- 3) about 50 digital satellite, Shuttle, and airborne radar images (1978 - 1995); and
- 4) about 15 hours of airborne video (1989 - present).

Field observations and measurements include:

- 1) feature mapping (1974 - present);
- 2) time lapse photography from in-situ camera systems (1993 - 1996);
- 3) sequential photography from reoccupation of marked photo stations (1946 - present);
- 4) discharge measurements and flow information from telemetering stage recorders (1991 - 1995);
- 5)ice-penetrating radar surveys (1990 - 1993);
- 6) high resolution marine seismic reflection surveys of Vitus Lake, the glacier's ice marginal basin (1991 and 1993);
- 7) seismic refraction surveys of the glacier's outwash plain (1991 - 1993);
- 8) dendrochronological and tree coring studies (1976 - present);
- 9) monitoring of movement and erosion stakes at selected terminus sites (1993 - present);
- 10) precision location of features using differential GPS (1992 - 1995); and
- 11) water sampling for water chemistry and suspended sediment load, (1976 - 1980, 1993, 1995).

Historical data include:

- 1) eighteenth, nineteenth, and early twentieth century exploration maps, description of voyages, and reports of expeditions;
- 2) nineteenth century published maps and nautical charts; and
- 3) late nineteenth and early twentieth century geological reports; and
- 4) field photography obtained from 1897 and 1905.

Description of Bering Glacier Data

Aerial Photography -- More than 75 vertical and oblique aerial photographic data sets, containing more than ten thousand aerial photographs of Bering Glacier have been collected. These sets date from 1938 to May 1996 and include images ranging in size from 9 in by 9 in to 35 mm. As the USGS, using differential GPS, has precisely determined the location of more than 100 geographic features within the Bering Glacier study area, photographs containing these features, especially those collected vertically, can be geographically referenced and used for precise change measurement and for inclusion in the Bering Glacier GIS.

The earliest aerial photographs, made by Bradford Washburn in 1938, while exploring mountain climbing routes in the Chugach and Saint Elias Mountains, clearly depict terminus position, outwash plain configuration and location, marginal lake size and level, and recent surge history. Later aerial photographs provide data to continue to monitor changes in these parameters. Since about 1960, vertical and oblique photography has been collected almost annually by the USGS. They have been the source of much detailed information for continuation of monitoring changes.

Since May 1993, more than 20 oblique color and black-and-white aerial photographic sets and more than 10 vertical aerial photographic sets have been collected to document surge related changes.

Landsat Imagery -- more than 50 multispectral scanner (MSS) and thematic mapper (TM) Landsat images dating from 1972 - 1992 have been obtained. As each of these images covers about a 200 km by 200 km area, virtually all of Bering Glacier can be observed at many single points in time. These images are being used in both an analogue and digital manner to monitor changes in terminus position, changes in snow cover and ablation, sediment production and dispersal, surge displacement of medial moraine features, and changes in proglacial vegetation. As all of these Landsat images are geographically registered, they will be a vital component in the information base of the Bering Glacier GIS.

Spaceborne Synthetic Aperture Radar Data (SAR) -- Since 1992, about 50 digital satellite SAR images of Bering Glacier have been collected by the SAR sensor on the European Space Agency's ERS-1 satellite. These images, downloaded at the University of Alaska's SAR Facility (ASF) in Fairbanks, have been processed by USGS to monitor and determine rate and style of ice displacement during the 1993-94 phase of the latest surge, changes in terminus position, changes in snow cover and ablation, and sediment production and dispersal. Bering

Glacier was selected by the National Aeronautics and Space Agency (NASA) to be an ecological research site for 1994 and 1995 environmental missions of the Shuttle Imaging Radar (SIR-C)experiment. As a result, two additional radar data sets of parts of the terminus were obtained. Digital SAR data can be merged with other digital remotely sensed data and incorporated into the Bering Glacier GIS. Mapped derivative information can be scanned into the GIS as well.

Airborne Synthetic Aperature Radar Data --Two other side looking, airborne radar images (SLAR), high-resolution X-Band, SAR radar images, of Bering Glacier were collected by the USGS in 1986 and 1990. They have been used to monitor changes in terminus position, changes in snow cover and ablation, sediment production and dispersal, and iceberg production.

Airborne video -- about 15 hours of airborne video has been collected between 1989 and May 1996. This video, collected in VHS, S-VHS, and 8 mm formats, shows numerous surface features of the glacier from before, during, and after the latest surge. These data are useful as a supplement to the numerous photographic data sets.

Feature mapping -- Since 1974, field studies have been conducted to "ground truth" many geomorphic and geographic features that had been identified from aerial photography. This has included confirming the identification of and age of moraines, and the character of surface and outcrop sediment deposits.

Time lapse photography -- Time lapse photography from in-situ camera systems has been used since 1993 to monitor changes during the latest surge of the glacier. In 1994, as many as five cameras were deployed simultaneously. Cameras ranged from a single 16 mm movie camera which took one image every five minutes to several 35 mm cameras which took one image every 24 hours. The 16 mm film has been converted to video.

Sequential photography -- reoccupation of marked photo stations has yielded many pairs, triplets, and multiple-year sequential photo sets which are excellent for monitoring change. In 1995, the authors relocated and revisited photo stations originally established in 1946 by USGS geologist Don J. Miller. Comparison of the 1995 photographs with the 1946 photographs document 50 years of change at many ice-marginal locations north of the piedmont lobe.

Discharge measurements and stage information from telemetering recorders -- In 1991 and 1993, USGS hydrologists determined the discharge of the Seal River, the largest distributary of the Bering Glacier. In both instances, discharge was calculated using the cross-sectional area method. Beginning in 1994, recording stage gauges have been used to monitor surge related discharge fluctuations, with the data telemetered to Fairbanks, AK. Several flood events associated with the surge have been identified.

Ice-penetrating radar surveys -- In 1990 and again in 1993, USGS collected a total of more than 100 ice thickness measurements using ice-penetrating radar. These surveys have provided detailed information about the depth to the bedrock underlying the glacier and the thickness of the ice at the time of the survey. The location of each survey point was determined using GPS. Knowing the elevation of the bed permits calculation of changes in glacier thickness through time. This has permitted monitoring of total thickness changes during the period 1972 - 1991, a period of time in which the glacier thinned as much as 165 m (20%) (Molnia and Post, 1995).

High resolution marine seismic reflection surveys -- high resolution marine seismic reflection surveys of Vitus Lake, the glacier's ice marginal basin were conducted in 1991 and 1993 using GPS navigation. These surveys, which yielded profiles of more than 500 km of the basin, showed that much of the basin is more than 200 m below sea level and is filled with as much as 110 m of recent sediment. This information, combined with a knowledge of ice margin locations and the date of and sequence of glacier retreat permits detailed monitoring of sedimentation rates and volumes. Since much of the area that was profiled was subsequently covered by advancing ice in the 1993-95 surge, a baseline of pre-surge depth and sediment thickness information now exists for comparison with post-surge retreat measurements.

Seismic refraction surveys of the glacier's outwash plain -- Seismic refraction surveys of the glacier's outwash plain were performed from 1991 to 1993. These data determined the depth to bedrock underlying the glacier's forelands and the thickness of sediment. Based on these measurements, it was determined that the forelands overlie a deep basin which extends several hundred meters below sea level and which connects to a deep submarine trough in the Gulf of Alaska.

Dendrochronological, paleobotanical, and tree coring studies -- Studies conducted since 1976 have resulted in 32 14C dates obtained from peat, sub-fossil wood, and shell samples collected by the authors from the margins of the glacier. Additionally, a 1,200 year tree ring chronology, with "floating" calendar dates for some samples reaching nearly 2,000 years, augment the other glacier data. This information has resulted in dating of many exposed moraines. Additionally, monitoring of recently formed moraines permits an understanding of rates of and types of vegetation development. This information is useful for determining the sequence and age of many twentieth century moraines around the margin of Bering glacier.

Monitoring of movement and erosion stakes at selected terminus sites -- Beginning in 1993, lines of stakes were set out at about 20 locations around the surging margin of the glacier. These lines were checked on a daily to weekly cycle to monitor short term rates of terminus change. Results showed that the western margin of the glacier advanced more rapidly than the eastern and that maximum daily rates of advance on land were about 5 m per day. In July 1995, one group of stations was placed to monitor the amount and rate of shoreline bluff erosion and retreat associated with the advance of the glacier's southeast margin. Interpretation of the resulting measurements suggest bluff retreat rates approaching 1.5 m per day.

Precision determination of feature locations using differential GPS -- Between 1992 and 1995, more than 100 geographic features identifiable on USGS vertical photography were precisely located using differential GPS. Exact positioning of these locations permits detailed calculation of changes in many different types of features. Additionally, each of these features can be incorporated into the GIS base map.

Water sampling - Between 1976 and 1980, and again in 1992, 1994, and 1995, water samples were collected from Vitus Lake and the Seal River. These samples were used to monitor changes in the suspended sediment load of the lake and river and to determine the temperature and salinity of the lake. Data collected in 1992 indicated that the lake was actually a marine embayment with near-marine salinities. The subsequent surge flushed nearly all of this marine water from the basin and changed salinities to those of nearly fresh water.

Analysis of eighteenth, nineteenth and early-twentieth century exploration maps, description of voyages, and reports of expeditions, nineteenth century published maps and nautical charts, and late nineteenth and early twentieth century geological reports has provided a much longer term perspective on the glacier's post-Little Ice Age history than could be obtained from present day measurements. For instance, a description of the character of the glaciers surface from the late 1830s by Belcher (1843) suggests that the glacier was surging at the time of his observation. Similarly, field photography obtained by an 1897 climbing expedition and a 1905 geological field party clearly show the character and position of parts of the glacier's margin. All of these historical data are useful for understanding how the glacier has behaved in the past.

Summary

A variety of techniques have been used to monitoring changes at Bering Glacier, Alaska. Monitoring has been accomplished through a multi-faceted approach involving the collection and analysis of remotely-sensed data, field measurements and observations, and the analysis of historical maps and reports. Ultimately, these data will be incorporated into developing a geographic information system (GIS). Integrating the results from these individual approaches has produced a detailed understanding of the twentieth century history of Bering Glacier and a comprehensive picture of the 1993-95 surge of the glacier.

References

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Molnia, B.F. and Austin Post, 1995, Holocene History of the Bering Glacier, Alaska: A Prelude to the 1993-1994 Surge. Phys. Geogr., 16, 87-117.

V.
APPENDICES

1. Planned Agenda for Workshop on Long-Term Monitoring of Glaciers of North America and Northwestern Europe
2. List of Attendees
3. List of Invitees Who Were Unable to Attend
4. Selected Background Reading [Pre-Workshop]
5. Selected Reading [Post-Workshop]
6. Importance of Revitalization of the USGS Glaciology Program by Robert A. Bindschadler, NASA Goddard Space Flight Center
7. Review of Past, Present and Future Earth Observing Platforms (USGS Biological Resources Division)
8. Available data from the World Glacier Monitoring Service
9. How to get data from the World Glacier Monitoring Service
10. International Arctic Science Committee (IASC) Priority Projects

Planned Agenda for
Workshop on Long-Term Monitoring of Glaciers of North America and Northwestern Europe

University of Puget Sound
Student Union Building
Tacoma, Washington

11-13 September 1996

10 Sep 96 (Tues): Arrive in Tacoma, WA by non-local attendees
Overnight at Tacoma area hotel

11 Sep 96 (Wed): AM SESSION 1 - Existing Remote Sensing Data Bases and Current Status of Glacier Monitoring: State/Country Summaries

Time		Rapporteur
8:00 - 8:30	Introduction	Richard S. Williams, Jr./ Jane G. Ferrigno
8:30 - 9:00	Alaska	Dennis C. Trabant
9:00 - 9:30	Canada (Western)	Michael Demuth
9:30 - 10:00	Canada (Arctic)	Roy M. Koerner
10:00 - 10:30	Break - Coffee, etc.	
10:30 - 11:00	Conterminous U.S./Mexico	Robert M. Krimmel
11:00 - 11:30	Greenland	Anker Weidick
11:30 - Noon	Iceland	Oddur Sigurðsson
Noon - 12:30	Norway	Jon Ove Hagen
12:30 - 2:00	Lunch at the Student Union	

PM SESSION 2 - Glacier Monitoring:
Ground, Airborne, and Satellite - Topical Summaries

Time		Rapporteur
2:00 - 2:30	World Glacier Monitoring Service	Wilfried Haeberli
2:30 - 3:00	Historical Reconstruction of Glacier Fluctuation from Remote Sensing Data Sets	Bruce M. Molnia
3:00 - 3:30	Airborne and Satellite Altimetry	James M. Garvin
3:30 - 4:00	Break - Coffee, etc.	
4:00 - 4:30	Satellite Remote Sensing (Imaging)	Dorothy K. Hall
4:30 - 5:00	Airborne and Satellite Remote Sensing of Svalbard (Norway)	Julian H. Dowdeswell
5:00 - 5:30	Global Glacier Monitoring with EOS ASTER	Hugh H. Kieffer
5:30 - 6:00	Glacier Monitoring with Classified Data Sets	Edward G. Josberger
7:00	Cookout at Krimmel home on Vaushon Island, Puget Sound	

12 Sep 96 (Thurs): AM Session 3 - Selection of Representative Glaciers for Long-Term Ground, Airborne, and Satellite Monitoring

Time	Activity
8:30 - 10:00	Discussion groups by country on which glaciers of North America and northwestern Europe should be included in a "representative" set of glaciers for long-term monitoring led by state/country Rapporteurs
10:00 - 10:30	Break - Coffee, etc.
10:30 - 11:30	Series of 10-min. presentations by Rapporteurs for the selected "representative" glaciers for each geographic area
11:30 - 12:30	General discussion by Workshop attendees on the use of the World Wide Web site and e-mail connection for exchanging information on fluctuation of "representative" glaciers of North America and northwestern Europe
12:30 - 2:00	Lunch at Student Union

PM Session 4 -Draft of Final Workshop Report

Time	Activity
2:00 - 3:00	Rapporteurs and Workshop Coordinators meet to write final draft of Workshop report
3:00 - 3:30	Break - coffee, etc.
3:30 - 5:00	Continued work on final draft of Workshop report
7:00	Dinner at the Upper Room (local restaurant)

13 Sep 96 (Fri): Field Trip to Nisqually Glacier, Mount Rainier National Park, WA
Field Trip Leader: Carolyn L. Driedger

Time	
9:00 am -	Departure from Tacoma area hotel via bus
10:30 am -	Start of series of stops along Rt. 706 within the Park boundary: (1) Flood deposits along Tahoma Creek from jökulhlaups from South Tahoma Glacier discharge; (2) Flood deposits along Kautz Creek; (3) Termini of Nisqually Glacier from bridge over Nisqually River
Noon	Arrival at Visitor Center, Paradise
Noon -1:00	Hike up to Alta Vista and/or Panorama Point with box lunches
1:00 - 2:00	Lunch at Alta Vista or Panorama Point overlooking Nisqually Glacier
2:00 - 2:30	Return to Visitor Center
2:30 - 3:00	Visitor Center
3:00 - 5:00	Drive back to Tacoma Sheraton Hotel
Evening	Dinner (own Arrangements)

14 Sep 96 (Sat): Travel home from Tacoma, WA for non-local attendees or
Optional two-day post-Workshop Field Trip to Bering, Childs, Sheridan, Portage, and Exit Glaciers, Southeastern Alaska led by Bruce F. Molnia. The costs of the post-Workshop Alaska Field Trip will be assumed by the participant. The estimated cost of the Alaska Field Trip is $1,000 $\pm$ $200 depending on the number of participants.

Workshop on
Long-Term Monitoring of Fluctuations of Glaciers
of North America and Northwestern Europe

University of Puget Sound, Tacoma, WA on 11-13 September 1996

List of Attendees

Scientist	Specialty
Carl S. Benson Geophysical Institute University of Alaska Fairbanks Fairbanks, AK 99775-7320 Tel: 907-474-7450 Fax: 907-474-7290 e-mail: benson@gi.alaska.edu	glaciology, glacier/volcano interaction, glacier facies, Alaskan glaciers, Greenland ice sheet
Robert A. Bindschadler Code 971 (Oceans and Ice Branch) NASA-Goddard Space Flight Center Greenbelt, MD 20771 Tel: 301-286-7611 Fax: 301-286-0240 e-mail: bob@laural.gsfc.nasa.gov	glaciology, radar, altimetry, satellite remote sensing, Greenland and Antarctic ice sheets, leader WAIS Project
Phil Brease Denali National Park and Preserve National Park Service P.O. Box 9 Denali National Park, AK 99755 Tel: 907-683-9551 Fax: 907-683-9639 e-mail: phil_brease@nps.gov	naturalist/interpreter, glaciers of Denali National Park, AK
Michael Demuth National Hydrology Research Institute Environment Canada 11 Innovation Blvd. Saskatoon, Saskatchewan S7N 3H5 Canada Tel: 306-975-5754 Fax: 306-975-5143 e-mail: demuthm@nhrisv.nhrc.sk.doe.ca	glaciology, Canadian glaciers, (mass balance, fluctuations), radar geophysics, natural science

Julian A. Dowdeswell
Centre for Glaciology
Institute of Earth Studies
University of Wales
Aberystwyth, Dyfed SY23 3DB
Wales, U.K.
Tel: 011-44-1970-622782
Fax: 011-44-1970-622780
e-mail: jud@aber.ac.uk

glaciology, airborne and satellite remote sensing, radio echo-sounding, satellite radar interferometry, glaciological remote sensing of Svalbard

Carolyn L. Driedger
U.S. Geological Survey
Cascades Volcano Observatory
5400 MacArthur Blvd.
Vancouver, WA 98661
Tel: 360-696-7867
Fax: 360-696-7866
e-mail: driedger@usgs.gov

hydrology, glacier/volcano interaction, radio-echosounding, Cascades glaciers, glaciers of Mt. Rainier specialist

John L. Dwyer
U.S. Geological Survey
EROS Data Center
Sioux Falls, SD 57198
Tel: 605-594-6060
Fax: 605-594-6567
e-mail: spectra@edcserver1.cr.usgs.gov

glaciology, Greenland ice sheet, satellite remote sensing

Keith Echelmeyer
Geophysical Institute
University of Alaska Fairbanks
Fairbanks, AK 99775-7320
Tel: 907-474-7477
Fax: 907-474-7290
e-mail: kechel@gi.alaska.edu

glaciology, airborne remote sensing, airborne laser altimetry, ice physics, mass balance

Dan Fagre
U.S. Geological Survey/BRD
Science Center, Glacier National Park
W. Glacier, MT 59926
Tel: 406-888-7993
Fax: 406-888-7990
e-mail: dan_fagre@nbs.gov

global change, ecosystem modeling, glaciers of Glacier National Park, MT, Biological Resources Division

Jane G. Ferrigno*
U.S. Geological Survey
955 National Center
Reston, VA 20192
Tel: 703-648-6360
Fax: 703-648-6524
e-mail: jferrign@usgs.gov

glaciology, co-editor Satellite Image Atlas of Glaciers of the World, satellite glaciology , satellite remote sensing, global perspective, author, Chapter G, Glaciers of Iran (USGS Prof. Paper 1386-G) and co-author Chapter A, Introduction, and Chapter K, Monitoring and Understanding Past and Present Changes in the Cryosphere, global perspective

Andrew G. Fountain
Dept. of Geology
Portland State University
Portland, OR 97207-0751
Tel: 503-287-3515
Fax: 503-725-3025
e-mail: bjaf@odin.cc.pdx.edu
e-mail: andrew@usgs.gov

glaciology, U.S. glaciers, representative to International Commission on Snow and Ice and to AGU's Committee on Snow, Ice and Permafrost

James B. Garvin*
NASA
Goddard Space Flight Center
Code 921
Greenbelt, MD 20771
Tel: 301-286-6565
Fax: 301-286-1616
e-mail: garvin@denali.gsfc.nasa.gov

astrogeophysics, quantitative geomorphology, airborne and satellite remote sensing altimetry,geophysics, Cascade glaciers, Iceland glaciers, Jan Mayen glaciers, co-author, Chapter K (USGS Prof. Paper 1386-K)

Jon Ove Hagen
Department of Geography
University of Oslo
Box 1042 Blindern
N-0316 Oslo, Norway
Tel: 011-47-2285-4038
Fax: 011-47-2285-7230
e-mail: j.o.hagen@geografi.uio.no

glaciology, Chairman of the International Arctic Science Committee's Committee on Arctic Glaciology

Dorothy K. Hall*
NASA/Goddard Space Flight Center
(Hydrological Sciences Branch)
Code 974
Bldg. 22, Rm. C79B
Greenbelt, MD 20771
Tel: 301-286-6892
Fax: 301-286-1758
e-mail: dhall@glacier.gsfc.nasa.gov

glaciology, satellite remote sensing of ice and snow, imaging sensors, glaciers of Alaska, Austria, and Iceland, co-author, Chapter K (USGS Prof. Paper 1386-K)

Steven M. Hodge U.S. Geological Survey Resources Division Ice and Climate Project University of Puget Sound Tacoma, WA 98416 Tel: 253-593-6516 Fax: 253-383-7967 e-mail: smhodge@usgs.gov	glaciology, radio-echosounding, glacier-balance relationship, U.S. glaciers, Greenland Water and Antarctic ice sheets
Janet Hren U.S. Geological Survey Office of the Director 107 National Center Reston, Va 20192 Tel: 703-648-4480 Fax: 703-648-5470 e-mail: jhren@usgs.gov	Environment Theme Coordinator for USGS
Edward G. Josberger U.S. Geological Survey Water Resources Division Ice and Climate Project University of Puget Sound Tacoma, WA 98416 Tel: 253-593-6516 Fax: 253-383-7967 e-mail: ejosberg@usgs.gov	glaciology, oceanography, classified U.S. data sets, climate-glacier fluctuation relationships
Hugh H. Kieffer U.S. Geological Survey 2255 N. Gemini Dr. Flagstaff, AZ 86001 Tel: 520-556-7015 Fax: 520-556-7014 e-mail: hkieffer@flagmail.wr.usgs.gov	astrogeophysics, satellite remote sensing of glaciers, Team Member on EOS ASTER
Roy M. Koerner* Terrain Sciences Division Glaciology Section Geological Survey of Canada 601 Booth Street Ottawa, Ontario K1A 0E8 Canada Tel: 613-996-7623 Fax: 613-996-5448 e-mail: koerner@gsc.emr.ca koerner@nrcan.gc.ca	glaciology, Arctic ice caps, glacial geology, Canadian glaciers, co-author, Chapter J, Glaciers of Canada (USGS Prof. Paper 1386-J)

Robert M. Krimmel*
U.S. Geological Survey
Water Resources Division
Ice and Climate Project
University of Puget Sound
Tacoma, WA 98416
Tel: 253-593-6516
Fax: 253-383-7967
e-mail: rkrimmel@usgs.gov

glaciology, mass-balance studies of conterminous U.S. and Alaskan glaciers, annual aerial documentation of glacier fluctuation, co-author, Chapter J, Glaciers of Alaska (USGS Prof. Paper 1386-J)

Norm Malinas
Environmental Research Institute of Michigan
P.O. Box 134001 (1975 Green Rd., 48105-2554)
Ann Arbor, MI 48113-4001
Tel: 313-994-1200, Ext. 2593
Fax: 313-994-5824
e-mail: malinas@erim.org.

remote sensing, SAR applications, classified U.S. data sets

Nelly M. Mognard-Campbell
Centre National d'Etudes Spatiales
(CNES-CESBIO)
c/o U.S. Geological Survey
Ice and Climate Project
University of Puget Sound
Tacoma, WA 98416
Tel: 253-593-6516
Fax: 253-383-7967
e-mail: nmognard@usgs.gov

sea ice; glaciers; ERS SAR data; liaison with CNES (France)

Bruce F. Molnia*
U.S. Geological Survey
917 National Center
Reston, VA 20192
Tel: 703-648-4120
Fax: 703-648-4227
e-mail: bmolnia@usgs.gov

marine geology and geophysics, remote sensing, glacial geology, tidewater glaciers, Bering Glacier, Alaskan glaciers, co-author, Chapter J, Glaciers of Alaska (USGS Prof. Paper 1386-J)

Bruce H. Raup
U.S. Geological Survey
2255 North Gemini Drive
Flagstaff, AZ 86001
Tel: 520-556-7022
Fax: 520-556-7014
e-mail: braup@flagmail.wr.usgs.gov

glaciology, EOS ASTER team for global glacier monitoring

James Roush
Denali National Park and Preserve
National Park Service
P.O. Box 9
Denali National Park, AK 99755
Tel: 907-683-9514
Fax: 907-683-9639
e-mail: jamie_roush@nps.gov

glaciological remote sensing, Alaskan glaciers

Greg Scharfen
National Snow and Ice Data Center (NSIDC)
University of Colorado
Campus Box 449
(1540 30th Street, Bldg. RL2 - Rm. 201)
Boulder, CO 80309-0449
Tel: 303-492-6197
Fax: 303-492-2468
e-mail: scharfen@kryos.colorado.edu

glaciology (glaciers, snow, sea ice, permafrost), satellite data, glaciological data archive and distribution center, NSIDC DAAC

James W. Schoonmaker, Jr.
U.S. Geological Survey
521 National Center
Reston, VA 20192
Tel: 703-648-7848
Fax: 703-648-7873
e-mail: jwschoonmaker@usgs.gov

geodetic engineering, field surveys, Antarctic ice sheet, Alaska glaciers, classified data sets, remote sensing and digital image processing

Oddur Sigurðsson*
Orkustofnun
Grensásvegi 9
ÍS 108 Reykjavík
Ísland (Iceland)
Tel: 011-354-569-6036
Fax: 011-354-568-8896
e-mail: osig@os.is

glaciology, glaciers of Iceland, annual fluctuation (termini and mass-balance) measurements, co-author, Chapter D, Glaciers of Iceland (USGS Prof. Paper 1368-D)

Stephan Suter
Eidgenössische Technische Hochschule Zürich
Versuchsanstalt für Wasserbau
Hydrologie und Glaziologie
Gloriastrasse 37/39
ETH-Zentrum
CH-8092 Zürich
Schweiz (Switzerland)
Tel: 011-41-1-632 4123
Fax: 011-41-1-632-1192
e-mail: suter@ezvaw7.vmsmail.ethz.ch
e-mail: stsuter@geo.unizh.ch

glaciology, World Glacier Monitoring Service, glaciological data archive and distribution center

Dennis C. Trabant
U.S. Geological Survey
Glaciology Project Office
800 Yukon Drive
Fairbanks, AK 99775-5170
Tel: 907-479-5645
Fax: 907-456-0356
e-mail: dtrabant@usgs.gov

glaciology, glaciers of Alaska, mass-balance measurements

Anker Weidick*
GEUS
Danmarks og Grønlands Geologiske Undersøgelse
Thoravej 8
DK-2400 København NV
Danmark (Denmark)
Tel: 011-45-31-106600 (will be changed)
Fax: 011-45-31-196868
e-mail: none

glaciology, glacial and Quaternary geology, Greenland ice sheet, author, Chapter C, Greenland (USGS Prof. Paper 1386-C)

Richard S. Williams, Jr.*
U.S. Geological Survey
Woods Hole Field Center
Quissett Campus, 384 Woods Hole Rd.
Woods Hole, MA 02543-1598
Tel: 508-457-2347
Fax: 508-457-2310
e-mail: rswilliams@usgs.gov

glaciology, co-editor, Satellite Image Atlas of the World, satellite glaciology, satellite remote sensing, co-author, Chapter D, Glaciers of Iceland (USGS Prof. Paper 1386-D), Chapter A, Introduction, and Chapter K, Monitoring and Understanding Past and Present Changes in the Cryosphere), global perspective

*Author, Satellite Image Atlas of Glaciers of the World, U.S. Geological Survey Professional Paper 1386 A-K

Workshop on
Long-Term Monitoring of Fluctuations of Glaciers
of North America and Northwestern Europe

University of Puget Sound, Tacoma, WA on 11–13 September 1996

<u>List of Invitees Who Were Unable to Attend</u>

Scientist	Speciality
Stanley G. Coloff U.S. Geological Survey Biological Resources Division 301 National Center Reston, VA 20192 Tel: 703-648-4083 Fax: 703-648-4238 e-mail: stan_coloff@usgs.gov	ecology, population dynamics, global change coordinator for Biological Resources Division (vice NBS)
Wilfried Haeberli* Geographisches Institut Universität Zürich-Irchel Winterthurerstrasse 190 CH-8057 Zürich Schweiz (Switzerland) Tel: 011-41-1-635-5120 Fax: 011-41-1-635-6848 e-mail: haeberli@geo.unizh.ch	glaciology, Director, World Glacier Monitoring Service, glacier hazards in Switzerland, Italy, Argentina, global perspective, co-author, Chapter K (USGS Prof. Paper 1386-K)
David A. Kirtland U.S. Geological Survey 519 National Center Reston, VA 20192 Tel: 703-648-4712 Fax: 703-648-5542 e-mail: dakirtland@usgs.gov	geography, global environmental change, operations research, global change program coordinator for NMD
Harry F. Lins U.S. Geological Survey 415 National Center Reston, Va 20192 Tel: 703-648-5712 Fax: 703-648-5295 e-mail: hlins@usgs.gov	hydroclimatology, global change program coordinator for WRD

Mark F. Meier*
Institute of Arctic and Alpine Research
University of Colorado
Campus Box 450
Boulder, CO 80309-0450
Tel: 303-492-6556
Fax: 303-492-6388
e-mail: Mark.Meier@Colorado.EDU

glaciology, glaciers and sea level, glaciers and climate, global perspective, co-author Chapter K (USGS Prof. Paper 1386-K)

Gordon L. Nelson
U.S. Geological Survey
Water Resources Division
4230 University Drive, Suite 201
Anchorage, AK 99508-4664
Tel: 907-786-7711
Fax: 907-786-7150
e-mail: glnelson@usgs.gov

glaciology, Alaskan glaciers, WRD District Chief for Alaska

C. Simon L. Ommanney*
Secretary General
International Glaciological Society
Lensfield Road
Cambridge CB2 1ER
England, UK
Tel: 011-44-1223-355974
Fax: 011-44-1223-336543
e-mail: Int_Glaciol_Soc@compuserve.com

glaciology, geography, glaciers of Canada co-author, Chapter J, Glaciers of Canada (USGS Prof. Paper 1836-J)

Richard Z. Poore
U.S. Geological Survey
906 National Center
Reston, VA 20192
Tel: 703-648-5270
Fax: 703-648-6647
e-mail: rpoore@geochange.er.usgs.gov

paleoclimatology, paleoenvironmental change, global change program coordinator for GD

*Author, Satellite Image Atlas of Glaciers of the World, U.S. Geological Survey Professional Paper 1836 A-K.

Selected Background Reading
for
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of North America and Northwestern Europe

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Key, C.H., Fagare, D.B., and Menicke, R.K.,----, Glacier recession in Glacier National Park, Montana; section *in* Krimmel, R.M., Glaciers of the Western United States: *in* Williams, R.S., Jr., and Ferrigno, J.G., editors, Satellite image atlas of glaciers of the world, U.S. Geological Survey Professional Paper 1386–J (Glaciers of North America, in preparation).

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Importance of Revitalization of the USGS Glaciology Program

by
Robert A. Bindschadler, NASA Goddard Space Flight Center

Glaciology is directly related to at least three major national responsibilities of the USGS:

- Assessing the "frozen water" component of the nation's natural resources,
- Evaluating the hazards associated with glaciers, and
- Contributing to the U.S. Global Change Research Program.

It remains to be determined how much permanent ice exists within the US, but there are many hydrologic basins of the United States that contain significant amounts of glacier ice. If inadequate water-resource management is continued, the future of glaciers will have an increasingly important impact on the viability of these watershed areas and the people living in them. An assessment of the glacier-ice volumes in these areas is needed, along with predictions of how future climate conditions might affect their continuing capability to contribute to the water supply and for how long.

Quite separate from the issue of water-resource management, glacier ice presents a variety of hazards to citizens of this country. High on the list are glacier-dammed lakes that can produce sudden outburst floods (jökulhlaups) (such as Russell "Lake", that formed briefly by the damming of Russell Fiord by Hubbard Glacier); rapidly retreating tidewater glaciers that produce large volumes of icebergs, potentially endangering shipping traffic (such as occurred at Columbia Glacier); outbursts of englacially stored water generated by subglacier geothermal activity and/or meltwater (believed responsible for the deadly "lahars" which have occurred repeatedly in Mt. Rainier National Park); and jökulhlaups produced by subglacier volcanic activity in the Pacific Northwest and Alaska. These effects require knowledge of glacier dynamics to undertake and interpret field-, airborne-, and satellite- measurement programs that can determine the risks of these hazards to the U.S.

Finally, the extended time series of mass balances on "benchmark" glaciers (South Cascade, Gulkana, Wolverine) has enormous value in recording long-term changes in mountain climates. Continuation of this unique data set must remain in the Survey's mission, but to increase the value and relevance of the data set, it must be put in a regional and global context. The value of these records could be further enhanced by extending this climate/glacier-behavior data set by better utilization of past maps, USGS and other photographic archives, and past, present, and future remotely sensed data from aircraft and satellites.

Implementation Plan

The USGS presently has most of the tools and personnel to achieve major progress on meeting all of these objectives. What is lacking since the retirement of Mark F. Meier in 1985 and the death of William J. Campbell in 1992, is a dynamic glaciologist with the vision, expertise, and managerial skills to execute a Bureau Program and to ensure that the products from the program are relevant to the USGS mission, the national interest, and the international scientific community. Traditional techniques have served the USGS's glaciology program well over years, but new remote sensing and GIS-based techniques can realize increased cost-effectiveness and scientific productivity. Satellite remote sensing will give the benchmark glacier data a much-needed regional context. GIS-based analysis will make past, present, and future data sets immediately comparable. It will also make the glacier data more accessible and useful to all Divisions of the USGS, to other bureaus in the U.S. Department of the Interior (e.g., Bureau of Reclamation, National Park Service, etc.) to other government agencies, and to collaborating colleagues in USGS counterpart agencies in other nations involved in glacier studies and monitoring.

This program should not stand in isolation. Strengthening of collaborations with glaciologists at the USGS's Cascade Volcano Observatory, the University of Washington, and other institutions in North America and Northwestern Europe, should continue. Image-analysis expertise in the Geologic Division, photographic/mapping expertise in the National Mapping Division, and field monitoring of glaciers in National Parks by the Water Resources Division and the Biological Resources Division offer the possibility of conducting a strong USGS glaciology program across the four science divisions. Equally important are associations with other nation's glacier-monitoring programs, especially USGS counterpart governmental agencies.

There is a rare opportunity to revitalize the USGS's program in glaciology into one that embraces national responsibilities that are part of USGS's mission, utilizes state-of-the-art techniques, and coordinates the broad talents of a group of very capable persons to achieve a meaningful bureau program of glacier research. The Water Resources Division, for example, has some of the best glacier surveyors in the world and a staff of professional glaciologists with proven track records. The USGS should be proud of their accomplishments. An internationally recognized glaciologist, at the forefront of developing remote sensing applications, capable of managing and sustaining a productive research team in a challenging funding environment, with extensive national and international contacts, is needed to reestablish the USGS as the lead Federal agency in glacier studies and to forge a strong cooperative scientific program with other institutions (U.S., Canada, and other foreign nations) that will serve the nation well as it enters the 21st century.

REVIEW OF PAST, PRESENT, AND FUTURE EARTH OBSERVING PLATFORMS*

USGS Biological Resources Division

*Excerpted from copies of viewgraphs prepared by the USGS Biological Resources Division, Office of Biological Information and Outreach (OBIO), Earth Observation Platforms, "An Overview," 2 April 1997, 17 p.

CURRENT DATA SOURCES AND RESOLUTION

SENSOR	SOURCE	PIXEL RESOLUTION (in meters for satellite imagery)
Satellite, Optical:	JERS-1	24
	IRS-1	36
	LANDSAT TM	30
	LANDSAT MSS	80
	SPOT PAN	10
	SPOT MSS	20
Satellite, Radar:	ERS-1	30
	JERS-1	18
	RADARSAT	varies
Airborne:	Air/Ortho Photo	varies
Geophysical:	Gravity	varies
	Magnetics	varies
	Radiometrics	varies
	Seismic	varies

SPATIAL RESOLUTION (PIXEL)

Low	>30 meter
Medium	6 meter- 30 meter
High	1 meter- 5 meter

SATELLITE ORBITS

Three types of orbits for earth observing systems:

Polar Orbit
Geostationary Orbit
Shuttle Orbit

Polar Orbit - satellite tracks near the North and South poles at an altitude above the earth at 500 to 1000 km. Polar orbits provides for coverage over most of the earth's surface.

Repeat Cycle - is expressed in days and represents the time taken for the satellite to return to the same position over the earth's surface. LANDSAT 5 has a repeat cycle of 16 days.

Sun-synchronus - the satellite passes over an area at approximately the same local sun time as the satellite passes over the equator.

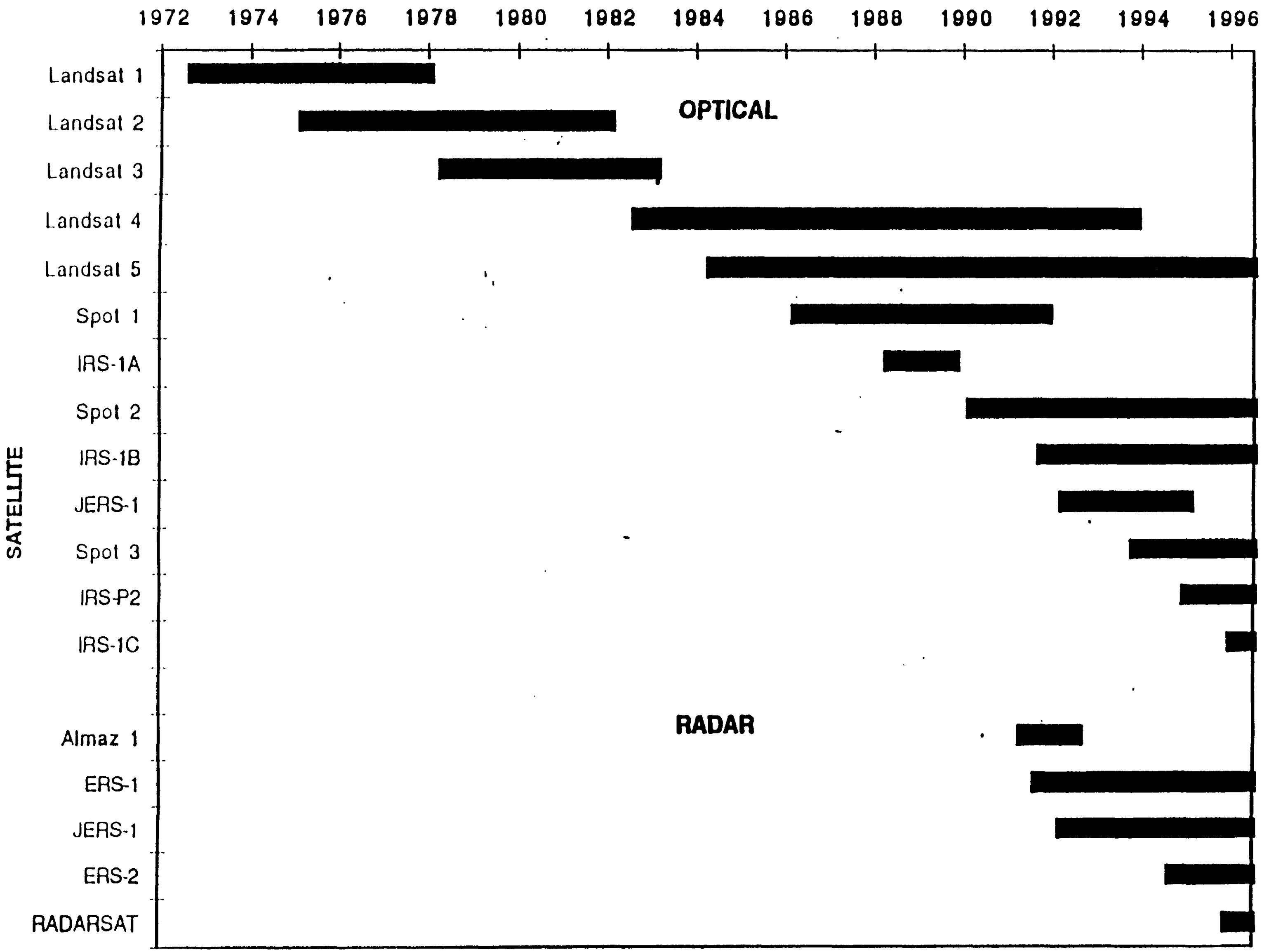
Period - time taken to complete one orbit around the earth.

Inclination - the angle which the satellite orbit makes with the equator is defined as its inclination. A polar orbit would have an inclination of 90 degrees. Landsat 5 has an orbital inclination of 98.2 degrees. It is measured on the North and South (or descending) part of the orbit.

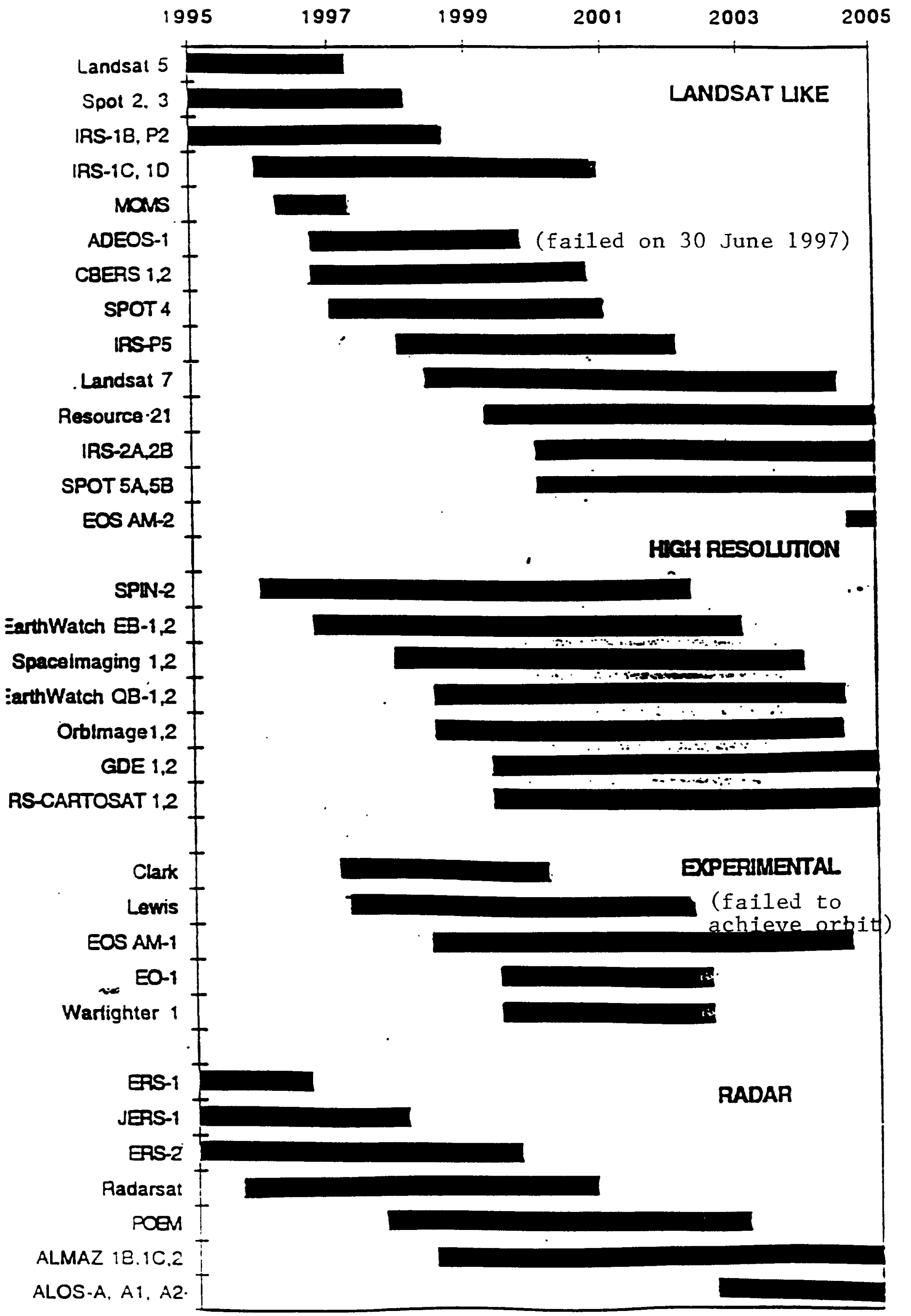
Coverage - represents the areas of the earth which are observed after one repeat cycle. For polar orbits this is usually given as maximum latitudes North and South.

Geostationary Orbits - the satellite possessed an orbital speed matching the rotation rate of the earth. At an altitude of 35,900 km. Coverage of the earth is limited to one specific hemisphere.

INTERMEDIATE RESOLUTION LAND IMAGING SATELLITES
THE FIRST QUARTER CENTURY



INTERMEDIATE RESOLUTION LAND IMAGING SATELLITES
THE NEXT TEN YEARS



LAND IMAGING SATELLITES PLANNED TO BE OPERATING IN THE YEAR 2000

COUNTRY	SAT OWNER	PROGRAM	INSTRUMENT(S)	LAUNCH	SENSOR TYPES	RESOLUTION IN METERS									STEREO Type	SW KM	GLOBAL COVER REPEAT days
							THEMATIC MAPPER BANDS										
						PAN	VNIR				SWIR		TIR	RADAR			
							1	2	3	4	5	7	6	res,band			
FREQUENT GLOBAL COVERAGE, LANDSAT LIKE CLASSIFICATION CAPABILITY																	
INDIA	Gov.	IRS-1 C,D	LISS-3, PAN, (WIFS)	'95	M&P	6		23	23	23	70				C/T	148	22
JAPAN	Gov.	ADEOS	AVNIR	'96	M&P	8	16	16	16	16					C/T	80	41
CHINA-BRAZIL	Gov.	CBERS	CCD, IRMSS	'97	M&P	20, 80	20	20	20	20	80	80	160		C/T	120	26
FRANCE	Gov.	Spot 4	HRVIR, (VEGETATION)	'97	M&P*	10		20	20	20	20				C/T	120*	26
INDIA	Gov.	IRS-P5	LISS 4, LISS-3'	'98	M			<10	<10	<10	70				C/T	148	22
U S	Gov.	Landsat 7	ETM+	'98	M&P	15	30	30	30	30	30	30	60			165	16
U S.	Com.	Resource 21	XXX	'99	M		10	10	10	10	20					200	4**
INDIA	Gov.	IRS-2A	LISS 4', LISS-3', (WIFS)	'00	M			5	5	5	70				F/A	148	22
HIGH RESOLUTION, SMALL AREA COVERAGE (PAN & VNIR ONLY)																	
RUSSIA	Gov.	SPIN-2	KVR-1000, TK-350	'96	P(f)	2,10									F/A	40,300	
U S	Com.	EarthWatch	EarlyBird	'96	M&P	3		15	15	15					F/A	36	120
U S	Com.	SpaceImaging	SS	'97	M&P	1	4	4	4	4					F/A	12	247
U S.	Com.	EarthWatch	QuickBird	'98	M&P	1	4	4	4	4					F/A	20	148
U S	Com	OrbImage	OrbView	'98	M&P	1&2	8	8	8	8					F/A	4&8	740,370
RUSSIA	Gov.	Almaz 1B	1 SLR, 3 SARs, 4 SCANNERS***	'98	M&P&R	2.5		4,10	4,10	4,10				5,40 S	F/A	20,170	
U S.	Com.	GDE	XXX	'99	P	1									F/A		
INDIA	Gov.	IRS-P6	PAN	'99	P	2.5									F/A	10	296
MULTISPECTRAL, HYPERSPECTRAL APPLICATION TESTS																	
U S.	Gov.	TRW Lewis	HSI	'96	H&P	5	128 bands @ 30				256 bands @ 30					8	370
U S./JAPAN	Gov.	EOS AM-1	ASTER, (MODIS)	'98	M			15	15	15	6 bands @ 30		5@90		F/A	80	49
U S	Gov.	EO-1	XXX	'99	M&H		128 bands @ 30				256 bands @ 30					TBD	16
U S	Gov.	Warfighter 1	XXX	'99	MorH		Minimum of 60 bands from 0.4 to 5 µm @ <10.								TBD	5 to >25	TBD
RADAR																	
CANADA	Gov.	Radarsat	SAR	'95	R									10-100 C		50-500	
ESA	Gov.	Poem	ASAR	'98	R									30 C		100	
RUSSIA	Gov.	Almaz 1B	1 SLR, 3 SARs, 4 SCANNERS***	'98	M&P&R	2.5		4,10	4,10	4,10				5,40 S	F/A	20,170	

Multispectral		M
Hyperspectral		H
Panchromatic		P
Radar		R
Film		(f)
R	Infrared	
VNIR	Visible and near IR	
SWIR	Short wave IR	
TIR	Thermal IR	

All satellites in polar sun synchronous orbits except SPIN-2 (65 Deg), ALMAZ 1B (73 Deg), QuickBird (> 52 Deg) and TBD Warfighter 1 (>45 Deg)

F/A = fore/aft stereo, C/T = side to side stereo. All stereo satellites have 2 to 3 day site repeat capabilities

(XXX) = Wide swath, lower resolution inst. used for near daily, large area vegetation mapping

* = Swath is achieved by two side by side instruments

** = 4 satellites are planned to provide 3.5 to 4 day global repeat coverage.

*** = SLR-3, SAR-3, SAR-10, SAR-70, OES, MSU-E, (MSU-SK, SROSM)

CURRENT, PLANNED AND PROPOSED LAND OBSERVATION SATELLITES

COUNTRY	SAT OWNER	PROGRAM	INSTRUMENT(S)	LAUNCH	SENSOR TYPES
FREQUENT GLOBAL COVERAGE, MULTISPECTRAL CLASSIFICATION FOCUS					
U.S.	Gov.	Landsat 5	TM	'85	M
INDIA	Gov.	IRS-1B	LISS-2, (LISS-1)	'91	M
FRANCE	Gov.	Spot 3	HRV	'93	M&P
INDIA	Gov.	P2	LISS-2	'94	M
INDIA	Gov.	IRS-1 C	LISS-3, PAN, (WIFS)	'95	M&P
GERMANY	Gov.	PRIRODA	MOMS-02	'96	M&P
JAPAN	Gov.	ADEOS	AVNIR	'96	M&P
INDIA	Gov.	IRS-1 D	LISS-3, PAN, (WIFS)	'97	M&P
CHINA-BRAZIL	Gov.	CBERS	CCD, IRMSS	'97	M&P
FRANCE	Gov.	Spot 4	HRVIR, (VEGITATION)	'97	M&P
INDIA	Gov.	IRS-P5	LISS 4, LISS-3'	'96	M
U.S.	Gov.	Landsat 7	ETM+	'98	M&P
U.S.	Com.	Resource 21	XXX	'99	M
INDIA	Gov.	IRS-2A	LISS 4', LISS-3', (WIFS)	'00	M
FRANCE	Gov.	Spot 5A	HRG, (VEGITATION)	'02	M&P
INDIA	Gov.	IRS-2B	LISS 4, LISS-3', (WIFS)	'04	M
FRANCE	Gov.	Spot 5B	HRG, (VEGITATION)	'04	M&P
U.S.	Gov.	EOS AM-2	LATI (MODIS)	'04	M&P
HIGH RESOLUTION, SMALL AREA COVERAGE (PAN & VNIR ONLY)					
RUSSIA	Gov.	SPIN-2	KVR-1000, TK-350	'96	P(f)
U.S.	Com.	EarthWatch	EarlyBird	'96	M&P
U.S.	Com.	SpaceImaging	SS	'97	M&P
U.S.	Com.	EarthWatch	QuickBird	'98	M&P
U.S.	Com	OrbImage	OrbView	'98	M&P
U.S.	Com.	GDE	XXX	'98	P
INDIA	Gov.	IRS-P6	PAN	'99	P
HI-RES, MULTISPECTRAL, HYPERSPECTRAL APPLICATION TESTS					
U.S.	Gov.	CTA Clark	W-VIEW	'97	M&P
U.S.	Gov.	TRW Lewis	HSI	'97	H&P
U.S./JAPAN	Gov.	EOS AM-1	ASTER, (MODIS)	'98	M
US	Gov.	EO-1	XXX	'99	M&H
US	Gov.	Warfighter 1	XXX	'99	MorH
RADAR AND RADAR PLUS OPTICAL					
RUSSIA	Gov.	Almaz 1	SAR	'91	R
ESA	Gov.	ERS-1	SAR	'91	R
JAPAN	Gov.	JERS-1	OPS, SAR	'92	M&R
U.S.-GER.-IT.	Gov.	Shuttle Radar	SIR-C/X-SAR	'94	R
ESA	Gov.	ERS-2	SAR	'94	R
CANADA	Gov.	Radarsat	SAR	'95	R
ESA	Gov.	Poem	ASAR	'98	R
RUSSIA	Gov.	Almaz 1B	1 SLR, 3 SARs, 4 SCANNERS*	'98	M&P&R
RUSSIA	Gov.	Almaz 1C	1 SLR, 3 SARs, 4 SCANNERS*	'01	M&P&R
JAPAN	Gov.	ALOS	AVNIR-2, VSAR	'02	M&P&R
RUSSIA	Gov.	Almaz 2	1 SLR, 3 SARs, 4 SCANNERS*	'04	M&P&R
JAPAN	Gov.	ALOS-A1	AVNIR-3, VSAR	'04	M&P&R
INDIA	Gov.	IRS-3	MULTI FREQ POL SAR	'04	R
JAPAN	Gov.	ALOS-B1	A-SAR	'06	R
JAPAN	Gov.	ALOS-A2	AVNIR-4, VSAR	'07	M&P&R
JAPAN	Gov.	ALOS-B2	A-SAR	'09	R

Multispectral	M	* = SLR-3, SAR-3, SAR-10, SAR-70
Hyperspectral	H	OES, MSU-E, (MSU-SK, SROSM)
Panchromatic	P	
Radar	R	(XXX) = Wide field of view, lower res. sensors
Film	(f)	

SYNTHETIC APERTURE RADAR APPLICATIONS

SAR Provides High-Resolution Imagery, Independent of Cloud Cover, Sensitive to Survace Roughness, Structure, and Dielectric Constant.

Flooding
Vegetation growth and leaf-shedding
Environmental damage to vegetation
Slash and burn agriculture
Logging
Change of surface moisture content
Change of vegetation moisture content
Rain and snow storms
Freezing and thawing changes
Erosion
Earthquakes
Surface motion (glaciers)
Land subsidence
Swelling in volcanically active regions

FUTURE CAPABILITIES

- Additional Revisit Cycles
-Stereo Imaging
-Programmable Sensors
-On-board Data Storage
-Improved Communications

FUTURE SENSOR AVAILABAILITY

Spot 3-4
IRS-P2,1B
ERS-1,2
Priroda-mom2
Lewis
Clark
Early Bird
CRSS
ASTROVISION
EXEGLASS
SEASTAR
ADEOS
RADARSAT

CRITICAL ISSUES

-Coverage frequency and timeliness

-Spatial resolution

-Sensor calibration

-Atmospheric Correction

Available data from the WGMS

The international data basis contains two different kinds of information about glaciers of the 20th century:

- glacier inventory data describing the spatial variability
- glacier fluctuation data documenting changes in time

Written publications

Inventory Data:	World glacier inventory - status 1988
Fluctuations Data:	Fluctuations of Glaciers 1959-1965 (Vol. I) Fluctuations of Glaciers 1965-1970 (Vol. II) Fluctuations of Glaciers 1970-1975 (Vol. III) Fluctuations of Glaciers 1975-1980 (Vol. IV) Fluctuations of Glaciers 1980-1985 (Vol. V) Fluctuations of Glaciers 1985-1990 (Vol. VI) Fluctuations of Glaciers 1990-1995 (Vol. VII)*
	Glacier Mass Balance Bulletin No. 1 (1988-1989) Glacier Mass Balance Bulletin No. 2 (1990-1991) Glacier Mass Balance Bulletin No. 3 (1992-1993) Glacier Mass Balance Bulletin No. 4 (1994-1995)

* to be published by the end of 1997

Digital data

Data quality

The WGMS cannot guarantee for the correctness of the inventory and fluctuation data. The accuracy of the data is the responsibility of the data collectors in the individual countries. All data are subject to plausibility checks while loading them into the database (Haeberli and Hoelzle 1995, Hoelzle and Trindler, 1997). There are some exceptions which are marked with 'unchecked'.

WORLD GLACIER INVENTORY (WGI)

Structure of the database

The WGI database contains glacier data describing the spatial variability of the worlds ice masses (IAHS(ICSI)/UNEP/UNESCO 1989). This database presently consists of three tables (see Fig. 1). The *WGI_Gla* table contains static information about the glaciers like location (latitude and longitude) and names. A second table *WGI_Var* stores variable information about the glaciers such as, for example, glacier length, area and the photo-, map- or satellite image year. The third table *WGI_Edi* contains information about the investigators of the different countries. Appendix A1 gives a detailed list of all items available within the World Glacier Inventory database.

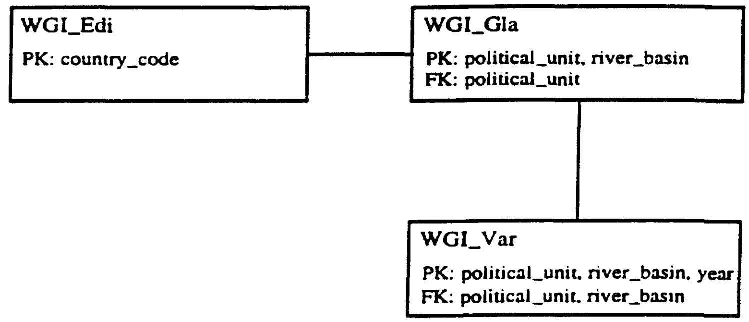


Fig. 1 *Database scheme for the World Glacier Inventory data. PK means primary key and FK means foreign key.*

Data extent

The following table gives an overview on the countries and mountain ranges from which detailed inventory data exist, the number of loaded glaciers and data quality.

TABLE 3.1 Countries and mountain ranges / regions from which detailed inventory data exist, the number of loaded glaciers and data quality. 'Y' means that data exist but have not yet been entered into the database; 'complete' that the whole country is covered.

Country (Denotation of political state) and Mountain Ranges / Regions	Number of loaded Glaciers	Data Quality / Remarks
Afghanistan (AF) • Panjshir • Safed Khirs	Y	
Argentina (RA) • Prov. of Rio Negro (Rio Manso) • Prov. of Mendoza • Prov. of Neuquen • South Patagonia (Arg. part) 47.5°S - 51.0°S	2,706	unchecked
Austria (A) complete	925	checked
Bhutan (BH) complete	Y	
Bolivia (RB) • Cordillera Oriental	1,696	checked
Canada (CD) • Vancouver Island • Stikine River • Yukon Territory • Southeast Ellesmere Island • Axel Heiberg Island	14,964	unchecked
Chile (RC) • Prov. of Santiago and O'Higgins • North Patagonian Icefield (Rio Baker)	1,294	unchecked
China (CN) • Altai Shan • Qilian Shan • Tian Shan	12,183	unchecked; survey year partly missing
CIS (SU) complete	20,908	unchecked; survey year missing

Colombia (CO) • Sierra Nevada de Santa Marta	Y	
Ecuador (EC) complete	113	unchecked
France (F) complete	1,130	checked
Germany (D) complete	5	checked
Greenland (GL) • West Greenland, 63° - 64°N	45	checked
Iceland (IS) announced	Y	
India (IN) • Baspa River	Y	
Indonesia (RI) complete	Y	
Iran (IR)	-	
Italy (I) complete	1,376	checked
Japan (J) complete	Y	
Kenya (KN) complete	Y	
Mexico (MX) complete	Y	
Mongolia (MG)	-	
Nepal (NP) • Ganges river drainage basin	130	checked
New Zealand (NZ) complete	3,153	checked
Norway (N) complete	2,998	checked
Pakistan (PK) • Nanga Parbat • Chitral	 69 Y	 checked
Peru (PE) • Northern Cordilleras (Blanca, Huallanca, Huayhuash, Raura, La Viuda, Huagaruncho, Central, Huaytaballanu, Chonta)	1,679	checked
Spain (E) complete	31	checked
Sweden (S) complete	303	checked
Switzerland (CH) complete	1,828	checked
Tanzania (TZ) complete	Y	
Turkey (TR)	-	
Uganda (UG) complete	Y	
United States (US) • Sierra Nevada • Front Range • Olympic Mountains • North Cascade Range • Brooks Range, Alaska	2,519	unchecked
Venezuela (VZ) complete	Y	
Total	**70,055**	

FLUCTUATIONS OF GLACIERS (FoG)

Structure of the database

The FoG database presently consists of seven tables (see Fig. 2). The data model follows a thematic grouping of the data in order to get a better overview.
The table *Glacier* contains the basic data of each glacier such as, for example, name and location (latitude and longitude). These data seldom change over time. Further on, the main differentiation is made by yearly and altitudinal changes. For example, the table *Mass_Balance_Overview* contains yearly variable mass balance information such as values for the accumulation and ablation area or the equilibrium line altitude (ELA). Mass balance data itself can be related to the whole glacier but also to specific altitudinal ranges. Therefore, a new table *Mass_Balance* was created storing data which depend on time and on altitude.
The same idea is behind the other two tables *Glacier_State* and *Glacier_Section*. The table *Glacier_State* contains yearly information such as, for example, length variation (qualitative and quantitative) or highest, median and lowest elevation. In the table *Glacier_Section*, altitudinal information such as changes in volume, area and thickness is stored additionally.
The table *Territory* contains information about country names and codes, the table *Spec_Events* on Special Events like glacier surges, calving instabilities, glacier floods, debris flows, mudflows, large ice avalanches and tectonic impacts (earthquake, volcanic eruption).
In Appendix A2 each item and its meaning are given in tabular form.

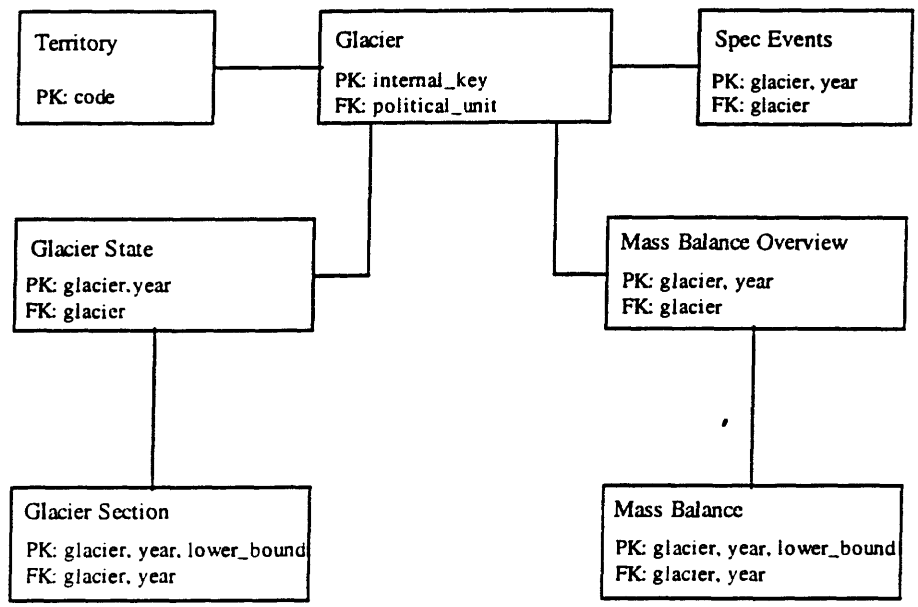


Fig. 2 *Database scheme for the Fluctuations of Glaciers data. PK: means primary key and FK: means foreign key.*

Data extent

Table 2 gives an overview on the countries from which fluctuation data exist and the number of glaciers with corresponding data. An additional column shows the number of glaciers for each country which entered the last edition of the Glacier Mass Balance Bulletin (MBB 4). This series resumes high quality up-to-date mass balance data. At the present state the database of the FoG contains data from the last four volumes of the IAHS publication series Fluctuations of Glaciers (IAHS(ICSI)/UNESCO 1977, 1985, IAHS(ICSI)/UNEP/UNESCO

1988, 1993a, in preparation). The data are stored according to general information on the observed glaciers, variations in front position (glacier length changes), mass balance, mass balance versus altitude, changes in volume, area and thickness. In addition, all mass balance data from the Glacier Mass Balance Bulletin are available in the same database (IAHS(ICSI)/UNEP/ UNESCO 1991, 1993b, 1994, 1996).

TABLE 2 Countries and count of glaciers within the Fluctuations of Glaciers (FoG) database and within the Glacier Mass Balance Bulletin No. 4 (MBB 4).

Country	FoG (count of glaciers with data within the database)	MBB 4 (count of glaciers with data in the publication)
Antarctica	39	
Argentina	10	
Australia	16	
Austria	142	8
Bolivia	2	2
Canada	107	4
Chile	36	
China	38	1
Colombia	20	
France	11	2
Germany	5	
Greenland	15	
CIS	177	9
Iceland	62	7
India	5	
Indonesia	6	
Italy	276	2
Japan	2	
Kenya	13	1
Mexico	2	
Nepal	14	
New Zealand	83	
Norway	52	14
Pakistan	37	
Peru	10	
Poland	4	
Spain	33	1
Sweden	21	4
Switzerland	118	2
Uganda	1	
United Kingdom	33	
United States	197	3
Venezuela	1	
Total	1,555	60

References

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HOELZLE, M. AND TRINDLER, M. (in press): Data management and application. In: Into the Second Century of World Glacier Monitoring - Prospects and Strategies (Haeberli, W., Hoelzle, M. and Suter, S.; eds.). UNESCO publishing, Paris.

IAHS(ICSI)/UNEP/UNESCO (1988): Fluctuations of Glaciers 1980-1985 (Haeberli, W. and Müller, P.; eds.), Paris.

IAHS(ICSI)/UNEP/UNESCO (1989): World glacier inventory - status 1988 (Haeberli, W., Bösch, H., Scherler, K, Østrem, G. and Wallén, C. C.; eds.). Nairobi.

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IAHS(ICSI)/UNEP/UNESCO (1993a): Fluctuations of Glaciers 1985-1990 (Haeberli, W. and Hoelzle, M.; eds.), Paris.

IAHS(ICSI)/UNEP/UNESCO (1993b): Glacier mass balance bulletin no. 2 (Haeberli, W., Herren, E. and Hoelzle, M.; eds.). World Glacier Monitoring Service, ETH Zurich.

IAHS(ICSI)/UNEP/UNESCO (1994): Glacier mass balance bulletin no. 3 (Haeberli, W., Hoelzle, M. and Bösch, H.; eds.). World Glacier Monitoring Service, ETH Zurich.

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IAHS(ICSI)/UNEP/UNESCO (in preparation): Fluctuations of Glaciers 1990-1995 (Haeberli, W., Hoelzle, M., Suter, S. and Frauenfelder, R.; eds.). World Glacier Monitoring Service, University of Zurich and ETH Zurich.

IAHS(ICSI)/UNESCO (1967): Fluctuations of Glaciers 1959-1965 (Kasser, P.; ed.), Paris.

IAHS(ICSI)/UNESCO (1973): Fluctuations of Glaciers 1965-1970 (Kasser, P.; ed.), Paris.

IAHS(ICSI)/UNESCO (1977): Fluctuations of Glaciers 1970-1975 (Müller, F.; ed.), Paris.

IAHS(ICSI)/UNESCO (1985): Fluctuations of Glaciers 1975-1980 (Haeberli, W.; ed.), Paris.

A1 The table and item list for the World Glacier Inventory (WGI) database

TABLE A1.1 WGI_Edi

Ctr_Code	Varchar2(2)	Not Null/PK	Country Code
Edi_Year	Number(4)		Year of the Edition
Edi_Name	Varchar2(20)		Editor names
Edi_Adr	Varchar2(30)		Editor addresses

TABLE A1.2 WGI_Gla

Political_Unit	Varchar2(2)	Not Null/PK	Political Unit part of the WGI-number (Position 1 and 2)
River_Basin	Varchar2(5)	Not Null/PK	Code for the determination of the hydrological catchment areas (Position 3 designates the continent, positions 4 to 7 are for the drainage code)
Free_Position	Varchar2(2)		Free ly chosen number (Position 8 and 9)
Local_Code	Varchar2(3)		Local Code helps to make the WGI-number clear (Positions 10 to 12)
Vaw _Add_Code	Number(3)	Not Null/PK	Additional Code to clear double WGI-numbers
Name	Varchar2(16)		Name
Card_Point_Lat	Varchar2(1)		Cardinal point (N or S)
Degrees_Lat	Number(2)		Latitude in degrees
Minutes_Lat	Number(4,2)		Latitude in minutes and seconds
Card_Point_Lon	Varchar2(1)		Cardinal point (E or W)
Degrees_Lon	Number(3)		Longitude in degrees
Minutes_Lon	Number(4,2)		Longitude in minutes and seconds
Coordinates	Varchar2(15)		Coordinates
Nr_States	Number(1)		Number of independant states
Official_Rem	Varchar2(255)		Official remarks
Internal_Rem	Varchar2(255)		Internal remarks
Fluctu_Key	Number(5)		Reference Key to the FoG

TABLE A1.3 WGI_Var

Political_Unit	Varchar2(2)	Not Null/PK	Political Unit part of the WGI-number (Position 1 and 2)
River_Basin	Varchar2(5)	Not Null/PK	Code for the determination of the hydrological catchment areas (Position 3 designates the continent, positions 4 to 7 are for the drainage code)
Free_Position	Varchar2(2)		Free ly chosen number (Position 8 and 9)
Local_Code	Varchar2(3)		Local Code helps to make the WGI-number clear (Positions 10 to 12)
VAW_Add_Code	Number(3)	Not Null/PK	Additional Code to clear double WGI-numbers
Year	Number(4)	Not Null/PK	Year of the map or photo year
Nr_Drainage_B	Number(1)		Number of drainage basins
Map_Scale	Number(4)		Map scale
Photo_Type	Varchar2(1)		Photo type
Photo_Year	Number(4)		Photo year
Total_Area	Number(8,3)		Total surface area
Area_Accuracy	Varchar2(1)		Accuracy rating of the area
State_Area	Number(8,3)		Total area in the state concerned
Exposed_Area	Number(8,3)		Total exposed surface area
Ablation_Area	Number(8,3)		Ablation area
Mean_Width	Number(4,1)		Mean width
Mean_Length	Number(4,1)		Mean length
Max_Len_Tot	Number(4,1)		Maximum length total
Max_Len_Expo	Number(4,1)		Maximum length exposed
Max_Len_Abla	Number(4,1)		Maximum length ablation area
Expos_Acc_Area	Varchar2(2)		Exposition accumulation area
Expos_Abl_Area	Varchar2(2)		Exposition ablation area
Highest_Elev	Number(4)		Highest elevation
Median_Elev	Number(4)		Median elevation (mostly mean elevation)
Lowest_Elev_Tot	Number(4)		Lowest elevation total
Lowest_Elev_Exp	Number(4)		Lowest elevation exposed
Mean_Elev_Acc	Number(4)		Mean elevation accumulation area
Mean_Elev_Abl	Number(4)		Mean elevation ablation area
Prim_Classific	Varchar2(1)		Primary classification
Form	Varchar2(1)		Form
Frontal_Chars	Varchar2(1)		Frontal characteristics
Longi_Prof	Varchar2(1)		Longitudinal profile

Source_Nouri	Varchar2(1)	Major source of nourishment
Acti_Tongue	Varchar2(1)	Activity of the tongue
Acti_From	Number(4)	Beginning of the period for which the tongue activity was assessed
Acti_To	Number(4)	End of the period for which the tongue activity was assessed
Moracl1	Varchar2(1)	Moraine classification
Moracl2	Varchar2(2)	Moraine classification
Snow_Line_Elev	Number(4)	Snow-line elevation
Snow_Line_Accr	Varchar2(1)	Snow-line elevation accuracy rating
Snow_Line_Date	Varchar2(8)	Snow-line elevation date
Mean_Depth	Number(4)	Mean depth
Depth_Accuracy	Varchar2(1)	Mean depth accuracy rating
Loading_Date	Date	Date of loading into database

A2 The table and item list for the Fluctuations of Glaciers (FoG) database

TABLE A2.1 Glacier

Internal_Key	Number(5)	Not Null/PK	Internal Key
Political_Unit	Varchar2(2)	Not Null/FK	Political Unit part of the WGI-number (Position 1 and 2)
River_Basin	Varchar2(5)		Code for the determination of the hydrological catchment areas (Position 3 designates the continent, positions 4 to 7 are for the drainage code)
Free_Position	Varchar2(2)		Free ly chosen number (Position 8 and 9)
Local_Code	Varchar2(3)		Local Code helps to make the WGI-number clear (Positions 10 to 12)
Local_PSFG	Varchar2(5)		This glacier number should be unique for each country.
Name	Varchar2(15)		Name of the glacier
Gen_Location	Varchar2(15)		Geographical location (general)
Spec_Location	Varchar2(15)		Geographical location (more specific)
Latitude	Number(4,2)		Latitude in degrees and minutes
Card_Point_Lat	Varchar2(1)		Cardinal point (N or S)
Longitude	Number(5,2)		Longitude in degrees and minutes
Card_Point_Lon	Varchar2(1)		Cardinal point (E or W)
Prim_Classific	Varchar2(1)		Primary Classification
Form	Varchar2(1)		Form
Frontal_Chars	Varchar2(1)		Frontal characteristics
First_Survey_FR	Date		Year of the first quantitative survey
First_Mass_Bal	Date		Year of the first mass balance survey
Expos_Acc_Area	Varchar2(2)		Exposition of accumulation area
Expos_Abl_Area	Varchar2(2)		Exposition of the ablation area
To_be_published	Number(4)		Publication number (Vol. I to VI)
MBB	Varchar2(1)		Mass Balance Bulletin Key
Remarks	Varchar2(500)		Remarks
Authors	Varchar2(100)		Names of the principal investigators

TABLE A2.2 Glacier_State

Glacier	Number(5)	Not Null/PK	Reference to the table Glacier Internal_Key
Year	Number(4)	Not Null/PK	Year is together with 'Glacier' the Primary Key
Highest_elev	Number(4)		Highest Elevation
Median_elev	Number(4)		Median Elevation
Lowest_elev	Number(4)		Lowest Elevetation
Snout_point_alt	Number(4)		Altitude of the snout
Error_Altitude	Number(4,1)		Estimated maximum error in altitude
Length	Number(5,2)		Length of the glacier
Variation_horiz	Number(6,1)		Quantitative variation between previous and present survey
Qualitative_var	Varchar2(2)		Qualitative variation between previous and present survey
Error_variation	Number(4,1)		Estimated maximum error in variation
Date_Survey	Date		Date of the survey
Method_Survey	Char (1)		Method of the survey
Reference_date	Date		Date of last survey
Published	Number(4)		Last year of publication series
Frontal_invest	Varchar2(50)		Information on the Investigator
Frontal_spons	Varchar2(100)		Information on the Sponsoring Agency
Frontal_remarks	Varchar2(500)		Remarks to the measurements

TABLE A2.3 Glacier_Section

Glacier	Number(5)	Not Null/PK	Reference on table Glacier_State
Year	Number(4)	Not Null/PK	Reference on table Glacier_State
Lower_Bound	Number(4)	Not Null/PK	Lower value of altitude interval
Upper_Bound	Number (4)		Upper value of altitude interval
Area	Number(8,3)		Area for each altitude interval
Area_Change	Number(6)		Area change for each altitude interval
Thickness_Chg	Number(6)		Thickness change for each altitude interval
Volume_Change	Number(12)		Volume change for each altitude interval
Reference_date	Date		Date of last survey
Published	Number(4)		Last year of publication series

TABLE A2.4 Mass_Balance_Overview

Glacier	Number(5)	Not Null/PK	Reference to table Glacier
Year	Number(4)	Not Null/PK	Year is together with 'Glacier' the Primary Key
Time_System	Varchar2(3)		Time system
Beginn_Period	Date		Begin of survey period
End_Winter	Date		End of winter season
End_Period	Date		End of survey period
Equilibr_Ln_Alt	Number(4)		Equilibrium line altitude
Min_Sites_Acc	Number(3)		Number of minimum measurement sites in the accumulation area
Max_Sites_Acc	Number(3)		Number of maximum measurement sites in the accumulation area
Min_Sites_Abl	Number(3)		Number of minimum measurement sites in the ablation area
Max_Sites_Abl	Number(3)		Number of maximum measurement sites in the ablation area
Acc_Area	Number(8,3)		Accumulation area
Abl_Area	Number(8,3)		Ablation area
AAR	Number(4,1)		Accumulation area ratio
Rating_ELA	Varchar2(1)		Rating of the ELA
Rating_AAR	Varchar2(1)		Rating of the AAR

TABLE A2.5 Mass_Balance

Glacier	Number(5)	Not Null/PK	Reference to table Mass_Balance_Overview
Year	Number(4)	Not Null/PK	Reference to table Mass_Balance_Overview
Lower_Bound	Number(4)	Not Null/PK	Lower value of altitude interval
Upper_Bound	Number(4)		Upper value of altitude interval
Area	Number(8,3)		Area for each altitude interval
Winter_Balance	Number(5)		Winter Balance
Summer_Balance	Number(5)		Summer Balance
Net_Acc	Number(5)		Net Accumulation
Net_Abl	Number(5)		Net Ablation
Net_Balance	Number(5)		Net Balance
Published	Number(4)		Last year of publication series
Mass_Bal_Invest	Varchar2(50)		Information on the Investigator
Mass_Bal_Spons	Varchar2(100)		Information on the Sponsoring Agency

Mass_Bal_Remarks	Varchar2(500)		Remarks to the measurements

TABLE A2.6 Territory

Code	Varchar2(2)	Not Null/PK	Country Code
Name	Varchar2(20)		Name of the Country
Report_Position	Number(2)		Position in the FoG report

TABLE A2.6 Spec_Events

Glacier	Number(5)	Not Null/PK	Reference to table Glacier
Year	Number(4)	Not Null/PK	Year is together with 'Glacier' the Primary Key
Type_Event	Number (4)		Code describing the type of event
Description	Varchar2(2000)		Description of the event
Data_Source	Varchar2(500)		Source of the data
Spec_Remarks	Varchar2(500)		Remarks to the event
Published	Number(4)		Last year of publication series

How to get data from the WGMS

There are 5 possibilities to get data from the WGMS:

1. if you prefer getting your data in a written form on paper we can either send you copies of our written publications (see 'Available data from the WGMS') or printouts of the requested data. Please use the latter proceeding to be sure to get the latest data as the database is regularly updated. For addresses see below.

2. you can get data in plain ASCII code on a diskette. Tell us what data you need and send us a diskette. For addresses see below.

3. you can get data in plain ASCII code via FTP. Tell us what data you need, the address of your computer (e.g. apache.ethz.ch or 129.132.2.75), the name and - if necessary - the password of your account and the directory where you would like to have your data. For addresses see below.
4. if you have a connection to the INTERNET and if you have access to an ORACLE database on a UNIX system you can directly login to the WGMS database via SQL*NET. Use the following statement: **sqlplus wgmsuser/wgms@rz** where 'rz' is an alias for: rz = (DESCRIPTION = (ADDRESS = (PROTOCOL = tcp) (HOST = apache.ethz.ch) (PORT = 1521)) (CONNECT_DATA = (SID = rz)))
 and has to be defined on your machine within a 'tnsnames.ora' file.
 A 'wgmsuser' has all 'select' rights to the WGMS database and therefore to the tables (see: 'Available data from the WGMS') via SQL statements.
 Here are some query examples:

 ### WGI
 This example shows a query on the World Glacier Inventory (WGI) database. It selects the sum of total area of all glaciers, which are presently stored in the database grouped by country:
 select political_unit, sum(total_area) from wgms.wgi_var group by political_unit

 Result:

Political_Unit	Sum (Total_Area)
A	542.23
CD	34,859.63
CH	1,341.69
CN	11,470.18
D	1.15
E	5.27
F	424.01
GL	1,070.20
I	754.29
N	35,865.51
NP	1,641.55
NZ	1,159.10
PE	1131.07
PK	301.26
RA	3,795.16
RB	509.50
RC	1,978.50
S	313.07
SU (CIS)	82,127.52
US	1,087.26

FoG
The last example shows a query on the Fluctuations of Glaciers (FoG) database. The following query allows one to obtain mass balance-, equilibrium line altitude- and accumulation area ratio data:

select a.name, b.year, b.equilibr_ln_alt, b.aar, c.net_balance from wgms.glacier a, wgms.mass_balance_overview b, wgms.mass_balance c
where a.name like 'STORGLACIAEREN'
and a.internal_key = b.glacier
and a.internal_key = c.glacier
and c.year = b.year
and c.lower_bound = 9999
and b.year = 1983
order by a.name,b.year;

Result:

Name	Year	Equilibr_Ln_Alt	AAR	Net_Balance
Storglaciaeren	1983	1,402	54	280

A 'wgmsuser' has the ability to print the selected data on a ASCII-File. With the following commands at the beginning of a question, a file will be written to the host computer:
spool test.dat
set pagesize 2000
select ... from ... where ...
spool off

5. By the end of 1997 it will be possible to directly access the WGMS database via World Wide Web. As soon as this will be possible there will be an anouncement on the WGMS Homepage or via the list server of IGS. The WGMS Homepage is reachable via:
http://www.geo.unizh.ch/wgms/

Addresses of the WGMS:

World Glacier Monitoring Service
Prof. Dr. W. Haeberli, Director
Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland
Phone: +41/(0)1/635 51 20/21
Fax: +41/(0)1/635 68 48
e-mail: haeberli@geo.unizh.ch

World Glacier Monitoring Service
Dr. M. Hoelzle
Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zentrum, CH-8092 Zürich Switzerland
Phone: +41/(0)1/632 40 94
Fax: +41/(0)1/632 11 92
e-mail: hoelzle@vaw.baum.ethz.ch
or
Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland
Phone: +41/(0)1/635 51 39
Fax: +41/(0)1/635 68 48

World Glacier Monitoring Service
S. Suter
Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zentrum, CH-8092 Zürich Switzerland
Phone: +41/(0)1/632 41 23
Fax: +41/(0)1/632 11 92
e-mail: stephan.suter@vaw.baum.ethz.ch
or
Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland
Phone: +41/(0)1/635 51 39
Fax: +41/(0)1/635 68 48
e-mail: stsuter@geo.unizh.ch

INTERNATIONAL ARCTIC SCIENCE COMMITTEE (IASC)*

IASC Priority Projects

Core Groups and Networks (Status on 20 April 1995):

Names and Addresses of IASC Core Group 2.1:

Mass Balance of Glaciers and Ice Sheets

Names and Addresses of IASC Network 2.1

Mass Balance of Glaciers and Ice Sheets

*Information furnished by Carl S. Benson, University of Alaska, Geophysical Institute

Address of IASC Secretariat:

Odd Rogne
Middlethunsgate 29
P.O. Box 5072, Majorstua
0301 Oslo, Norway
Tel: 47-22-95-96-00
Fax: 47-22-95-96-01
e-mail: iasc@polar.no

IASC Core Group 2.1

Mass Balance of Glaciers and Ice Sheets

CANADA	Dr. Roy M. Koerner Terrain Sciences Division Geological Survey of Canada 601 Booth Street Ottawa, Ontario K1A OE8	Fax: Phone:	1-613-996-5448 1-613-997-7623
DENMARK	Dr. Niels Reeh Danish Center for Remote Sensing Electromagnetics Institute Technical University of Denmark B348 DK-2800 Lyngby	Fax: Phone:	45-4593-1634 45-4525-3800
FRANCE	Dr. Bernard Lefauconnier LGGE BP 96 38402 St Martin d'Hères CEDEX	Fax: Phone:	33-76-82-4200 33-76-82-4201
JAPAN	Dr. Okistugu Watanabe National Institute of Polar Research 9-10 Kaga 1-Chome, Itabashi-ku Tokyo 173	Fax: Phone:	81-3-3962-5719 81-3-3962-4711
NORWAY (Chairman)	Dr. Jon Ove Hagen Dept. of Geography University of Oslo Box 1042 Blindern 0316 Oslo	Fax: Phone: e-mail:	47-22-85-7230 47-22-85-4038 j.o.hagen@geografi.uio.no
RUSSIA	Dr. Andrei F. Glazovsky Deputy Director Geographical Institute Staromonetny Street 29 Moscow 109017	Fax: Telex:	7-095-230-2090 411781 GLOBE SU
RUSSIA	Dr. Vladimir Kotlyakov Geographical Institute Staromonetny Street 29 Moscow 109017		

SWEDEN (Secretary)	Dr. Per Holmlund Dept. Of Physical Geography Stockholm University S-1069 Stockholm	Fax: 46-8-164818 Phone: 46-8-164811
UNITED KINDDOM	Dr. Julian A. Dowdeswell Centre for Glaciology Institute of Earth Sciences University of Wales Aberystwyth, Dyfed SY23 3DB	Fax: 44-1970-622780 Phone: 44-1970-622782 e-mail: jud@aber.ac.uk

Note: We asked the WG for advice on a group of 5-7 persons. As the WG contains many active and good scientists, there were problems making a selection. Geographical coverage of glaciers has been one of the criteria for the Core Group.

IASC Network 2.1

Mass Balance of Glaciers and Ice Sheets

CANADA	Dr. David Fisher Geological Survey of Canada	Fax:	1-613-996-5448
CANADA	Dr. Gerald Holdsworth University of Calgary	Fax:	1-403-282-4609
FINLAND	Dr. John C. Moore Arctic Centre, University of Lapland Box 122 FIN-96101 Rovaniemi	Fax: Phone:	358-60-324-777 358-60-324-757
FRANCE	Dr. Louis Reynaud LGGE, Domaine Universitaire 54, rue Moliére, P B 96 38402 St Martin d'Hères, CEDEX	Fax:	33-76-824201
GERMANY	Prof. H. Miller AWI Institute for Polar and Marine Research P.O. Box 120161 D-27515 Bremerhaven 12	Fax: e-mail:	49-471-483-149 miller@awi-bremerhaven.de
ICELAND	Dr. Helgi Björnsson Science Institute University of Iceland Dunhaga 5 107-Reykjavik	Fax: Phone: e-mail:	354-1-28801 354-1-694730 hb@raunvis.hi.is
NETHERLANDS	Prof. Dr. J. Oerlemans IMOU, University of Utrecht P.O. Box 80 005 3508 TA Utrecht	Fax: Phone:	31-30-543163 31-30-533272
POLAND	Dr. Jacek Jania Dept. Of Geomorphology Univ. of Silesia, Fac. Of Earth Science ul. Bedzinska 60 41-200 Sosnowiec	Fax: Phone: Telex:	48-32-664351 48-32-662025 315920

SWITZERLAND	Prof. Atsumu Ohmura Department of Geography Swiss Federal Institute of Technology Winterthurerstr. 190 CH-8057 Zürich	Fax: 41-1-362-5197 Phone: 41-1-257-5220 or 11
USA	Dr. Richard Alley College of Earth and Mineral Sciences Pennsylvania State University 0306 Deike Building University Park, PA 16802	e-mail: ralley@essc.psu.edu
USA	Dr. Roger Barry World Data Center - A for Glaciology Campus Box 216 University of Colorado Boulder, CO 80309-0216	e-mail: roger.barry@colorado.edu
USA	Dr. William Harrison Professor of Physics Geophysical Institute P O Box 757320 University of Alaska Fairbanks, AK 99775-7320	Fax: 1-907-474-7290 Phone: 1-907-474-7558 e-mail: harrison@dino.gi.alaska.edu
USA	Dr. Mark Meier Institute of Arctic and Alpine Research University of Colorado at Boulder 1560 Thirtieth St. # 261 Campus Box 450 Boulder, CO 80309	Fax: 1-303-492-6388 e-mail: mark.meier@colorado.edu
USA	Dr. Terry Tucker Research Division, Snow and Ice Branch CRREL Hanover, NH	Fax: 1-603-646-4644
USA	Dr. Ed Waddington Department of Geosciences University of Arizona Tuscon, AZ	