Report GD-32

GLACIOLOGICAL DATA

PAPERS AND RECOMMENDATIONS:

Snow Watch 2002 Workshop
and
Workshop on Assessing Global Glacier Recession

National Snow and Ice Data Center
World Data Center for Glaciology, Boulder

December 2003

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PREFACE

This issue contains the reports and recommendations from two workshops. The Snow Watch 2002 continued a series that began in 1978. The most recent workshop was hosted by NOAA in Camp Spring, MD, 31 October through 1 November, 2002. It was convened by Bruce Ramsay, whose assistance is much appreciated.

The Workshop on Global Glacier Recession was held in Boulder, CO, 16-18 March 2003. Funding for the workshop was provided by NSF (EAR-0307144) through a grant to Roger Barry. The responsible Program Manager was Dr. Douglas James (GEO/EAR). Contributing funds were contributed by Drs. Jane Dionne (OPP), H. Richard Lane (GEO/EAR), Cassandra Dudka (NSF International), Julie Palais (OPP), and David Verado (GEO/ATM).

Thanks are due to Kathy Zellers, CIRES, who coordinated the workshop logistics, Daryl Kohlerschmidt, NSIDC, for clerical support, and Amy Casey, NSIDC, for editorial assistance.

Roger G. Barry
Director
National Snow and Ice Data Center
World Data Center for Glaciology, Boulder

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National Snow and Ice Data Center
World Data Center for Glaciology, Boulder

SNOW WATCH 2002 WORKSHOP INTRODUCTION

31 October - 1 November 2002
National Oceanic and Atmospheric Administration
Room 4527, Silver Spring Metro Complex 3 (SSMC3)
1315 East-West Highway
Silver Spring, Maryland, USA 20910

Snow Watch is an informal, ad hoc group that has met at intervals over the past 25 years to assess the status of data on large-scale snow cover. The first Snow Watch was held in 1978 (published in Glaciological Data GD-11, 1980). It was organized by George Kukla, Alan Hecht, and Don Wiesnet. The second meeting was held in 1985 (published in GD-18, 1986), organized by George Kukla, Roger Barry, Alan Hecht, and Don Wiesnet. The third Snow Watch was held in 1992 (published in GD-25, 1993), organized by Ellsworth LeDrew, Barry Goodison, and Roger Barry. The latest meeting was organized by Bruce Ramsay, Dorothy Hall, David Robinson, and Roger Barry.

The timing of the 2002 meeting was particularly appropriate in view of new, daily snow cover data planned by NOAA-NESDIS, the availability of MODIS snow maps, and extensive work on passive microwave mapping of snow cover extent and snow water equivalent since the early 1990s.

Roger G. Barry

SNOW WATCH 2002 AGENDA

THURSDAY, OCTOBER 31, 2002

INTRODUCTION AND WELCOME

Convener: Bruce Ramsay

Co-conveners: Roger Barry, Dorothy Hall, Dave Robinson

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   and Dorothy K. Hall

   A BLENDED SNOW COVER DATA SET

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   CURRENT AND FUTURE SNOW MAPPING AT NOAA/NESDIS

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Dorothy K. Hall, George A. Riggs, Greg R. Scharfen, and Marilyn Kaminski

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   DEVELOPMENT OF A GRIDDED NORTH AMERICAN SNOW DEPTH AND WATER EQUIVALENT DATA SET FOR GCM EVALUATION - RESULTS WITH AN ENHANCED SNOWPACK MODEL

   R. Brown, B. Brasnett and D. Robinson

   RELATIONSHIPS BETWEEN SPATIAL PATTERNS OF SNOW WATER EQUIVALENT AND ATMOSPHERIC CIRCULATION FOR CENTRAL NORTH AMERICA, 1978 - 2001

   C. Derksen, E. LeDrew, and A. Walker

THE NORTHERN HEMISPHERE'S SPRING SNOW "DROUGHT"

David A. Robinson

AN ANALYSIS OF THE SPRING SNOW "DROUGHT" OF RECENT DECADES IN TERMS OF SNOW-AO RELATIONSHIP ON WEEKLY TO MONTHLY TIME SCALES

Anjuli Bamzai

RELATION OF SPRING SNOW "DROUGHT" OF RECENT DECADES TO PHASE OF AO AND PNA DURING PREVIOUS WINTER SEASON

Anjuli Bamzai

FRIDAY, 1 NOVEMBER 2002

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3. Snow cover climate interactions and associations (empirical, and modeled)

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   Richard L. Armstrong and Mary Jo Brodzik

   PRELIMINARY RESULTS FROM AMIP-2: SNOW EXTENT AND WATER EQUIVALENT SIMULATIONS

   Allan Frei, James Miller, David Robinson, Ross Brown, Thomas Mote, and Andrew Grundstein

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4. Snow cover hydrology

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   SNOW COVER AND ITS ABLATION IN THE APPALACHIAN MOUNTAINS

   Daniel J. Leathers

   STREAMFLOW RESPONSE TO SNOW COVER EXTENT CHANGE IN LARGE SIBERIAN RIVERS

   Daqing Yang, David Robinson, Yuanyuan Zhau, and Thomas Estilow

   THE IMPACTS OF ANOMALOUS SWE ON THE ENERGY AND WATER BUDGETS IN THE RED RIVER BASIN OF MINNESOTA AND NORTH DAKOTA

   Andrew Grundstein

   THE AUTOMATED MULTISENSOR SNOW MAPPING SYSTEM

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   A COMPARISON OF TWO SATELLITE-BASED SNOW COVER PRODUCTS FOR THE COLORADO RIVER BASIN

   S.J.S. Khalsa, A. Nolin, A. Barrett

BREAKOUT SESSIONS

FUTURE PRODUCTS

SNOW COVER AS A CLIMATE CHANGE INDICATOR

SNOW COVER CLIMATE INTERACTIONS

SNOW HYDROLOGY

SNOW WATCH 2002 ABSTRACTS

Planned Contributions of the WCRP Climate and Cryosphere (CliC) Project to Snow Cover Studies

Roger G. Barry

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Formal discussions within the World Climate Research Programme (WCRP) since 1997 have addressed the question of the role of the cryosphere in the climate system. In March 2000 a Science and Coordination Plan for a new Climate and Cryosphere (CliC) project was approved by the WCRP Joint Scientific Committee. The concept of this plan and particular topics of concern for snow cover are discussed here.

The overall science goal of CliC is to assess and quantify the impacts of climate variability and change on components of the cryosphere and their consequences for the climate system, and determine the stability of the global cryosphere. To achieve this, CliC aims to:

- Enhance the observation and monitoring of the cryosphere.
- Improve understanding of the physical processes and feedbacks through which the cryosphere interacts within the climate system.
- Improve the representation of cryospheric processes in models.

Integration of existing cryospheric projects within a global research structure, together with new efforts addressing current gaps, is required in order to:

- Enhance links between regional and global climatic components studies.
- Promote appropriate treatment of cryospheric processes in climate models.
- Assemble and make accessible quality-controlled, well-documented, comprehensive, and coherent global gridded data sets necessary for driving and validating climate models.

Relevant cryospheric elements relating to snowfall and snow cover include:

- Improved solid precipitation measurements
- Spatial variability of snow water equivalent (SWE)
- Contribution to runoff
- Interactions with frozen ground, glaciers, ice sheets and sea ice
- Better knowledge of altitudinal distribution and characteristics

The principal scientific questions relate to the interactions of snow cover and seasonally frozen ground and their influence on the hydrologic cycle and the impact of changes in snow cover on water resources. Another element of CliC will address monitoring cryospheric indicators of climate change, including snow extent and SWE. Please find more details at http://clic.npolar.no.

Passive Microwave Derived Snow Cover Products for Canadian Regions – Supporting Research and Operational Applications

Anne Walker, Arvids Silis, Chris Derksen, and Murray Mackay

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The Climate Research Branch (CRB) of the Meteorological Service of Canada has a long-standing research program focused on the development of methods to retrieve snow cover information from passive microwave satellite data for Canadian regions. Algorithms that derive snow water equivalent (SWE) have been developed by CRB and university collaborators and validated for a number of landscape regions, including prairie, boreal forest and taiga. The SWE algorithms are used with SSM/I data to generate regional snow cover products that support a number of research and operational applications. Maps depicting SWE distribution over areas in western Canada are produced on a regular basis each winter (e.g. weekly) using SSM/I data accessed in near-real time. These maps are distributed to a variety of users such as national and provincial water resource agencies, agricultural agencies, hydropower companies, and meteorological forecast offices to support their operational activities. The distribution of SWE maps by e-mail and the Internet (State of the Canadian Cryosphere web site: *www.socc.ca*) has widened the range of applications for the products over the past few years. Within the Climate Research Branch (CRB), passive microwave-derived snow cover information is contributing to research on snow cover and climate interactions, including the investigation on linkages between snow cover and atmospheric circulation and validation of the Canadian Regional Climate Model. Passive microwave-derived SWE data sets are also provided to university collaborators within the Canadian Cryospheric System (CRYSYS) project to investigate the climate and hydrological significance of snow cover variability at study sites throughout Canada.

This presentation will provide an overview of the status of passive microwave snow cover retrieval in Canada and the related challenges for SWE algorithm development and validation. Examples of the regional snow cover products currently being generated with SSM/I data will be presented, with descriptions of the various research and operational applications for which they are being used. Potential future enhancements to SWE retrieval with new satellite passive microwave sensors such as Advanced Microwave Scanning Radiometer (AMSR) (EOS Aqua and ADEOS-2) will also be discussed, including plans for AMSR snow cover field validation campaigns in Canada.

Global Snow Depth Monitoring Using Passive Microwave Data

Richard E.J. Kelly[1,2], Alfred T.C. Chang[2], James L. Foster[3], and Dorothy K. Hall[4]

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[2, 3] Hydrological Sciences, NASA/Goddard Space Flight Center, Greenbelt, MD

We describe an approach to estimate global snow cover using satellite passive microwave data. Snow cover is detected using the high-frequency scattering signal from natural microwave radiation, which is observed by passive microwave instruments. Developed for the retrieval of global snow depth and snow water equivalent using Advanced Microwave Scanning Radiometer-EOS (AMSR-E), the algorithm uses passive microwave radiation along with a microwave emission model and a snow grain growth model to estimate snow depth.

The microwave emission model is based on the Dense Media Radiative Transfer (DMRT) model that uses the quasi-crystalline approach and sticky particle theory to predict the brightness tem-

perature from a single layered snowpack. The grain growth model is a generic, single-layer model based on an empirical approach to predict snow grain size evolution with time. Gridding to the 25 km EASE-grid projection, a daily record of Special Sensor Microwave/Imager (SSM/I) snow depth estimates was generated for December 2000 to March 2001. The estimates are tested using ground measurements from two continental-scale river catchments (Nelson River, USA and the Ob River, Russia).

This regional-scale testing of the algorithm shows that for passive microwave estimates, the average daily snow depth retrieval standard error between estimated and measured snow depths ranges from 0 cm to 40 cm for point observations. Bias characteristics are different for each basin. A fraction of the error is related to uncertainties about the grain growth initialization states and uncertainties about grain size changes through the winter season that directly affect the parameterization of the snow depth estimation in the DMRT model. Also, the algorithm does not include a correction for forest cover, and this effect is clearly observed in the retrieval. Finally, error is also related to scale differences between *in situ* ground measurements and area-integrated satellite estimates. With AMSR-E data, improvements to snow depth and water equivalent estimates are expected, since AMSR-E will have twice the spatial resolution of the SSM/I and will better characterize the subnivean snow environment from an expanded range of microwave frequencies.

A Blended Snow Cover Data Set

David A. Robinson and Thomas Estilow

Department of Geography, Rutgers University, Piscataway, NJ

To date, there is no research-quality data set in direct support of climate and global change studies that contains files of snow extent, depth, and water equivalent, and incorporates information from multiple observing systems. This presentation will discuss a blended data set that is currently under development at Rutgers. Northern Hemisphere continental snow data are being integrated using the best available visible and microwave satellite data and surface observations. The analysis period runs from the late 1960s through the present. High-resolution, digital files of snow extent will be spatially and temporally complete, while depth and especially water equivalent will have regions and intervals where data are not available. Included in the presentation will be a discussion of the methods used to measure snow, along with the strengths and weaknesses of satellite and station techniques.

Current and Future Snow Mapping at NOAA/NESDIS

Bruce H. Ramsay

Office of Research and Applications, NOAA/NESDIS,
Camp Springs, MD

The NOAA/NESDIS operational Northern Hemisphere snow and ice map migrated from a 190 km resolution weekly product (1966-1999) based on visible data only, to a 24 km resolution daily product including the use of microwave data in June 1999. The National Centers for Environmental Prediction (NCEP) of the National Weather Service have articulated new requirements that provide NESDIS with new directions in the development and operational implementation of a 1 km resolution, twice-daily global snow and ice map, and an associated snow depth or snow water equivalent global map.

There are now automated 4 km Western Hemisphere (Geostationary Operational Environmental Satellite (GOES), Advanced Very High Resolution Radiometer (AVHRR), Special Sensor Microwave/Imager (SSM/I) and global (AVHRR/3) snow and ice map products feeding the Interactive Multisensor Snow and Ice Mapping System in the Satellite Analysis Branch (SAB). By March 2003 these products will be enhanced to 1 km (where available), and the AVHRR/3 global snow and ice map will be augmented with the integration of AMSU snow and ice products. Near real-time MODIS imagery is available in SAB at resolutions of 250 m, 500 m, and 1 km, and includes global 500 m snow and ice maps. In the relatively near future, the Meteorological Operation (METOP) will provide us with operational global 1 km imagery.

The IMS will be upgraded in November 2003 to accommodate the higher-resolution automated input products and provide an improved resolution for the daily NH snow and ice map. The current product is mapped on a 24 km grid (1024 x 1024), and the resolution will be enhanced by using a 4 km grid (6144 x 6144). The IMS land/sea mask used in mapping the final product is expected to change slightly. A careful analysis is being done on points that are classified as flood plains, bogs, dry lake beds, etc., to determine if they should be considered land or water in the static land/sea mask.

Plans are in place to run a parallel test with the current IMS during the 2003-2004 NH snow season. The switch to the new IMS 4 km snow and ice map product will occur after the beginning of 2004. For the first few snow seasons, the new 4 km product will be resampled into a format that replicates the 24 km product to help ease the transition for users. Please contact Donna McNamara (Donna.Mcnamara@noaa.gov), Team Leader, Environmental Applications Team, NOAA/NESDIS/OSDPD, with any questions or comments on the operational product.

Development of a Gridded North American Snow Depth and Water Equivalent Data Set for General Circulation Model (GCM) Evaluation: Results with an Enhanced Snowpack Model

R. Brown[1], B. Brasnett[2] and D. Robinson[3]

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[2] Meteorological Service of Canada, Canadian Meteorological Centre, Dorval, Montreal, Quebec, Canada

[3] Dept. of Geography, Rutgers University, Piscataway, NJ

This presentation will provide an overview of the development and validation of a high-resolution (1/3 degree) gridded data set of snow depth and estimated SWE values for North America covering the Atmospheric Model Intercomparison Project II (AMIP II) period (1978-1996). The data set was derived from observed daily snow depth observations over Canada and the USA using a modified version of the operational snow depth analysis scheme employed at the Canadian Meteorological Centre (Brasnett, 1999). The main modification was the addition of a more detailed snowpack model (it took into account mixed precipitation, rain-melt, warm and cold snow aging, and mass loss from sublimation and blowing snow) for computing snow density and the background or first-guess field for the analysis. The background field used 6-hourly values of air temperature and precipitation from the European Centre for Medium-range Weather Forecasting (ECMWF) ERA-15 reanalysis product. Snow aging and sublimation losses were optimized for the snow-climate classes defined by Sturm et al. (1995), and the snow-climate classes used as input to the analysis process.

Evaluation of the historical analysis with independent in situ and satellite data revealed that the gridded data set was able to successfully capture the important features of the North American snow cover climate such as continental-scale variation in snow cover extent (SCE) and SWE. The snow depth climatology revealed a number of improvements over the Foster and Davy (1988) product, namely an improved representation of the snow line in June and October, and a more realistic spatial distribution of snow accumulation over the western cordillera.

The data set successfully captured interannual variability in SCE and SWE during the November to April period, but was less successful in the May-October period when the snowline was located over northern data-sparse regions. Overly rapid melt of snow in the spring contributed to this problem at high latitudes. The gridded snow depth and SWE data set represents an important new source of information for the evaluation of climate and hydrological models, satellite algorithm development, and climatological applications. The monthly snow depth and estimated

SWE climatologies are available for downloading from the Canadian Cryospheric Information Network (http://www.ccin.ca). Further details of this work are provided in Brown et al. (2002).

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Relationships Between Spatial Patterns of Snow Water Equivalent and Atmospheric Circulation For Central North America, 1978 - 2001

C. Derksen[1], E. LeDrew[2], and A. Walker[1]

[1]Climate Research Branch, Meteorological Service of Canada, Downsview, Ontario, Canada

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Characterizing regional snow cover patterns and identifying the atmospheric triggers to their accumulation and ablation is significant, given the important role that snow cover plays in global energy and water cycles. Satellite passive microwave data are useful sources of snow cover information for synoptic scale studies of this nature because of all-weather imaging capabilities, rapid scene revisit, a time series of rigorous length, and the ability to derive quantitative estimates of snow water equivalent (SWE). In this study, 23 winter seasons (December, January, February 1978/79 to 2000/01) of five-day averaged (pentad) passive-microwave derived SWE imagery are used to examine the seasonal snow cover characteristics of a ground-validated western North American study area. Previous analysis has shown that SWE retrievals are systematically lower for SMMR seasons relative to SSM/I seasons, so a pentad-to-pentad change-in-SWE (ΔSWE) data set was used to ensure cross-platform consistency through the passive microwave time series.

Rotated principal components analysis (RPCA) identified eight dominant patterns of ΔSWE within the time series – the positive and negative phases of the first four rotated components. 500 mb geopotential height and 700 mb temperature fields produced from gridded National Center for Environmental Prediction (NCEP) data illustrate that physically logical and consistent tropospheric patterns are associated with the ΔSWE components. Regional SWE increases (as characterized by ΔSWE PC1+, PC2-, PC3+, PC4+) are observed when there is a deep, 500 mb Arctic low over eastern North America, displacing a ridge westward over the eastern Pacific, resulting in strong north-south advection of cold Arctic air through the continental interior. Alternatively, regional patterns of decreasing SWE (as characterized by ΔSWE PC1-, PC2+, PC3-, PC4-) are associated with an eastward migration of the 500 mb ridge, allowing advection of warm air into central North America from the southwest. Difference-of-means tests illustrate that significant regional differences in tropospheric circulation are evident between the dominant spatial modes of snow accumulation versus ablation in western North America. The location and phase of the difference centers-of-action suggest that tropospheric circulation coincident to dynamic snowpack changes in central North America is similar to the Pacific/North American teleconnection pattern.

The Northern Hemisphere's Spring Snow "Drought"

David A. Robinson

Department of Geography, Rutgers University, Piscataway, NJ

Evaluation of satellite data indicates a reduction in the extent of snow cover over Northern Hemisphere lands since the late 1980s compared to the previous 20 years. Analyses of station observations over portions of Eurasia and North America suggest that the recent decreased coverage is unprecedented in spring over the past century. Weekly visible-wavelength satellite maps of Northern Hemisphere snow cover produced by the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Data and Information Service (NESDIS) are used to evaluate large-scale snow extent. To date, these maps constitute the longest satellite-derived environmental data set available.

The tendency towards less late-season cover in recent years begins in February. During 8 of the first 20 years of record, February snow extent exceeded the January value. This has occurred only once in the past 16 years. This snow "drought" is associated with observations of warmer spring temperatures, the timing of phenologic green-up, and seasonal atmospheric CO_2 levels. Clearly, the implications of the snow signals with regard to climate change are quite important. Research continues to improve our understanding of the role of snow cover in the climate system. New data sets are being prepared, and empirical and modeling investigations of linkages between snow and other climate variables are under way.

An Analysis Of The Spring Snow 'Drought' Of Recent Decades In Terms Of Snow-AO Relationship On Weekly To Monthly Time Scales

Anjuli Bamzai

Center for Ocean-Land-Atmosphere Studies, Calverton, MD

Based on weekly AVHRR satellite-derived global snow cover data for the period 1972-2001, the climatology and interannual variability of snow onset day-of-year, snowmelt day-of-year, and number of snow-free days in a year, is presented. A linear trend analysis at each grid point indicates the increase in number of snow-free days over large, coherent regions of the Northern Hemisphere is primarily due to a trend in early snow melt day-of-year. This trend is consistent with the inverse relationship between snow cover-Arctic Oscillation (AO) index, as evidenced in both the weekly and monthly data. On weekly time scales, composite snow extent anomalies are maximum when AO leads snow cover by a week. Composite snow cover anomalies are maintained several weeks after the AO is in the anomalous phase, particularly for AO in its negative phase. Maps of composite snow cover anomalies for AO leading snow cover by one week, delineate the spatial structure of snow anomalies. Monthly lagged correlation between snow cover and AO, for the raw as well as detrended data, show significant inverse correlation between wintertime AO and concurrent/subsequent snow anomalies.

Relation of Spring Snow "Drought" of Recent Decades to Phase of AO and PNA During Previous Winter Season

Anjuli Bamzai

Center for Ocean-Land-Atmosphere Studies, Calverton, MD

Based on monthly AVHRR satellite-derived snow cover data for the period 1972-2001, the climatology and standard deviation of spring snow cover are presented. The climatology and interannual variability for the initial and latter 15-year record is also examined. There has been a dramatic decrease in spring snow cover during the second half of the record over large-scale regions of the Northern Hemisphere. To further understand and attribute the cause of this spring "drought" in recent decades, composite snow cover anomalies are constructed for anomalous phases of El Niño Southern Oscillation (ENSO), Arctic Oscillation (AO), and Pacific North Amer-

ican (PNA) during preceding winter season. The response to ENSO is complex. The response to PNA phase is distinct over North America, whereas the response due to AO has a signature over eastern North America as well as Eurasia. The trend in spring snow cover is shown to be consistent with the relatively larger number of years with winter AO and PNA in a particular anomalous phase during the latter part of the record.

Monitoring Global Snow Cover Using Passive Microwave Satellite Remote Sensing: Long-Term Climatologies from Historical Data Sets and Near Real-Time Products from EOS Data

Richard L. Armstrong and Mary Jo Brodzik

National Snow and Ice Data Center (NSIDC), Cooperative Institute for Research in Environmental Sciences (CIRES), University

Snow cover is an important variable for climate and hydrologic models due to its effects on energy and moisture budgets. Seasonal snow can cover more than 50 percent of the Northern Hemisphere land surface during the winter, resulting in snow cover being the land surface characteristic responsible for the largest annual and interannual differences in albedo.

Passive microwave satellite remote sensing can augment measurements based on visible satellite data because of the ability to acquire data through most clouds or during darkness as well as provide a measure of snow depth or water equivalent. It is now possible to monitor the global fluctuation of snow cover over a 24-year period using passive microwave data (Scanning Multichannel Microwave Radiometer (SMMR), 1978-1987 and Special Sensor Microwave/Imager (SSM/I), 1987-present). A comparison of Northern Hemisphere snow extent derived from passive microwave (SMMR and SSM/I) and visible data (NOAA snow extent charts) is presented.

Both passive microwave and visible data sets show a similar pattern of interannual variability, although the maximum snow extents derived from the microwave data are consistently less than those provided by the visible satellite data, and the visible data typically show higher monthly variability. Trends in annual averages for the two data sets are similar, decreasing at rates of approximately 2 percent per decade. During shallow snow conditions of the early winter season, microwave data consistently indicate less snow-covered area than the visible data. This underestimate of snow extent results from the fact that shallow snow cover (less than about 5.0 cm) does not provide a scattering signal of sufficient strength to be detected by the microwave algorithms.

As the snow cover continues to build during the months of January through March, as well as into the melt season, agreement between the two data types continually improves. This occurs because as the snow becomes deeper and the layered structure more complex, the negative spectral gradient driving the passive microwave algorithms is enhanced. The increased accuracy during the period of spring melt is fortunate, as this is the most important period of the snow cover season in terms of snow hydrology, thus allowing confident application of these snow water equivalent data to hydrologic forecasting and modeling.

The only region where the passive microwave data consistently indicate snow and the visible data do not is over the Tibetan Plateau and surrounding mountain areas. In an effort to determine the accuracy of the microwave algorithm over this region, we are comparing satellite data with surface snow observations through a collaborative study with the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Lanzhou, China. Finally, we are developing a procedure that blends snow extent maps derived from MODIS data with snow water equivalent maps derived from both SSM/I and NASA Advanced Microwave Scanning Radiometer-EOS (AMSR-E). The purpose of this blend is twofold: 1) to provide an optimal product that combines the particular advantages of the two sensors while simultaneously reducing their particular limitations when applied alone, 2) to provide a data structure and common image format for the use of MODIS data for validation of snow extent derived from AMSR-E. Examples from our current prototype MODIS and SSM/I blend are presented.

Preliminary Results from AMIP-2: SNOW EXTENT AND WATER EQUIVALENT SIMULATIONS

Allan Frei[1], James Miller[2], David Robinson[3], Ross Brown[4], Thomas Mote[5], Andrew Grundstein[5]

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5Dept. of Geography, University of Georgia, Athens, GA

Simulated snow covered area (SCA) and snow water equivalent (SWE) over Northern Hemisphere land by AMIP-II general circulation models (GCMs) are evaluated. SCA is evaluated using a data set derived primarily from NOAA visible band satellite imagery. SWE is evaluated using two new independently derived gridded data sets, one of which covers all of North America, the other only the Northern Great Plains. Both are based on observations, and incorporate snowpack modeling results.

With regards to SCA, at continental to hemispheric scales we find improvements over AMIP-1 models, including the elimination of temporal and spatial biases in simulations of the seasonal cycle, as well as improved simulations of the magnitude of interannual variability. At regional spatial scales, two regions over Eurasia are identified where models consistently either under- or over-estimate SCA. With regards to SWE, GCM strengths and weaknesses over particular North American regions, such as the Northern Great Plains, are identified.

Snow Cover and its Ablation in the Appalachian Mountains

Daniel J. Leathers

University of Delaware, Department of Geography, Newark, DE

Snow cover and its ablation are important elements of the hydrologic system in many areas of the world. One such area is the central portion of the Appalachian Mountains where snow melt was a factor in the majority of major flooding events during the last 50 years across many stream basins. Unfortunately, the link between major ablation events and atmospheric conditions is not well documented in this area, hampering the forecasting of such events and their associated flooding potential. This research utilizes a unique synoptic weather-typing technique and a physically based snowpack model to investigate the relationships between weather events and the energy fluxes responsible for snow melt in stream basins in central Pennsylvania and northern West Virginia. During large ablation events, sensible and latent heat fluxes are generally the most important fluxes involved in the ablation process. Depending upon the synoptic-scale weather situation, other energy fluxes (i.e. net radiation, down-welling shortwave radiation, etc.) may dominate the energy input to the ablating pack. The importance of diverse snowpack characteristics (i.e. albedo, density, grain size) are also considered in the context of ablation. Pre-1948 hourly data is also used in this analysis to drive the snowpack model.

Streamflow Response to Snow Cover Extent Change in Large Siberian Rivers

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The Lena, Yenisei and Ob rivers are the three largest rivers in the Arctic regions. They contribute more than 45 percent of total freshwater inflow to the Arctic Ocean and have great impacts to the regional/global ocean and climate systems. Snowcover melt and associated floods are the most important hydrologic event of the year in the northern river basins. To better understand the streamflow regime and variation in the high latitude regions, this research uses the weekly NOAA snow cover extent data to study the streamflow hydrology in Siberia. The focus of this research is to examine the streamflow response to snow cover extent change on a weekly basis, particularly during the spring melt period.

In this analysis, we calculated the basin-mean snow cover extent over the watersheds for the entire NOAA records (1966-present) and generated a weekly snow cover time series. We used these weekly data to examine the seasonal changes of snow cover extent, such as defining the weekly snow cover climatology, determining the dates of snow cover formation/disappearance and duration of snow cover, and quantifying the rates of snow cover change during the accumulation and melt seasons. We examined the weekly correlation of streamflow with basin-mean snow cover extent, and determined the consistency between snow cover and runoff changes during the snowmelt period. We also investigated the associations between snow cover and runoff anomalies, identified extreme snowmelt runoff cases, and examined their correspondence with snow cover and climate conditions. Based on these analyses, we defined the weekly relation between snowmelt runoff and snow cover changes for the watersheds.

This study explores the potential of using remotely sensed snow cover information to improve our capability of snowmelt runoff modeling and forecasting over large northern river basins. The results demonstrate that the NOAA weekly snow cover extent data are useful for understanding and predicting streamflow changes in arctic regions. Snow water equivalent data obtained from ground and via remote sensing will be examined in further studies.

SNOW WATCH WORKING GROUPS

Snow Watch Working Group 1: Surface Observations

Ross Brown, Chair, Roger Barry, Andrew Grundstein, Bruce Ramsay, Daqing Yang

Station Networks

The main snow surface networks comprise:

- Snowfall and solid precipitation measurements at climate and synoptic stations
- Daily snow depth observations (ruler, stake, or auto-sensor) at climate and synoptic stations
- Manual snow surveys
- Automated SWE measurement systems such as snow pillows

These data are collected by a variety of government agencies and organizations for mainly operational purposes (e.g. input to weather forecast and hydrological models). However, these data are also needed for climate monitoring, process studies, and for validation of climate model and satellite algorithms. The requirements for snow cover monitoring in support of global climate monitoring were presented by Cihlar et al. (1997). For various reasons (but mostly due to shrinking budgets), surface-based networks have experienced major declines since the 1980s. National governments were requested to identify critical gaps in networks and to propose strategies to fill these gaps as part of the implementation of a Global Climate Observing System (GCOS). For example, the Canadian National Plan for cryospheric monitoring in support of GCOS (Brown and O'Neill, 2002) proposed network optimization, increased partnering, and increased use of remote sensing as strategies for limiting the effects of decreasing surface networks.

Recommendations

- Identify surface stations of particular importance for climate monitoring and/or research activities at “Super Sites.” The Super Site concept corresponds to Tier 1 of the GCOS observing strategy, and was recommended in the WCRP Climate and Cryosphere (CliC) Project Draft Implementation Plan (http://clic.npolar.no/impl/IP260202.doc.pdf) as a mechanism for focusing resources on particular snow cover processes and snow cover-atmosphere-hydrology interactions.
- National data collection agencies provide maps of snow surface networks online, and update these on an annual basis.
- Carry out an international survey of the current status and data availability of snow surveys, snow courses, and snow pillows.
- Carry out an assessment of the current number and spatial distribution of snow depth observations reported over the GTS (these data are being archived at NCDC).

Measurement Standards

Measurement standards such as procedures and equipment are one of the key issues confronting the monitoring of snowfall, solid precipitation, snow depth, and SWE. Procedures have been developed to correct solid precipitation for the most commonly used gauges and shield types (Goodison et al., 1998). However, in some cases, the metadata required to carry out these corrections are not readily available. The automation of winter precipitation measurement has added to this problem by creating inconsistencies in solid precipitation time series. The US procedures for snowfall reporting changed for the 2002/2003 winter season with the introduction of snowboards at coop stations. The snowboards, together with an increase in the clearing frequency to once every six hours implemented about five years ago, are expected to generate some changes in maximum reported snowfall amounts.

Recommendations

- We endorse the recommendations of the WCRP Workshop on Determination of Solid Precipitation in Cold Climate Regions held in Fairbanks in June 2002. (http://acsys.npolar.no/meetings/precip/summary.pdf).
- More detailed gauge intercomparisons are required to document the impact of automation.
- Make metadata readily available on gauge and shield type.
- Provide corrected precipitation time series at a select number of key stations (Super Sites).

Historical Data

Historical snow depth (HSD) data are important for climate monitoring and for snow cover-climate relationships. For example, the availability of the HSD data set for the Former Soviet Union (FSU) has enabled a large number of studies on snow cover-atmosphere linkages over Eurasia. Historical daily snow depth data are now available for the US and Canada; the main remaining gaps are European countries, China, and the Southern Hemisphere. Considerable care is required in the interpretation of historical snowfall data due to changes in equipment and observing procedures.

Recommendations

- Update FSU snow data sets (HSD and snow course transects).
- Obtain Mongolian and Tibetan historical snow cover data.
- Make Alaskan SNOTEL data available. (Daqing Yang reported that current SNOTEL data are available online at http://www.ambcs.org and that historical data can be obtained by contacting Rick McClure at rmcclure@ak.usda.gov)
- Carry out an inventory of Southern Hemisphere snow data sets.
- Investigate methods for extracting information on snow from mass balance records and other paleo-proxy records.
- There is a need to create daily gridded historical snow depth and snowfall data sets for research on snow-climate interactions.
- Publish national climatologies of snow depth, SWE, and density for climate model evaluation. In particular, there is little published information on the seasonal variation in snow density at continental scales.

Field Programs

Recommendations

- We endorse the CliC concept of “Super Sites” for instrument comparisons, process and scaling studies, and model and satellite algorithm development. Develop a list of potential Super Sites.
- Develop an inventory of snow field sites with data suitable for running detailed snowpack models, e.g. Col de Porte, Sleepers River, Weissflujoch, Davos, Mammoth Mountain, BERMS, etc.

Progress Since Snow Watch '92

There was no specific WG whose task was looking at surface networks in the last SNOW WATCH. However, important progress has been made in three key areas that were flagged for attention at the 1992 meeting:

- Data Rescue - considerable progress has been made in rescuing snow data from the FSU (snow depth and snow sources) and in making Canadian and US snow data available to the research community. China and Europe are the two remaining areas where snow data are not readily available.
- Observing Practices - the completion of the WMO precipitation intercomparison project has provided a standard way to correct for precipitation undercatch (Goodison et al., 1998).
- Metadata - the adoption of FGCD metadata standards and the sharing of data sets via the Z39.50 search protocol has promoted extensive documentation of data sets. However, there is still much work to be done (e.g. documentation of precipitation measurements).

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Snow Watch Working Group 2: Spatial Variability

Dorothy Hall, Chair, Chris Derksen, Allan Frei, Siri Jodha Khalsa, Tom Mote, Greg Scharfen

History of Accomplishments

A brief history of accomplishments since the last Snow Watch meeting in 1992:

In approximately the last ten years there have been many important accomplishments in the snow community. Some of them are listed below (not in priority order).

Major advances have been made in satellite remote sensing, as opposed to those accomplished using ground measurements. For example, the spatial resolution of the passive-microwave sensors had been relatively constant since the early 1970s, at around 30 km2. With the launch of the Advanced Microwave Scanning Radiometer (AMSR) on the Aqua satellite in May of 2002, the resolution has increased to about 10 km^2. Important advances in determination of snow water equivalent (SWE) from space are expected as a result of the resolution increase. In addition, snow/cloud discrimination using visible, near-IR, and short-wave IR sensors has improved dramatically with the inclusion of a 1.6 mm band on the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Frequency Radiometer (AVHRR) sensors, providing greatly improved measurement of snow covered area (SCA). Also, the improved resolution (up to 250 m) of MODIS permits detailed basin-scale studies of SCA on a daily basis when not precluded by cloud cover.

It had been widely recognized that the NOAA weekly SCA maps, begun in 1966, were of great importance, but they had been developed in an inconsistent manner. Especially problematic were the maps from 1966 to 1972, in part because of the poorer satellite data available for mapping as compared to data available in more recent years. The Rutgers group has developed a detailed, quality-controlled reanalysis of that entire data set, resulting in a consistent snow cover record, now of far greater use to the climate community.

NOAA began providing daily SCA maps in 1998 using the Interactive Snow and Ice Mapping System (IMS), effectively replacing the weekly maps in 1999. The new maps are not only more frequent, but have dramatically improved spatial resolution (from 190 km^2 for the weekly maps, to 24 km^2 for the IMS maps).

SCA maps are increasingly automated. The MODIS daily SCA maps, at 500 m resolution, and 0.05° resolution for climate studies, are global and fully automated, which is important for long-term climate studies as the maps are developed in a consistent manner. Ongoing improvements in the snow-mapping algorithms are implemented during periodic reprocessing of the MODIS data. The IMS maps are largely automated but include some human interpretation and use of persistence when cloud cover restricts the incorporation of new observations. The value of some routine observation for quality control was recognized. NOAA also has a daily, automated experimental snow product.

Important field measurement programs have been undertaken, namely the BOREAS and CLPX experiments. The BOREAS experiment permitted the Canadians to improve the regional SWE operational maps of the Canadian Prairies.

Negative “progress” was also noted. The importance of maintaining meteorological stations was emphasized, and it was noted that many meteorological stations have been closed due to a lack of funding during the last 10 years. It is important to note that satellite data can never fully replace in situ measurements.

Important Future Issues

Climate-modeling products necessary for validating general-circulation models (GCMs) are required. Modelers state that they will be able to run their GCMs at increasingly higher spatial resolutions in the near future and they require SCA, SWE, and fractional-snow cover (FSC). They also like uniformity in gridding, as many modelers express a desire for latitude/longitude grids. Error estimates for SCA, SWE, and FSC products are essential. Furthermore, automated regridding and knowledge of errors associated with regridding are needed.

Data set synergy and data fusion are necessary for future improvements of snow products. For example, several researchers are developing SCA/SWE products using both visible/near-IR and passive-microwave satellite products. Researchers are currently working on “blended” products, combining all types of data (satellite, station, snow course, etc.)

K- or Ka-band satellite-borne radars would be potentially very useful for snow-cover and SWE studies. Such instruments should be planned and launched in the near future.

There has been very little work on seasonal snow cover of the Southern Hemisphere, in part because it has not been feasible to view the Southern Hemisphere on a daily basis until recently. The extensive cloud cover has precluded detailed studies. With the advent of MODIS data available to download from the Internet, such studies are now possible, and should be emphasized for both climatological and water-resource purposes. Southern Hemisphere snow line studies would also have value for climate studies.

Snow Watch Working Group 3: Time Series and Change Detection

David A. Robinson, Chair; I. Appel, A. Bamzai, M.J. Brodzik, A. Chang, N Elgindi, R. Kelly, D. Leathers, T. Mote, and A. Walker

Overview

This working group focused on snow cover time series and change detection. Our concern was where monitoring and research endeavors should be focused. We realize that acquiring accurate observations of snow cover, or any climate variable for that matter, requires considerable effort that is not often newsworthy. However, it is important work, and accurate data are a must for forecasting, diagnostic, and modeling initiatives. With proper databases, sound statistical/ analytical techniques, and creative approaches, we will continue to gain increased confidence in our evaluation and understanding of snow cover variability and potential long-term trends. This can only help to increase our understanding of the climate system, identify natural and anthropogenic snow signals, and discover linkages between variations in snow and other components of the cryospheric and climate systems.

Snow Cover Records

Not only has a decade of satellite data increased the length of global snow cover records since Snow Watch 1992, but the quality of these observations has increased. Earlier satellite-derived snow maps have been reanalyzed, new sensors have recently begun to map snow, maps primarily using visible data are being created daily, not weekly, and daily station observations of snow depth, and in some cases, snow water equivalent, are increasingly available. This includes station records of snow cover that extend back a century.

Despite these gains, more attention must be paid to gathering and blending data records from station and satellite sources. This includes metadata gathering efforts to help assure that identified variations may confidently be attributed to real changes, not a function of observational inconsistencies. Documentation of surface observations is needed, paying attention to such factors as time of observation, land use changes, etc. Overlapping periods of observation when sensors change are also a necessity. Such important quality assurance/quality control must be made part of the culture or it will not be accomplished in a satisfactory manner.

Statistical Evaluation

Before attempting to extract any signal in a snow time series, one must first make sure to eliminate as much error as possible from the observations. The past decade has seen improvement in error analysis for most climate variables, however more attention remains to be paid to snow cover. With more complete and seemingly higher-quality data available, additional quality assurance will lead to more confident analyses, including the possibility of differentiating between potential natural and anthropogenic signals.

Creativity

Snow scientists have long exhibited creativity in the collection and analysis of snow cover information. Future years will no doubt continue this. Data gathering efforts should continue expanding time series in space and time. This includes Southern Hemisphere continental cover and snow over sea ice and ice sheets. Additional in situ records must be assembled for regions and earlier periods where such observations are currently unavailable to the international research community. While it is certainly difficult, it would be most useful if natural proxies for snow cover variability in the distant past were discovered, whether the past is measured in centuries, millennia, or longer. All such data sets should continue to be integrated, using geographic information systems and innovative interpolative techniques.

With improved data in hand, creative efforts should focus on examining temporal and scalar snow cover issues. The sensitivity of interannual variability of snow with respect to the climate system needs continued attention. This includes processes associated with the deposition, evolution, and ablation of cover at local, regional, continental, and global scales, making sure that investigations cut across various scales. Evaluations of variability and trends must examine a variety of snow parameters, including, for example, seasonal start, end, length, ablation days, extreme events, water equivalent, depth, albedo, and patchiness. Observed variability and trends should be evaluated with respect to model reconstructions and projections.

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Section 2: Workshop on Assessing Global Glacier Recession

National Snow and Ice Data Center
World Data Center for Glaciology, Boulder

ASSESSING GLOBAL GLACIER RECESSION WORKSHOP AGENDA

SUNDAY, MARCH 16, 2003

THE STATE OF WORLD GLACIERS

Roger Barry

CHALLENGES AND STRATEGIES FOR WORLDWIDE CLIMATE-RELATED GLACIER MONITORING IN THE 21ST CENTURY

Wilfried Haeberli

WHY ARE WE HERE? GLACIER VARIATIONS AND THEIR RELATION TO CLIMATE, SEA LEVEL, AND EVERYTHING

Mark Meier

OBSERVATIONAL EVIDENCE OF ACCELERATION IN GLACIER WASTAGE: UNCERTAINTY IN PREDICATION

Mark Dyurgerov

GLACIER MASS BALANCE TRENDS IN SVALBARD AND SCANDINAVIA

Jon Ove Hagen

TWO-MINUTE POSTER OVERVIEWS

DISCUSSION AND WORKING GROUP ORGANIZATION

GROUP #1 - ASSESSMENT OF GCOS GLACIER VARIABLES AND IDENTIFYING GAPS

GROUP #2 - EXTENDING AND IMPROVING THE WORLD GLACIER INVENTORY

GROUP #3 - GLACIER MAPPING TECHNIQUES

BRIEF DISCUSSION GROUP REPORTS

MONDAY, MARCH 17

GLACIER MAPPING AND DATABASES

Roger Barry

ORAL PRESENTATIONS

GLACIER MAPPING BASED ON HISTORICAL DATA AND ASTER IMAGERY: PROSPECTS AND PROBLEMS

Tanya Khromova

GLACIER INVENTORY OF CHINA AND GLACIER CHANGE IN THE PENQU AREA, TIBETAN PLATEAU

Li Xin

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD
Richard Williams

GLIMS - GLOBAL LAND ICE MEASUREMENTS FROM SPACE
Jeff Kargel

ACCURACY ASSESSMENT OF MEASURING GLACIER TERMINUS CHANGES FROM SPACE
Dorothy Hall

DEMONSTRATION OF THE GLIMS DATABASE—DISCUSSION FOLLOWS
Bruce Raup

DISCUSSION AND WORKING GROUPS

GROUP #1 - ASSESSMENT OF GCOS GLACIER VARIABLES AND IDENTIFYING GAPS

GROUP #2 - EXTENDING AND IMPROVING THE WORLD GLACIER INVENTORY

GROUP #3 - GLACIER MAPPING TECHNIQUES

BRIEF DISCUSSION AND WORKING GROUP REPORTS

POSTER SESSION/RECEPTION

TUESDAY, MARCH 17

CRITICAL REGIONS AND SPECIAL REGIONAL/NATIONAL PROBLEMS

Roger Barry

SHORT REPORTS

Anthony Arendt, Vladimir Aizen, William Manley, and others

GENERAL DISCUSSION

DISCUSSION AND WORKING GROUP REPORT WRITING

GROUP 1 - ASSESSMENT OF GCOS GLACIER VARIABLES AND IDENTIFYING GAPS

GROUP 2 - EXTENDING AND IMPROVING THE WORLD GLACIER INVENTORY

GROUP 3 - GLACIER MAPPING TECHNIQUES

PLENARY SESSION

FINAL RECOMMENDATIONS AND DISCUSSION

NSIDC VISIT

ASSESSING GLOBAL GLACIER RECESSION: RESULTS OF THE WORKSHOP

Roger G. Barry, Workshop Coordinator

Summary

A three-day workshop was convened at NSIDC to evaluate current methods of determining the worldwide recession of mountain glaciers over the last half-century. Recent evidence suggests an acceleration of glacier mass loss in several key regions. A more comprehensive evaluation of glacier changes is imperative to assess ice contributions to global sea level rise and the future of water resources from glacierized basins. The World Glacier Inventory now documents about 44 percent of the world's estimated 160,000 glaciers, but an immense task remains in order to complete the inventory. The recent availability of high-resolution Landsat-7 ETM+ and ASTER images, together with new digital inventories of glaciers in the former Soviet Union and China, in combination with GIS techniques, affords one avenue to a practical solution of these problems.

The broader impacts of this workshop included bringing together experts from leading groups. There was a training dimension in the involvement of all participants in three working groups and through the demonstration of new GIS-based mapping techniques using ASTER imagery and digital databases (http://nsidc.org/data/glims/). The conclusions and recommendations will assist scientists and program managers to strengthen the use and interpretation of glacier observations, the archiving of glacier data, and their fuller incorporation into the Global Climate Observing System (GCOS) strategy for terrestrial observations for climate (Haeberli *et al.*, 2000) as set out in the Second Report on the Adequacy of the Global Observing System for Climate (GCOS, 2003). This report has been prepared by GCOS for the U.N. Framework Convention on Climate Change, 2003 Conference of the Parties (COP-9). Glacier observations are one of the identified cryospheric/terrestrial variables. Hence, this workshop report will also provide a U.S. contribution to the evolving World Climate Research Programme (WCRP) Climate and Cryosphere (CliC) project (http://clic.npolar.no) and to the forthcoming 2005/06 assessments of the Intergovernmental Panel on Climate Change (IPCC).

Rationale

1. Modern integrated strategies of worldwide glacier monitoring include the repeated compilation of detailed glacier inventories to obtain global coverage of information about climate change effects. After 25 years of coordinated international efforts, unique material is now available, enabling repetition of detailed analyses and deduction of the most significant change patterns for numerous glaciers in various parts of the world (Haeberli et al., 1999). However, the current inventories documenting close to half of the world's glaciers remain preliminary and urgently need upgrading with a view to global assessments and future monitoring. Also, there are few specifics for many ice bodies, especially for large glaciers and outlet glaciers associated with ice caps and ice sheets.
2. Glaciers in low latitudes are rapidly receding (Kaser and Osmaston, 2002), and recent work (Dyurgerov and Meier, 2000; Haeberli and Hoelzle, 1995; Arendt et al*.,* 2002; Meier et al*.,* 2003) suggests acceleration since the late 1970s, especially in the European Alps and Alaska. This trend has also been identified in the Tien Shan by Cao (1998) and Khromova *et al.* (2003).
3. Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has recognized the value of glaciers as an important indicator of global climate change (IPCC, 2001). The Sec-

ond Adequacy Report on the Global Observing Systems for Climate has reaffirmed the importance of glacier observations. (See http://www.wmo.ch/web/gcos/networks.htm)

They record a finding that: “Glacier and ice sheet mass-balance surveys should continue using surface, aerial, and satellite techniques. Geographically representative glaciers should be added to the plans for the future. Countries with data should consider preserving their records in accessible formats and media and contributing them to archives for future use” (GCOS, 2003).

4. Mountain glacier recession is responsible for 15 to 20 percent of the current rise in eustatic sea level (Dyurgerov and Meier, 1997); it is also important to water resources for consumption and hydropower, to runoff amount and its timing, and it will have significant impacts on tourism. Alpine Clubs are already alarmed at the loss of ice climbs (Bowen, 2002), and the scenic impact will affect economies in alpine countries/regions; for example, Kilimanjaro is projected to have no ice remaining within two decades. Ice loss will also open up new terrain, lead to plant and animal migrations (as observed in the Andes and Alps) and expose new mineral resources (gold mining in the Tien Shan). High-altitude mountain ice caps are rapidly disappearing in low latitudes. Such ice caps contain important ice core records of past climates. There is an urgent need to acquire cores from such ice bodies before the records are lost (Thompson *et al.,* 1993).
5. Catastrophic events, such as the rock-ice avalanche at Kolka Glacier, northern Ossetia, Russia, in September 2002 (Institute of Geography, 2002; Kääb *et al.,* 2003), and the development and growth of dangerous glacier-dammed lakes, due to the progressive disintegration of debris-covered glacier tongues, as in the Nepal-Bhutan Himalayas and elsewhere, pose major societal and economic hazards.

Status and Goals

- High-resolution global data are being collected by Landsat ETM+, ASTER (Williams and Ferrigno, 1988; Bishop *et al.,* 2000; Kieffer *et al.* 2000) but at the present rate of analysis it will take decades for a full picture to emerge on changes in global ice area, extent, volume, and other glaciological parameters.
- We need to assemble the leading specialists mapping glacier change and converge on common techniques that can be applied to large-area (mountain range) assessments of current ice cover compared with that of the 1950-60s, or earlier. For most of the former Soviet Union glaciers (Kotlyakov, 1997) and for China, for example, there are now digital maps of the areal extent of glaciers for the 1960-70s. Canada has many 1970-80s maps in manuscript form for the Arctic and Cordillera. There may be similar information in some Andean countries and elsewhere. In Patagonia, 1970s maps have been digitized and compared with more recent maps. The baseline study of the areal extent of the Earth’s glaciers based on 1970s Landsat MSS images and involving more than 80 glaciologists worldwide, is nearing completion (Williams and Ferrigno, 1988-2003). (See http://pubs.usgs.gov/fs/fs130-02.).

  This work compares glacier area on Landsat images with historical records and establishes a reference point for comparisons with future higher-resolution satellite data.
- A broader approach is needed to enable:
  - Rapid assessment of large-scale trends via some means of data mining and, if feasible, standard procedures to scale up.
  - Early identification of critical areas/ice bodies needing detailed study to take into account the potential socio-economic impacts of ice decrease in specific mountain regions.
  - An adequate number of trained people to work on these topics and to contribute to enhanced awareness of glaciers in the developing world.

Workshop Results

The workshop featured keynote papers by experts in the field, selected short reports, contributed illustrated posters, and discussion groups, each with an identified chair and rapporteur. The keynote talks focused on internationally coordinated monitoring strategies and techniques that meet the basic requirements concerning relevance of the data and feasibility of long-term programs. The discussion groups addressed the status of various activities and actions needed to address the central issue.

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WORKSHOP WORKING GROUP ASSESSMENTS

Working Group 1: Assessment of GCOS Variables

Wilfried Haeberli (Chair), Jon Øve Hagen, Vladimir Aizen, Roger Barry, Richard S. Williams Jr., Andrew G. Fountain, Rajesh Kumar, Alejandro E. Machado (rapporteur)

There are three GCOS components: Atmosphere, Oceans, and Terrestrial.

Variables for each component were chosen for relevance to observation of climate change, and feasibility of measurements. Of the 14 terrestrial variables, 3 are for Cryosphere-Frozen Ground, Snow Cover, Glacier/IceCaps.

We endorse the use of the integrated system of observing the GCOS variables as described by the Global Hierarchical Observing Strategy (GHOST), within which the glacier/ice cap variable has been adopted. This observing strategy contains the following tiers as defined by GCOS Report 33 (GCOS, 1997).

1. Transects along environmental gradients (continental / maritime)
2. Extensive and process-oriented glacier mass-balance and flow studies within major climatic zones for calibrating numerical models
3. Regional glacier mass changes within major mountain systems, observed with a limited number of strategically selected index stakes combined with precision mapping at about decadal intervals (small glaciers), and with geodetic airborne or satellite laser altimetry/kinematic GPS for large glaciers.
4. Representative, long-term observations of glacier length changes (a minimum of about 10 sites within each major mountain range) should be selected to represent different glacier sizes and dynamic responses. Assessments on the basis of (a) intercomparison of geometrically comparable glaciers, (b) dynamic fitting of glacier flow models to long time series of measured cumulative length change, and (c) mass-change reconstructions using concepts of mass conservation.
5. Global coverage by glacier inventories repeated at time intervals of a few decades (satellite imagery/GIS/DEM/laser altimetry), analyses of existing and newly available data (e.g. ICESat data) following regionally adapted parameterization schemes.

Recommendations

We make the following comments and recommendations:

***Tier 1* —**Glacier/ice cap observations have the potential to play an important role in large-scale latitudinal/longitudinal environmental transects and should be included in multidisciplinary efforts, such as the Long-Term Ecological Research Program (LTER) program in the USA, the IGBP Mountain Initiative, and the WCRP CliC project (see http://clic.npolar.no/). Such programs should also identify sites that represent steep elevation gradients that include glacier observations at smaller scales (high mountains).

***Tier 2*—**About 10 to 20 glaciological field stations exist worldwide, where long-term process studies take place. These produce data sets suitable for calibrating/testing numerical models and provide an important training opportunities for research educational programs and corresponding capacity building. It is essential to continue these fundamental in-situ activities. We stress the importance of the existing long-term mass balance measurements and the addition of new representative “benchmark” glaciers, as many existing “representative” glaciers will likely disappear within a few decades, with adequate overlap to ensure the continuity of the long-term record.

Tier 3—Glacier/ice cap mass change observations that combine field-based and remotely sensed measurements are being revolutionized by new technologies (GPS, geodetic airborne or satellite laser altimetry/LIDAR, high-resolution imagery, InSAR). Geodetic and photogrammetric measurements are also being improved. These new methods facilitate repeated observations of glacier volume changes over larger spatial scales and for long observational periods. Continuation of index stake measurements provide high temporal resolution and allow calibration of remotely sensed data.

Tier 4—We recommend refining the concept of "representative" glaciers by establishing a task group to define a suitable classification system for GCOS. We identified the following first-order classification basis: maritime/continental, climate zone, glacier size, glacier regime, etc. We recommend that this classification defines a set of representative (benchmark) glaciers for each glacierized region. This task group could be organized through International Commission on Snow and Ice (ICSI), the WCRP CliC project, and the World Glacier Monitoring Service (WGMS).

Tier 5—New technologies enable the production of digital-based inventories over large glacierized areas of the world, as demonstrated by the presentations at this workshop. These global inventories will further benefit from continuing acquisition of Landsat ETM+ and ASTER data, ASTER stereo capabilities, and data products from missions, such as ICESat, and data products from CryoSat.

Crosscutting Issues

There is a clear need for the following:

1. The development/implementation of computer-assisted image analysis for accurate and repeatable glacier mapping
2. An enhanced Global Terrestrial Network for Glaciers (GTN-G)/WGMS structure to accommodate high volume and new formats from remotely sensed data
3. Ensuring the preservation and integrity of the long-term archive of the data, World Data Centers (WDC), World Glacier Inventory (WGI), Mass Balance Bulletin (MBB), Fluctuations of Glaciers (FoG), and current/future digital databases
4. The organization of data and results suitable for public-policy decision makers and IPCC activities (sea-level change, water resources, hydropower production, environmental hazards, landscape evolution, quality of life, and economic impacts, etc.)
5. Implementation of recommendations given limited resources

Working Group 2: World Glacier Inventories

J. Kargel (Chair), Andrew Barrett (Rapporteur), Graham Cogley, Marl Dyurgerov, Jean-Pierre-Dedieu, Florence Fetterer, Mark Meier, Simon Ommanney, Martin Sharp, Dennis Trabant

History of Glacier Inventories

A brief history of the evolution of the World Glacier Inventory has been prepared by Dr. Mark Meier (see Appendix 1).

Current Inventory Efforts

The global WGMS inventory effort is no longer actively maintaining and expanding the inventory; it is frozen at about 40 percent completion. The current annual cost of WGMS maintenance is $100,000. There are several loosely coordinated inventory efforts that have been completed recently or are ongoing around the world. Nepal and Bhutan have recently been completed by the International Centre for Integrated Mountain Development (ICIMOD). It is noteworthy that major gaps exist for the USA and Canada, two of the world's richest nations. This suggests that the lack of completeness is due more to a failure to persuade funding agencies of the importance of the WGI than to lack of interest. The new GCOS (2003) report may help to redress this situation; the completion of a baseline inventory of the world’s glaciers has a very high scientific priority.

The Global Land Ice Measurement from Space (GLIMS) is a broad ongoing inventory effort (along with dynamic assessment) that is being pursued aggressively at some regional centers (covering for instance the Swiss and French Alps, the Antarctic Peninsula, Canadian Arctic, conterminous “lower 48” U.S., Patagonia, China, Central Asia, parts of Antarctica, and other parts of the world (see http://www.glims.org/).

China’s inventory effort, reported by Li Xin, and those of the GLIMS project in general, have adopted (or used as a mandatory set of attributes in addition to other attributes) the set of WGMS glacier attributes. GLIMS relies heavily on ASTER and other satellite data such as Landsat 7 ETM+).

Bill Manley is using USGS topographic maps of Alaska circa 1960 to produce a digitized historic database; Andrew Fountain is using topographic maps and ASTER imaging to produce a robust database for the conterminous U.S.A. glaciers. Tatiana Khromova and colleagues are doing the same for Central Asia and are making rapid progress in change detection by comparing ASTER images with historic archives. Giovanna Lorenzin is using a multi-instrument database (satellite radar interferometry, multispectral systems and ice-penetrating airborne radar) to map coastlines and grounding lines in the Australian area of interest in Antarctica. Ferrigno and Williams (1998), http://pubs.usgs,gov/factsheet/fs50-96, in collaboration with the British Antarctic Survey, UK, and other Antarctic Treaty nations (Ferrigno et al., 2002) http://pubs.usgs,gov/factsheet/fs130-02, are using early Landsat MSS, later Landsat TM, and RADARSAT images to produce a series of “Coastal-Change and Glaciological Maps of Antarctica,” which includes a preliminary inventory of outlet glaciers, ice streams, and other glaciers in Antarctica and an analysis of changes on each of the 24 maps in an accompanying pamphlet.

Despite major advances made possible by use of data from a variety of satellite systems, there remain major analysis challenges to filling out the database. Progress toward completing the global inventory has been slow and not uniform around the world. There is a strong need for early completion of a global, comprehensive inventory, even if sacrifices must be made in order to get speedy results.

Although work effort is naturally going to proceed simultaneously in all levels, the basic idea is that completion of the world inventory should proceed in the sequence from Level 0 through

Level 3. We also encourage inventory efforts dedicated to digitization of glacier data contained in maps and other historic archives, as well as extension of the work to this decade using satellite and other observations.

Definition of Inventory

Four levels are defined:

Level 0**—**Planned as a very near-term global raster image of exposed ice. An initial inventory can be improved using 250 m picture element (pixel) MODIS data to produce a global raster image of exposed glacier ice and exposed snow patches. Further improvements to 50 m resolution (where global grid cells at 50 m resolution are indicated as containing either some ice or no ice) are possible but will require more in-depth analysis of multiple image and other data sets and will take more time to complete. Level 0 is distinguished from other levels by being maps of exposed ice, which may include perennial snowfields and snow patches but will exclude debris-covered parts of glaciers. It is not strictly a glacier database.

It should be noted that archives of Level 0+ Landsat Multispectral Scanner (MSS) images exist at EROS Data Center (EDC), Canada Centre for Remote Sensing (CCRS), and European Space Agency (ESA). Optimum Landsat MSS images have been identified for all glacierized regions of the world in the ten geographic area volumes of the Satellite Image Atlas of Glaciers of the World.

Level 1**—**For the bare minimum set of glacier attributes designed to allow the simplest possible analog or machine-made measurements and greatest speed toward completion of the world's inventory, while still allowing analysis of some of the most important first-order global glaciological issues of human significance. The raster data set comprises:

Basic geometry (location = latitude/longitude, and elevation of the centroid determined by math or eyeball; maximum and minimum elevation), and a limited number of two-bit binary descriptive codes (yes/no calving, yes/no surge-type, yes/no debris-covered; yes/no ice sheet, ice field or ice cap; yes/no floating terminus; yes/no grounded terminus; or add a bit to allow “uncertain”); maximum/minimum elevation; and date. The diameter of circle that encloses a glacier provides a crude and easily measured proxy for glacier length. We emphasize that this is the most crucial level of data. We highly recommend that those doing inventory and dynamic analysis pay immediate attention to this level.

Level 2 **—**For additional important parameters that require a higher level of analysis but are still not too intimidating or time-consuming. It is recommended that glacier identifications (IDs) must include, minimally, WGMS ID if available; glaciers can have other IDs. This level adds certain, but not all, of the WGMS parameters. Include equilibrium-line altitude (ELA), a critical climatically-dependent variable, actual length along flow lines, area, aspect, and links to mass balance studies, length variation studies, and climatological and hydrological stations, if present.

Level 3 **—**Requires more sophisticated analysis to obtain any additional desired glacier attributes. Include outline of glacier, include stable geodetic ground control points near glaciers, x-y-z surface topography of glacier, maps of debris cover, maps of proglacial and supraglacial lakes and ponds, surface flow-vector fields, etc. NOTE: Most people will determine area by getting the outline first, so chances are most people will determine the tier-3 outline by the time they get the tier-2 area.

Mechanisms to Bring These Steps About

- Submit a draft of this document through Cryolist and GLIMS bulletin boards.
- Publish an *EOS* article summarizing the Workshop.
- Publish an ICE article.
- Hold a symposium at an IGS meeting, and follow up with an *Glaciology* article.

- Make an AGU presentation.
- Publish a demonstration paper in a peer-reviewed journal (Martin Sharp to lead, Mark Meier to contribute science analysis) to show the limits and uses of existing inventories. Include Chinese and other new inventories. Highlight important scientific results obtained from present incomplete inventory, and the compelling need to complete the inventory.
- Expand the three Working Groups established at this Glacier Recession Workshop to include all chief players in inventory efforts. Goals should be to produce detailed recommendations based on the best available expertise, and to communicate to the global community the foremost need to complete an inventory of exposed ice and secondly an inventory of glaciers (including debris-covered ice). The excellent work being conducted toward Level 2 and Level 3 goals should not ignore the need to finish Level 1 first, though work at all levels realistically will be happening simultaneously.
- Establish a structure within the Glacier Inventory Working Group to address several important specific problems, including small glaciers, ice fields/ice caps and outlet glaciers in the southern Andes, those glaciers outside the polar ice sheets, the two ice sheets and their outlet glaciers/ice streams, with subgroups addressing each of these levels.
- Provide input from members of Working Group 2 to the next IPCC report via Mark Dyurgerov, who is a member of the Scientific Assessment addressing land ice contributions to sea-level changes.
- Provide electronic links of inventory to dynamic data (benchmark glaciers, field measurements (mass balance, etc.), and other sources of information (such as air photo archives). Link to the person who is responsible for the accuracy of inventory data entries.

Working Group 3: Glacier Mapping

Dorothy Hall (Chair, day 1), Greg Scharfen (Chair, day 2), Bruce Raup (Rapporteur), Michael Bishop, Hester Jiskoot, Anthony Arendt, Bill Manley, Giovanna Lorenzin, Francisca Bown, Siri Jodha Singh Khalsa, Bruce Molnia, Hal Pranger, Tatiana Khromova, Koni Steffen

1. Why do we care about glaciers?
    a. Glaciers affect water resources, natural hazards (impact on humans). Near real-time images show ongoing catastrophic changes: surges, outburst floods (jökulhlaups).
    b. Glaciers are climate indicators.
    c. Glaciers contribute to sea level change.
2. Where are the glaciers? First, before change detection.

1. Glacier triage
    a. Pick "important" glaciers first, for sea-level rise, water resources, etc.
    b. Identify areas lacking in field measurements, problematic in other ways, such as persistent cloud cover.
2. Processing inputs
    a. What is the required pixel resolution for multi-spectral imagery? The community needs pixel resolution sufficient for their needs (5 m pixels), but very high resolution yields a surfeit of data that cannot all be analyzed while insufficient resolution does not allow many critical issues to be addressed. What is an optimum pixel resolution for mapping and monitoring key glacier variables?
    b. DEMs
    c. Multi-angle imagery. Enables sampling of Bidirectional Reflectance Function (BDRF)
    d. Field measurements
    e. Data integration – using multispectral data and topography
3. Outputs from glacier mapping
    a. Vector data for glacier outlines, snowlines, etc.
    b. Data sets should form basis for analysis of spatial and temporal patterns.
    c. Parameters that feed into models: Albedo, velocity, ice-surface elevation, DEM change, ice-surface temperature, air temperature, ELA, volume
    d. Integration of remote sensing, GIS, field measurements, and numerical modeling to assess glaciers. Integration is necessary for extrapolation to regions lacking field measurements. Satellite observations can validate aspects numerical simulations of glacier change.
    e. Frequency of measurements. Answer depends on the application, but ideally, once per year, at end of the melt season.
4. Need systematic approach to error assessment. Need for defined standard processing streams and protocols, with strict error specifications: Stage 1, Stage 2, etc. Michael Bishop will produce first draft of this. This field should be added to the GLIMS database.
5. Regional Centers should oversee the implementation of error-estimate protocols. This will help ensure data quality.

6. Lower hurdles are needed for compiling a global database. Credit should be given to data providers. Citation standards need defining. A common-attribute dictionary would be useful.
7. Additional glacier variables are ice thickness and ice-surface elevation.

List of Glacier Inventories

A list of glaciers and a global map of their distribution prepared by Dr. H. Jiskoot is contained in Appendix 2.

It is important to separate:

1. Inventory (tables)

from

2. Inventory (polygons).

Major geographical gaps are for the following:

- Glaciers peripheral to ice sheets
- Inventories are missing within the Chilean administrative “Aysen” and “Magallanes” regions (southern Patagonia). This glacier area, excluding the (Northern and Southern Patagonian Icefields, is estimated to be 5.300 km^2 (Casassa, 2003; Rivera et al*., 2003)*
- Afghanistan
- Argentina, south of ~32° S
- South American Andes are generally patchy
- Poland, Czech (Tatra Mountains)
- Aleutians (Alaska)
- Karakoram - currently being worked on by University of Leeds, UK, group, mostly from InSAR
- Ice caps, ice fields, and associated outlet glaciers
- Greenland and Antarctic ice sheets and associated outlet glaciers and ice streams

Summary of Overall Workshop Recommendations

Unifying Themes

- Remote sensing and field scientists should immediately begin to combine efforts to provide world glacier monitoring and inventory.
- We have a well-designed monitoring strategy. It is integrated to include the multiple levels of the ways we monitor glaciers via remote sensing and field measurements.
- The quality of measurements, error estimates, and verification of measurements needs to be a part of all programs.
- Periodic assessment of the monitoring strategy (not just repeated measurements) is required.
- Cross training of field scientists and remote-sensing scientists needs to be undertaken, especially in the developing world.
- Encouragement of inter-institutional research programs for renewed glacier modeling and monitoring.
- Glacier-fluctuation measurements have the advantage of historical and modern measurement that could take the time series from the “Little Ice Age” to the present. This means that proxy data must be integrated with the modern (field and remote sensing) data.

Recommended Actions

1. Scan available field maps and put them on the Web at NSIDC and scan the 1:1 million-scale glacier maps of Canada.
2. Identify the location and outline (area) of all glaciers worldwide at present before they have disappeared, complete existing inventories and maps, and fill the “gap” regions. For glacier-outline maps this should ideally be based on satellite images for speed and consistency. Mapping efforts should transcend political boundaries.
3. In the near term, identify the “important” glaciers and map them first. Importance should be defined in terms of specific applications, including climate signal, impact on humans (e.g. water resources and natural hazards), and sea-level change.
4. Define standard definitions of parameters: location of ice divides, length, etc. (GLIMS is producing an illustrated dictionary of glacier parameters).
5. Give highest priority to directly measured quantities (outlines, DEMs), versus derived data such as ELA.
6. Establish a certain amount of standardized automation in image analysis to produce glacier maps.
7. Develop a systematic approach to quality assessment of glacier measurements derived from remote sensing data (first priority is geometric correction; second priority is radiometric calibration). A standardization document is currently being compiled (Michael Bishop). The quality level should be incorporated in all glacier databases. For global assessment studies, highest-quality data should be used whenever possible for analysis.
8. Mapping efforts should incorporate remote sensing, GIS, field data, and numerical modeling, as appropriate. The optimum pixel resolution for satellite sensors needs to be defined.
9. Glacier maps should be used as information for the assessment of temporal glacier changes.
10. Credit should be given to data providers, and citation standards should be implemented for map data.

11. The glaciological community should ensure continuity of satellite measurements suitable for glacier mapping.
12. Field measurements remain essential for the proper interpretation and evaluation of information derived from satellite data.
13. Satellite imagery with sufficiently high spatial resolution is desired for glacier mapping.
14. Ideally, satellite imagery covering the world's glaciers should be acquired once per year, at the end of the melt season.
15. Coordination and data management costs need to be considered.

WORKSHOP PAPERS AND PRESENTATIONS

Observational Evidence of Accelerated Glacier Wastage: Uncertainty in Prediction

Mark Dyurgerov, INSTAAR

The Importance of Glacier Volume Change: Some Examples

The observational results and analysis of glacier volume change have been published and widely discussed in IPCC-96 and IPCC-01 (Warrick et al., 1996; Church et al., 2001) and elsewhere. These reports have substantially changed the attitude of the scientific community toward the role of "small" glaciers into global processes, such as sea level rise, ocean ventilation, and changes in gravity field. Multidisciplinary interest in glaciological data has risen, which implies a need for stricter data quality requirements and faster dissemination.

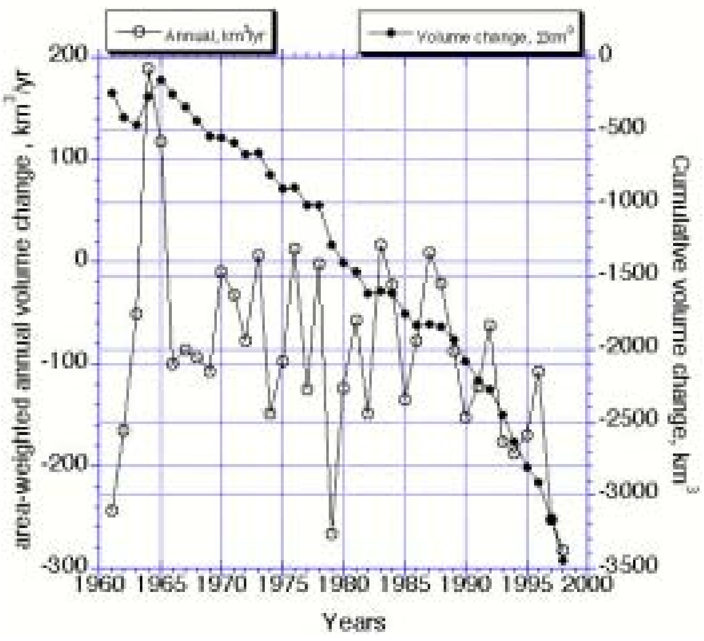


Figure 1. Glacier Volume Change

Here are the results of glacier volume change, calculated for all mountain and subpolar glaciers on Earth. Surface area of these glaciers is about 680,000 km^2. The results presented here are in km^3 of water equivalent. The time period is from 1961 to 1998 because of data availability.

Two general questions were usually asked. The first, (presented in Figure 1), is how "global" curves are calculated. The second questions concerns the accuracy of these calculations.

We have calculated these results as area-weighted, using the specific net or annual glacier mass balances, the area of individual glaciers, and the area of a region. We have also improved the data quality by eliminating errors and filling the gaps in time series. In many cases, mass balance data were not available, so we used data from regional analogues with similar climate conditions. These details are given in the Occasional Paper (Dyurgerov, 2002, available online at INSTAAR and NSIDC.)

The second question is the accuracy of these curves (Figure 1). Again, all details are given in (Dyurgerov, 2002). To summarize, I will refer to the estimate given by IPCC-2001, which estimated the error as much as 30 percent of the annual value. I am more pessimistic, so my estimate is 40 percent. This is the total random error caused mostly by data extrapolation from the individual time series to the larger scale.

In my opinion, the results of direct observations and data extrapolation to the larger scale (Global scale is presented here) is more realistic compared to any other modeled results, for the following reasons:

- Observational data include the results of all processes, whereas models cannot consider all processes, such as mechanical ablation of ice and snow and internal accumulation.
- Observational mass balance data are corrected for dynamic response time as the changes in surface area have usually been included in time series calculations.
- Mass balance values were measured at many points and averaged over the glacier area, integrated with local variability in snow accumulation and ice ablation, and allowed estimation of the range in variability of natural processes and observational error.
- Observational data carry information independent of meteorological measurements, so that independent estimates of changes in climate can be made from glaciological observations.

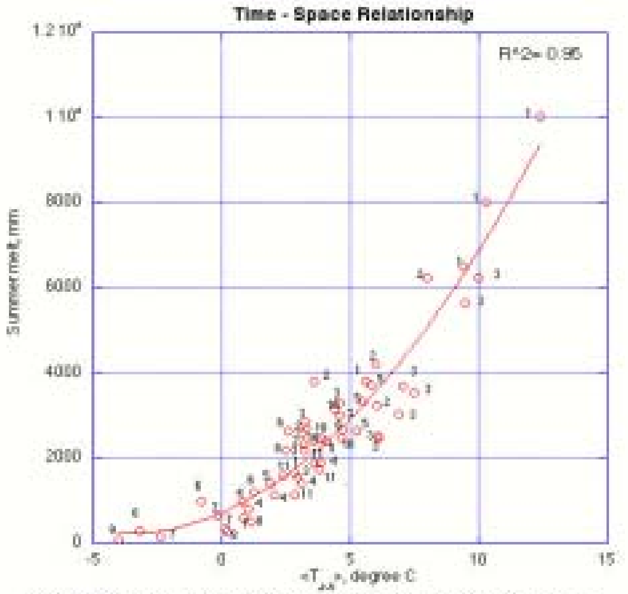
Explanation of Peaks and Valleys

Some of these can be explained by strong explosive volcanic eruptions, such as Mt. Agung in 1964, several volcanic eruptions in Kamchatka (Sheveluch, Tolbachik, Kluchevskaya) during 1970 to 1980, El Chichon in Mexico in 1982, and Mt. Pinatubo in 1991. The global cooling in connection with the last eruption reduced mass lost by glaciers by 360 km^3, which is equal to 1 mm of sea-level drop for the two years following eruption years (1992, 1993).

The timing of these events is amazingly consistent with peaks on the global curve. After one to two years, glaciers return to the previously established trend of mass wastage. The bottom line for all of these “peaks and valleys” is that change in glacier volume, globally averaged, is very sensitive to external forcing.

The other problem is the interpretation of the change in the cumulative curve. The change in 1988 with the acceleration of glacier wastage is obvious and statistically significant, with a 95 percent confidence level. This was pointed out by (Haeberli et al, 1999). I have studied several variables and have found that the increase in summer air temperature has been the main forcing element.

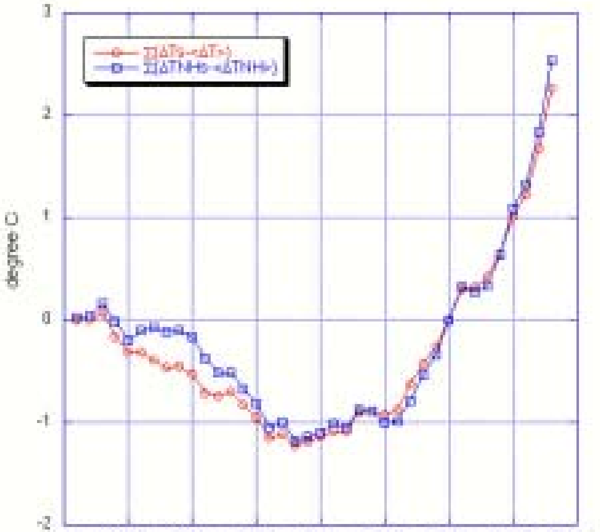
The relationship between summer air temperature and glacier annual ablation rate is shown in Fig. 2. This relationship was introduced in 1966 by (Krenke and Khodakov, 1997).



Relationship between summer ablation and average summer temperature <TJ-A>. The number at the points corresponding to the regions: (1) Fedchenko Glacier (Pamir), (2) Altai, (3) Polar Urals, (4) Suntar Khayata (Sibirea) , (5) Scandinavia, (6) Novaya Zemlya, (7) Franz Josef land, (8) W. Spitzbergen, (9) Mirny, Antarctic, (10) Alps, (11) Zailiisky Alatau (adapted from Krenke & Khodakov, 1997)

Figure 2. Ablation and Temperature (Krenke-Khodakov, 1966)

This is the large-scale, time-space relationship between ablation and temperature. Geographical locations of selected glaciers presented here are from North to South subpolar regions and in between. This relationship represents a certain period of time; several years with different climate conditions. This empirical relationship can be applied to estimate the glacier ablation change through space and time. Globally averaged summer air temperature increased +0.3°C between 1961 to 1987 and 1988 to 1998. Figure 3 shows the air temperature departure.



Change in summer air temperature (ΔTs - summer, global, < ΔTs> - summer global averaged over 1961-90; ΔTNHs, <ΔTNHs> the same for Northern Hemisphere) compare to 1961-90 reference period

Figure 3. Average Temperature Change

An approximation of the Krenke-Khodakov relationship has been applied to the warmer period, with the summer temperature of +0.3°C higher (1988-98) to estimate the change in the glacier annual ablation rate (Figure 4).

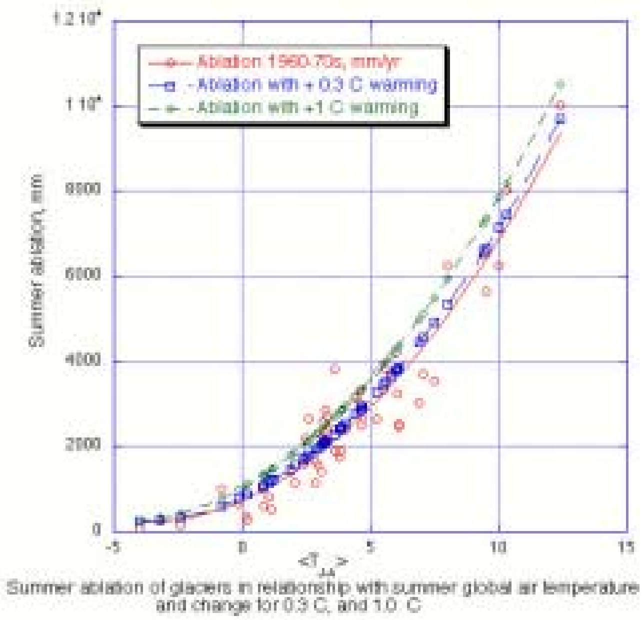


Figure 4. Adaptation to Warmer Climate

Another calculation was made for summer air temperature change for a +1.0° climate change scenario. The important feature of this global relationship is that the sensitivity of meltwater production by glacier change has been nonlinear (Braithwaite and Zhang, 1999). The change in absolute temperature has also been nonlinear, showing a larger increase in cold, subpolar regions, and a smaller increase in humid, maritime regions. The changes in spatial sensitivity and absolute temperature somehow compensate each other. As a result, cold subpolar glaciers have become warmer, or more maritime, and maritime glaciers are disappearing more quickly.

The process, on a global scale, seems even more complex as the sensitivity has been changing with time (Figure 5).

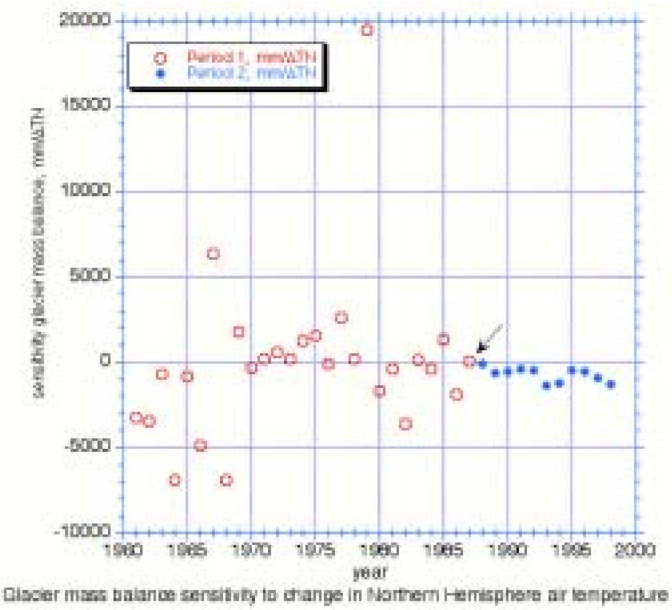


Figure 5. Mass Balance Sensitivity

It is found that the averaged global sensitivity increased over time, and the variability of sensitivity has decreased. In other words, less change in summer temperature is required to achieve the same increase in glacier wastage. The air temperature in previous epochs cannot be used as an example of what may happen at the present time with the same forcing.

Go back to the global change in glacier volume (Figure 1). It is clear that glaciers on Earth are far from their steady state. To estimate how far the glaciers are from their steady state and how much their size must change to adjust to the present-day climate, we have used observational data from our database (Dyurgerov, 2002).

All available observational data were regressed with annual mass balances (b) and related to the accumulation area ratio (AAR). From these regressions I have determined the steady-state conditions for about 90 glaciers in the world. I used the commonly accepted statement that AAR_0 with mass balance zero (b=0) is the steady state condition (Meier, 1962; IAHS, 1991, 1993, 1994, 1996; WGMS, 1999, 2001, and 2002). I have also calculated the average <AAR> over the observation period of 10-15 years. The difference between this “real climate” and glacier regime conditions expressed in <AAR> and steady state, expressed in AAR_0, may show how much a glacier needed to reduce or increase its surface area to adjust to the present climate. Thus, $\langle AAR \rangle - AAR_0$ is the parameter that quantifies the state of a glacier compared to its steady state.

The calculations made for about 90 glaciers in the world and the average value of difference $\langle AAR \rangle - AAR_0 = -7.3$ percent. In other words, accumulation area is 7.3 percent of the deficit. We can say also that glaciers need to lose about 7 percent of their entire area to compensate for the deficit in accumulation. The extreme numbers of $\langle AAR \rangle - AAR_0$ have been found for Lewis Glacier (East Africa, -43.9 percent), and maximum values for Storsteinfjelbreen (Skjomen, N. Norway, +22.6 percent).

How long will it take to adjust? It is entirely individually for every glacier. It can only be estimated very roughly. The rate of area decrease differs between 0.2 percent per year to 2 percent per year (Alps, Northwest USA, Northwest regions of Central Asia); thus, we can expect the full adjustment averaged globally for about 10-20 years, in case the climate does not change after the major shift in 1998.

Use Observational Results to Predict Global Glacier Volume Change

Following the conclusion that observational data have some advantages compared to recent modeled results, we can use the compiled data of globally averaged glacier volume change (Figure 1) to look into the future. One requirement is important: for future estimates, use the data over the period after the last shift in climate. I propose that the last such shift in 1998 is the strongest, and climate and corresponding glacier mass balance sensitivity will not change until the end of 21st century. Thus, extrapolation of volume loss from 1988 to 1998 may give the realistic expectations to the end of 21st century (Figure 6).

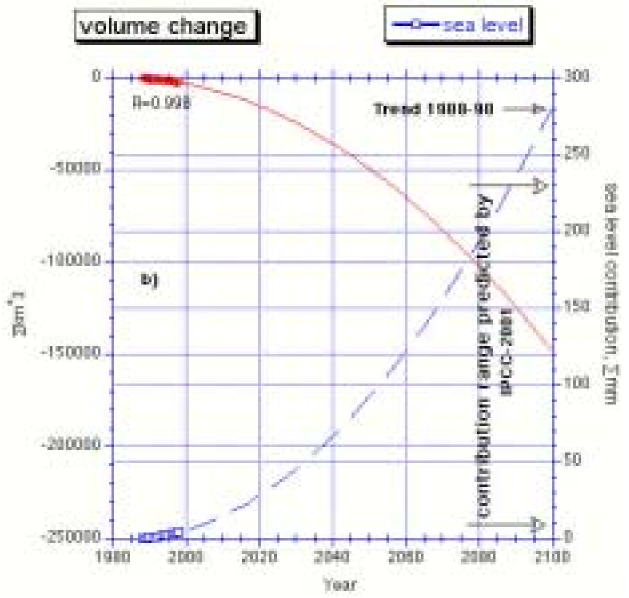


Figure 6. Sea Level Rise

The best fit of observational data polynomial approximation is applied to determine an expected value of 150*10^3 km^6 of volume loss to 2100. Averaged globally, this volume translates to glacier thickness change for about - 240 m. In other words, all glaciers by the area less than 20-25 km^2 will disappear. Note that about 85 percent of all observed benchmark glaciers with the longest records are smaller than this size. In such a perspective, our descendants will lose 85 percent of the existing observational network.

Another view of this result is that it is well above the maximum value predicted by IPCC-2001 when we translate the volume loss into the contribution to sea level rise (Figure 6). Note that our extrapolation is based on “natural” events extracted from observations, compared to those modeled by IPCC 2001, with much larger predicted change in air temperature. The question of prediction remains open, and even becomes more complex: is present-day global warming really enough to lose glaciers in many mountain regions in the world? What consequences will there be in such a loss?

Conclusion

Realistic knowledge of glacier regimes and their involvement in global processes depends on data from direct observations. This is more true now than it was 1-2 decades ago. Direct observations cannot be substituted by modeling results. The lack of and continuing decline in observational networks does not improve our confidence in glacier assessment and their impact on environmental changes.

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Volume Changes of Alaska’s Glaciers as Measured by Airborne Laser Altimetry

Anothony Arendt, Keith Echelmeyer, William Harrison, Craig Lingle, Virginia Valentine

Alaska’s glaciers are a critical region in the context of sea level rise. Rapid glacier melting is contributing (about 9 percent in the last fifty years) to rising sea level via mass input.

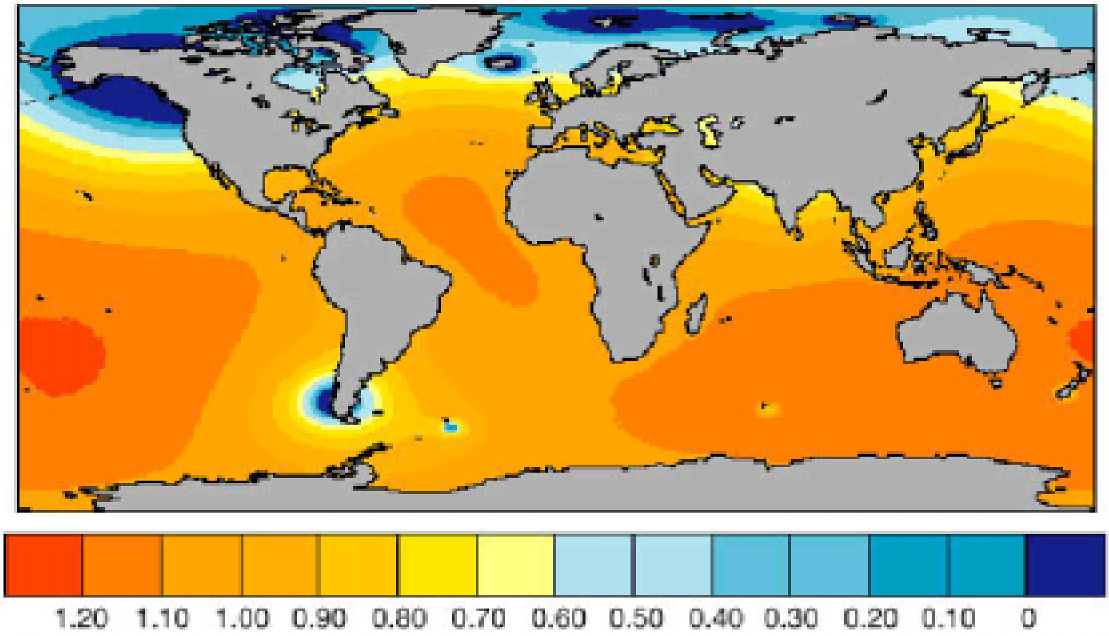


Figure 7. Normalized global sea level variations due to mountain glacier wastage as estimated by Meier (1984).

Airborne laser altimetry is an effective method for monitoring glacier volume changes. Laser altimetry works by bouncing laser signals from an airplane off a glacier. Using Global Positioning System (GPS), researchers track the aircraft's position relative to the glacier.

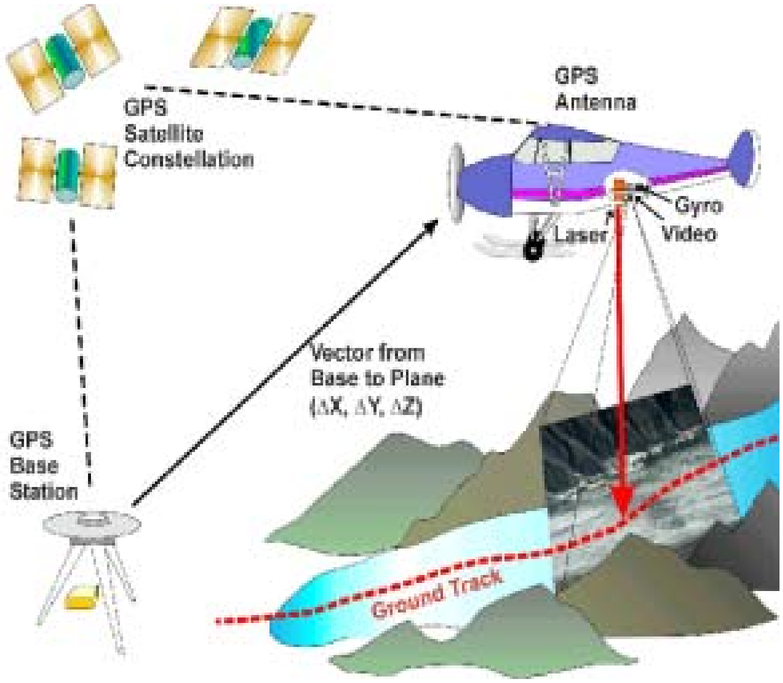


Figure 8. Laser Altimetry Illustration

Calculated volume and area changes show that more than 95 percent of the glaciers have thinned in the last fifty years. For example, the Columbia glacier thinned at its terminus by 300 m from the 1950s to the mid-1990s, and in the last five years has thinned approximately 150 m.

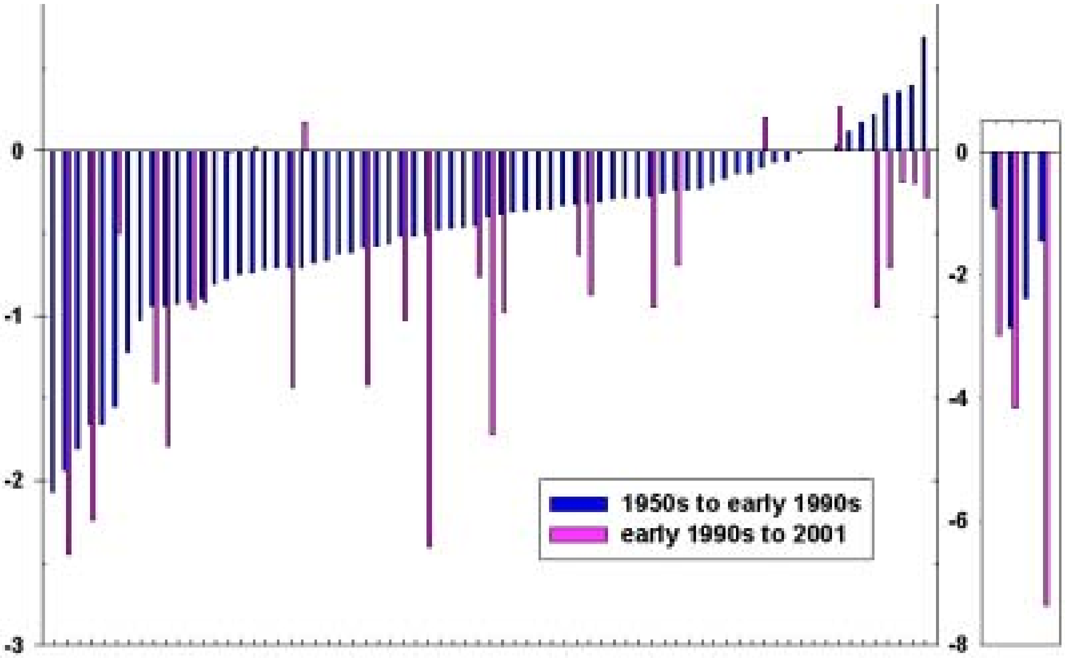


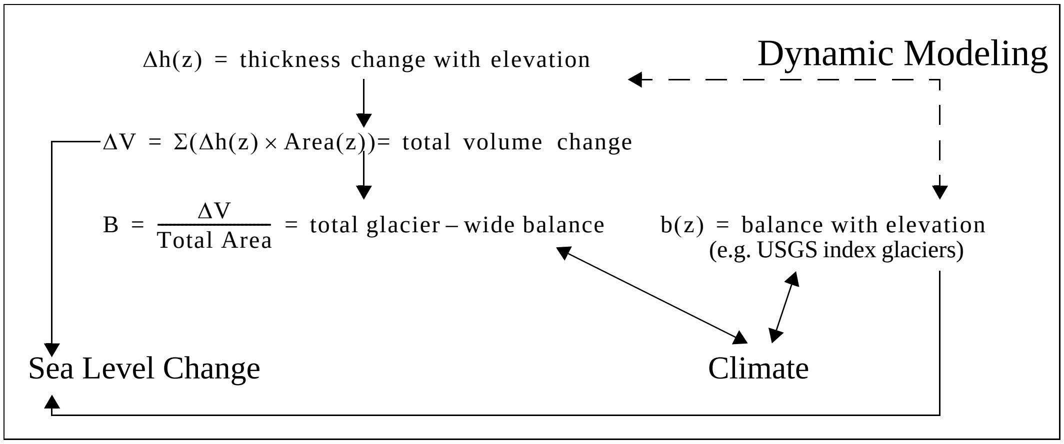
Figure 9. Glacier-wide Average Annual Thickness Change (m/yr)

The following table shows the contribution of arctic glaciers to rising sea level.

Time Period	**Volume Change**	
	km^3 Water Equivalent/year	**mm/year Sea Level Equivalent**
Early: 1950s to 1990s	-46 ± 7	0.13 ± 0.02
Recent: 1990s to 2001	-88 ± 28	0.24 ± 0.08

Table 1. Arctic Glaciers and Sea Level Rise

The following flow chart shows glacier changes and their links to sea level and climate change.



Mass Balance

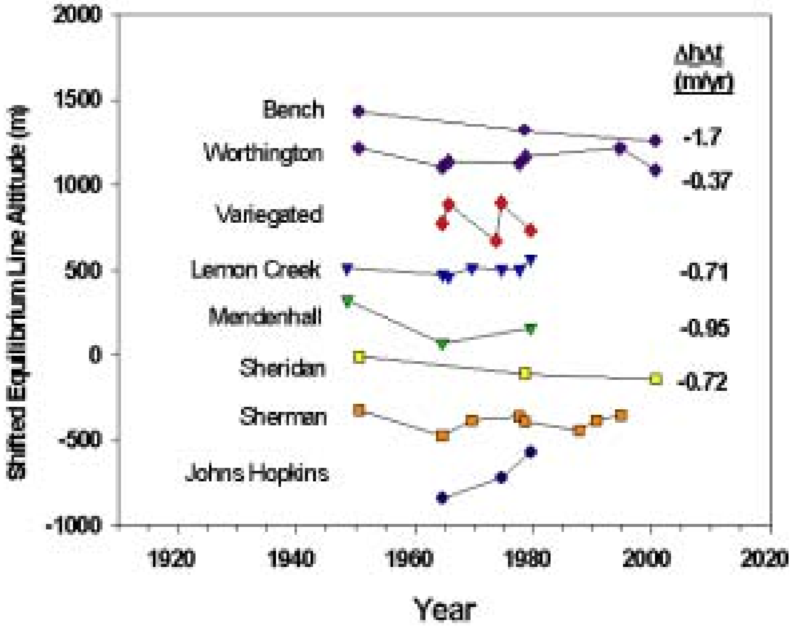
The US Geological Survey (USGS) has maintained a long-term (1960s to present) mass balance and weather data set. We use a degree-day mass balance model to relate changes in temperature and precipitation to the mass balances of Gulkana glacier, located in Alaska’s interior. Simulations predict that the observed change in summer temperature (+0.8 deg. C) at Gulkana Glacier caused a change in glacier-wide balance of -0.30 m/year, similar to -0.34 m/year measured by altimetry.

Potential Role of Satellite Remote Sensing Data

Remote sensing data may provide a more current outline of present-day glacier extent for the recent period measurements. There is the possibility of using Landsat or ASTER images to map the elevations of late summer snow lines as a proxy for equilibrium line altitudes (ELAs). Another important aspect is that maps of ELAs may be used to define climate regions, important for extrapolation of glacier volume changes.

Altimetry measurements give us different information than conventional methods of glacier change detection. For example, rates of length/area changes do not necessarily equal rates of glacier mass change, and monitoring changes in ELA might not be an effective method for monitoring changes in glacier mass.

The following chart shows the variations in ELA in various Alaskan glaciers. The numbers on the right side indicate the thickness change rate as measured by altimetry in the early period (1950s to 1990).



Recommendations and Conclusions

- Airborne laser altimetry would be an excellent tool for monitoring volume changes of glaciers in other “critical regions.”
- Satellite remote sensing should be used to update glacier areas and possibly ELAs.
- Conventional mass balance programs are important to help describe links between glacier changes and climate.

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Determining the Coastline of Antarctica Using Remote Sensing Techniques

Giovanna Lorenzin

The Project

Our objectives in this study were to define a complete and accurate coastline from 45ºE to 136º E, and from 142º E to 160º E. This area comprises the Australian Antarctic Territory. Additional goals were to provide the scientific community with a complete and accurate data set and hydrographic charting.

Scientific research included updating Scientific Committee on Antarctic Research (SCAR) data for the Antarctic Digital Database (ADD).

Methodology

The methodology we used in this study involved mapping in consultation with AAD glaciologists. We used IMAGINE v8.4 software for on-screen digitizing and creating a visual interpretation. We enhanced images where necessary, and did a “proof of concept” study to validate grounding line interpretation.

What is a “Coastline” in Antarctica?

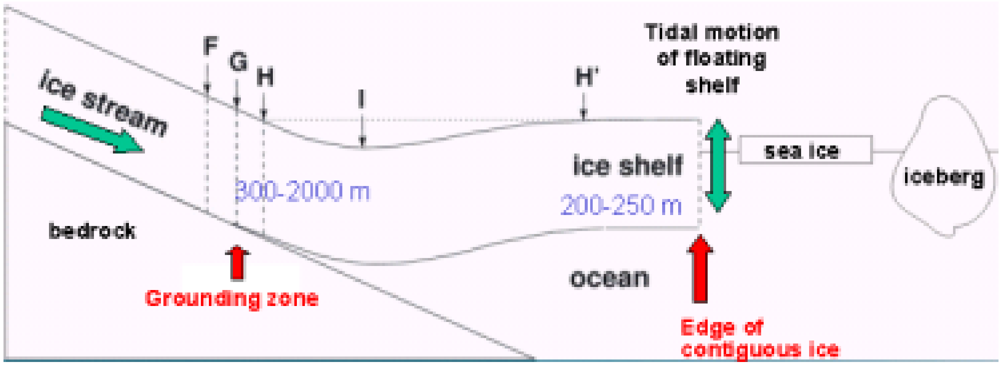
Two coastlines categories were identified:

1. The edge of permanent contiguous ice, including glacier fronts, ice coasts, ice walls, rock coasts, etc. This coastline is easy to identify from imagery.
2. The grounding line, or the boundary between grounded ice and floating ice, usually between an ice sheet, outlet glacier or ice stream. This coastline is more difficult to detect from imagery alone, but there are clues in visual changes in slope, ice melts at end of slope, surface crevassing and irregularities, etc.

Grounding Zone and Edge of Permanent Ice

The following graphic illustrates the differences between the two coasts:

- F - flexure point — Limit of flexure of the ice from tidal movement
- G - grounding point — base of the ice where it first loses contact with bedrock
- H - hydrostatic point — ice free floating
- I - inflection point — change in slope between ice stream and shelf



Data Sets

The main data we used for mapping:

- 47 Landsat 7 ETM+ (30x30 m pixel size) scenes
- 13 Landsat 4,5 TM (30x30 m pixel size) scenes
- 16 new Landsat 7 ETM+ scenes to replace Landsat 4,5 TM scenes — Same epoch (1999-2002)
- Various vector data sets from AAD, derived from aerial photography

The following supplementary data was used for verification:

- 18 Radarsat (12.5x12.5 m pixel) scenes
- Aerial photography
- 1M and 250K topographic maps

Positional Accuracy

All imagery obtained was already referenced by satellite ephemeris data. The imagery was in the Universal Transverse Mercator (UTM) projection in WGS84. Approximate absolute locational accuracy was based on geodetic station comparisons:

- Landsat 7 ETM+ (< +/-100 m (approx.))
- Landsat 4,5 TM (1-2 km + (approx.))
- Radarsat (200-400 m (approx.))

The following image of Antarctica's Proclamation Island shows the positional accuracy used:

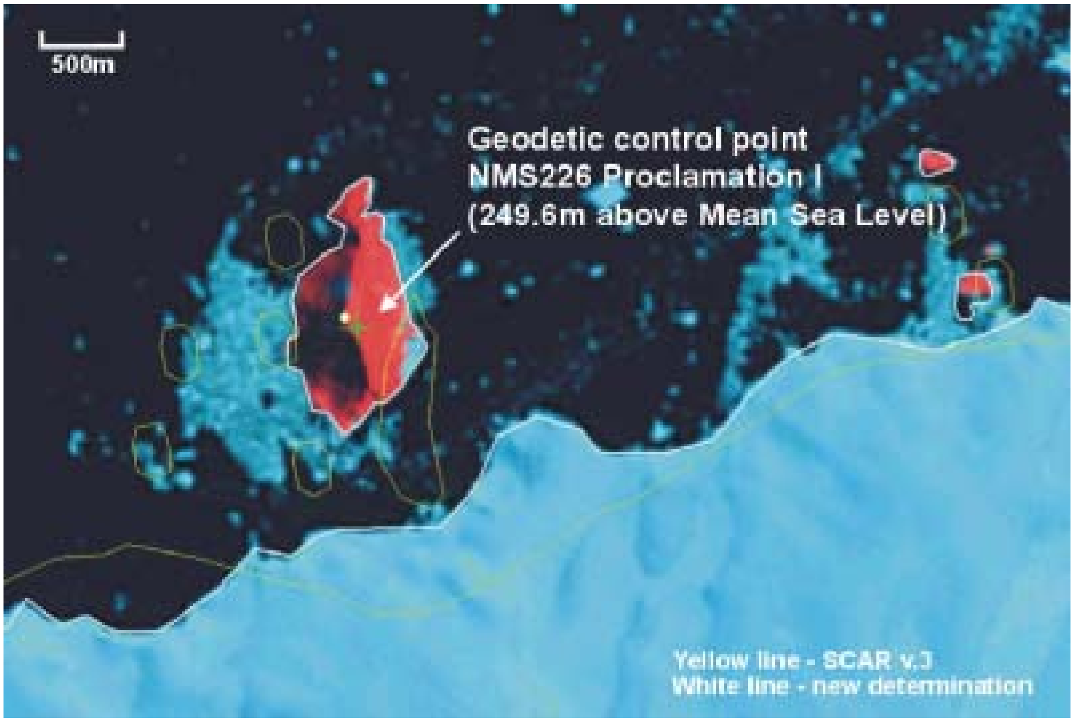


Figure 10. Proclamation Island

Imagery Enhancements

Methods used for enhancing images included band combinations, contrast stretching, and other techniques. The best combination of bands we found were the middle infrared (IR) and visible (RGB 742) bands to highlight rocks against ice. Non-linear contrast stretching increases the visibility of areas obscured by shadows and highlights areas of subtle surface differences (eg.ice rises). Histogram equalization highlights areas of subtle surface change.

Other enhancement techniques included resolution merge of multispectral-pan over areas requiring high definition, shadow reduction, and contrast enhancements.

Feature interpretation helps to point out lines and points in the geography:

Lines

- Rock coast
- Ice coast
- Ice rise
- Grounding line
- Closing line (glacier, shelf)
- Ice wall
- Glacial front
- Glacial tongue
- Ice shelf front
- Multi-year ice shelf
- Non-contiguous glacial tongue

Points

- Island
- Rock
- Glacier
- Ice rise
- Ice shelf
- Multi-year ice shelf
- Glacial tongue
- Non-contiguous glacial tongue
- Void

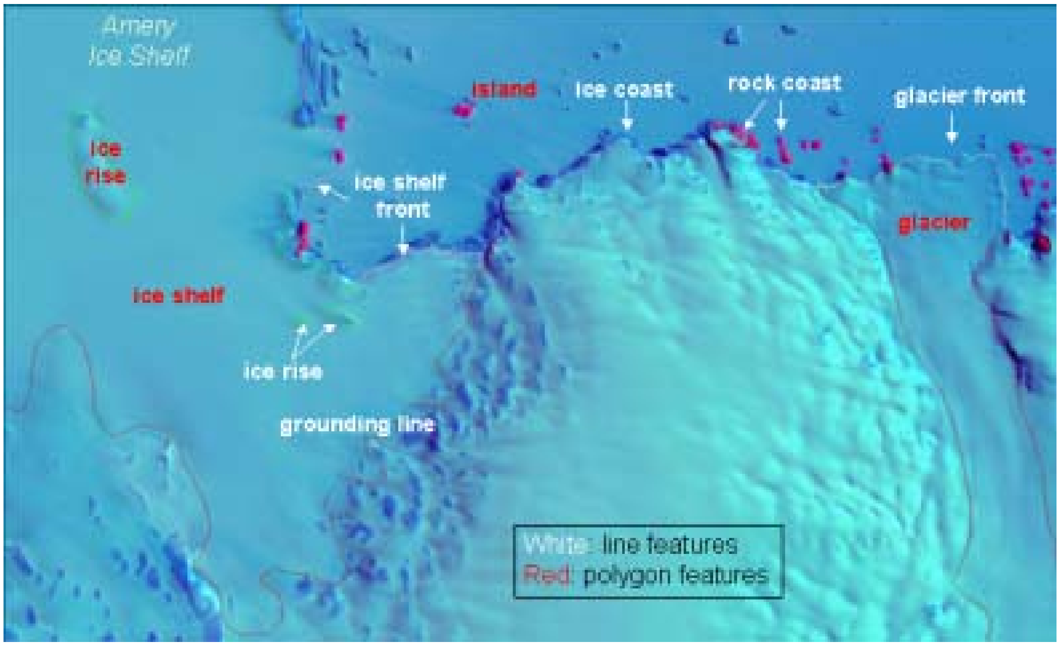


Figure 11. Feature Interpretation of the Amery Ice Shelf

Feature Accuracy

Classification confidence Accuracy of the definition given to a feature based on glaciological interpretation (non-imagery related).	
DEFINITE	Classification is true to real-world.
PROBABLE	Classification is expected to be true.
INFERRED	There is evidence to suggest that classification is true.
SPECULATIVE	Classification is a best guess from the available information.
Location confidence The accuracy of the location of the feature, as it appears on the source data.	
ACCURATE	Feature location is true to its real-world location.
APPROXIMATE	Feature location is approximated and may deviate from the true location.
INFERRED	Feature location is interpreted but may not necessarily correspond to the true location.
Prominence The visibility quality of a feature on the source data.	
OBVIOUS	Feature is easily identifiable from the source.
EVIDENT	There is sufficient evidence to suggest existence of feature.
VAGUE	Feature is not clearly identifiable and is largely indistinct.

Proof of Concept Pilot Study

While the grounding line is not straightforward to determine from imagery alone, the aim of the pilot study is to scientifically validate the location of all grounding line already defined from satellite imagery.

The study includes two test sites of high complexity representative of all features that might be encountered and used the following methods:

- SAR interferometry
- Ice radar profiling
- High-resolution imagery assessment
- Low sun-angle L7 imagery

SAR Interferometry

SAR interferometry uses coherent SAR pairs of images acquired over a time interval - ERS-1 and ERS-2 (1-day apart) tandem mission. It uses the surface backscatter property "phase" of radar signal.

This method is useful for:

- Detecting minute vertical tidal motions of floating ice relative to grounded ice, such as delineating ice sheets' grounding-line positions
- Monitoring ice velocities and flow direction

An interferogram or "fringe" image shows relative phase differences between separate points in an image, with contributions from topography, horizontal ice flow motion, tides, and atmospheric pressure.

Each fringe represents a particular phase difference, about 3 cm of vertical displacement of one point with respect to another.

Differential interferometry In SAR provides a combination of two interferograms to eliminate topography contributions and shows only horizontal ice flow and vertical ice motion. It also maintains a clearer grounding zone definition.

The grounding zone was mapped independently to check accuracy of initial determination from Landsat 7 ETM+ - blind test. The study confirmed initial determination (mostly within 1 km), and identified more areas of grounded ice. In the following SAR image, the white line is derived from a Landsat 7 image, and the black line is interpreted from an interferogram.

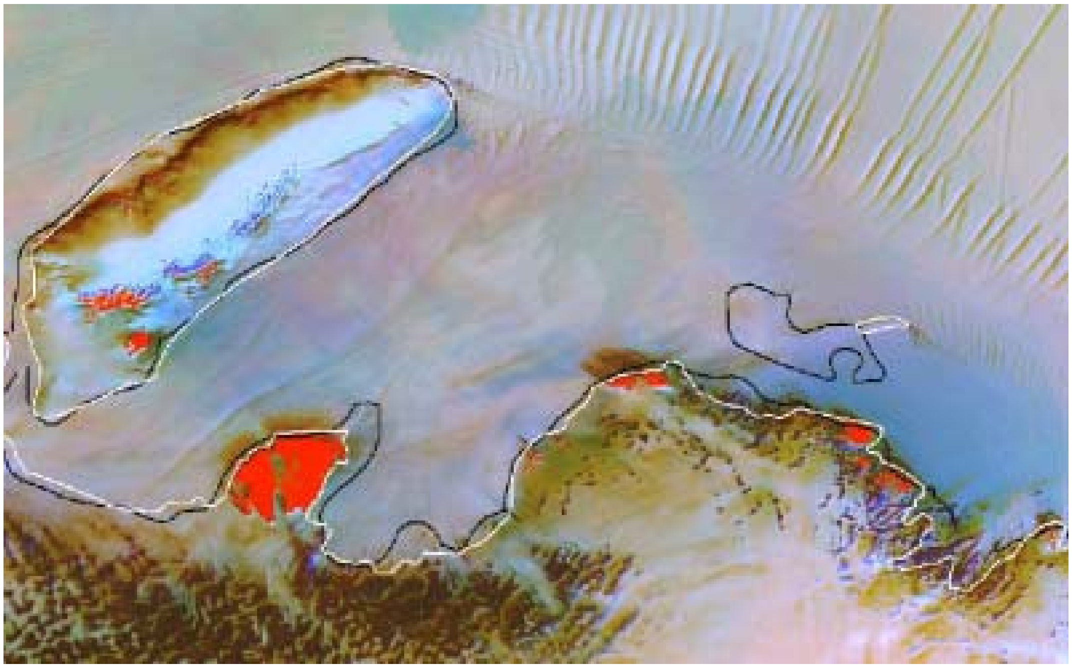


Figure 12. Landsat 7 ETM+ image mosaic of eastern Amery Ice Shelf - RGB 742 with non-linear contrast enhancement

Ice Radar Survey

In the initial ice radar survey, the ANARE Mark III ice radar was fitted to the helicopter. The radar used 150 MHz center frequency, a beam width of 32°, and 7 m ice range resolution. The helicopter was flown 150-200 m from ice surface.

Landsat 7 ETM+ low Sun Elevation Angle Imagery

Different illumination direction from the standard scenes was acquired normally on the descending part of the orbit. Enhancement of structural/topographic features was a key attribute for identifying grounding areas. Some grounded areas that were already identified stand out clearly in these images.

The following images show Landsat 7 ETM+ low sun elevation angle imagery. The image on the left is a standard Landsat 7 ETM+ image. The image on the right was taken with a low sun angle.

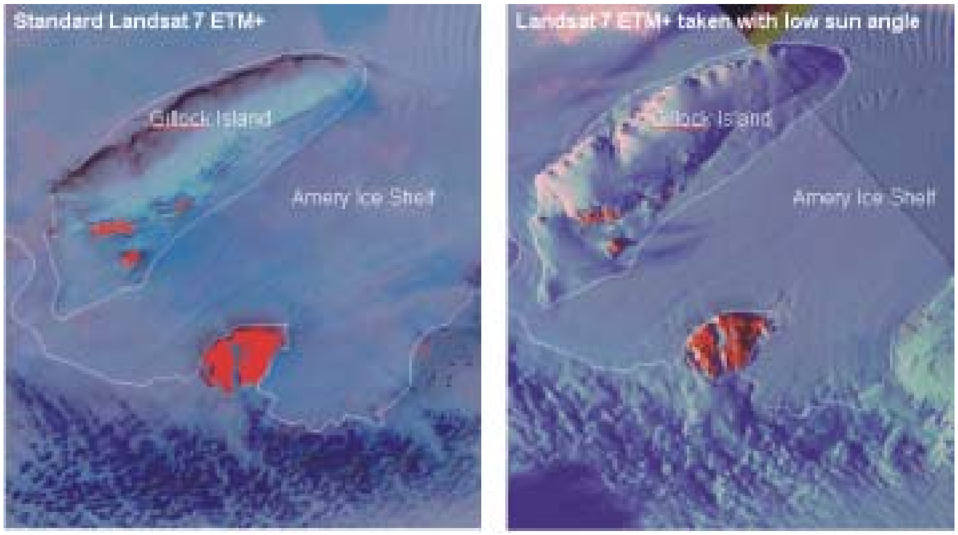


Figure 13. Landsat 7 Low Sun Angle Comparison

Results

In the new coastline determination vs. SCAR v.3 data:

- 60 percent is reasonably similar. There is ~=< 10 km difference on well-defined ice and rocky coasts.
- 35 percent is different. There is ~= 10-20 km for some glaciers, grounding lines, islands/ ice coasts.
- 5 percent is extremely different. It shows ~= 20-80 km, which is probably a result of poor controls on some ice shelves (e.g. Shackleton Ice Shelf) and glaciers.

In the following image shows the new coastline that was derived by SCAR v4 in red. The old coastline, drived from SCAR v2, is shown in green.,

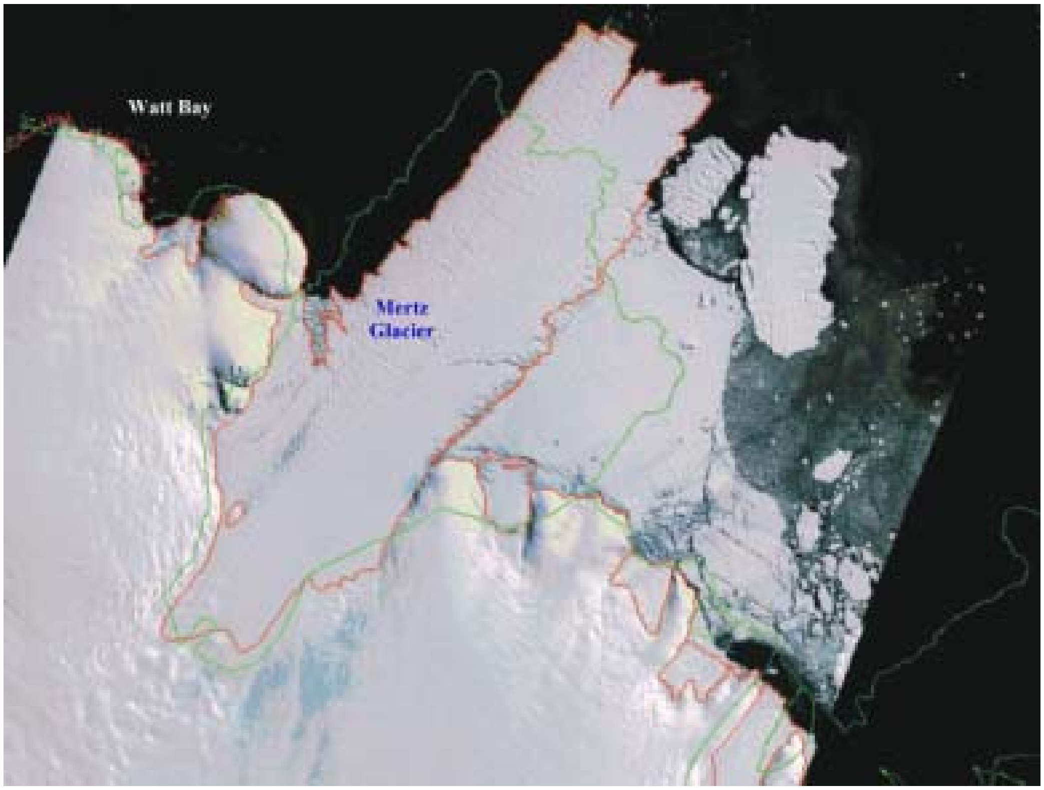


Figure 14. SCAR version 2 and version 4 coastline differences.

The new coastline vs. SCAR data set is an improvement that shows Landsat 7 ETM+ data is suitable for coastline mapping because of its imagery resolution, acceptable positional accuracy, and “one epoch” availability.

The “proof of concept” study greatly assisted in grounding zone validation. We found that very high-resolution imagery is not particularly helpful for grounding zone definition, but may assist in defining very small features such as islands.

Accuracy Assessment of Measuring Glacier Changes from Space at a Variety of Temporal and Spatial Scales

Dorothy K. Hall
Richard S. Williams, Jr., Klaus J. Bayr, Wolfgang Schoner, Janet Y.L. Chien, and
Robert A. Bindschadler

Introduction

Precise measurements of glacier changes are important for small glaciers that are receding rapidly. These data determine the rate of recession, which we can then relate to meteorological parameters. Measuring the changes of small glaciers or ice caps from space has become increasingly accurate, although it is generally not possible to determine the accuracy of glacier changes when registering maps or aerial photography with satellite data. For example, it can be difficult to measure glacier-terminus recession when the terminus is debris-covered. The map below shows an index map of the glacierized areas of Iceland, which is one of the areas of our study.

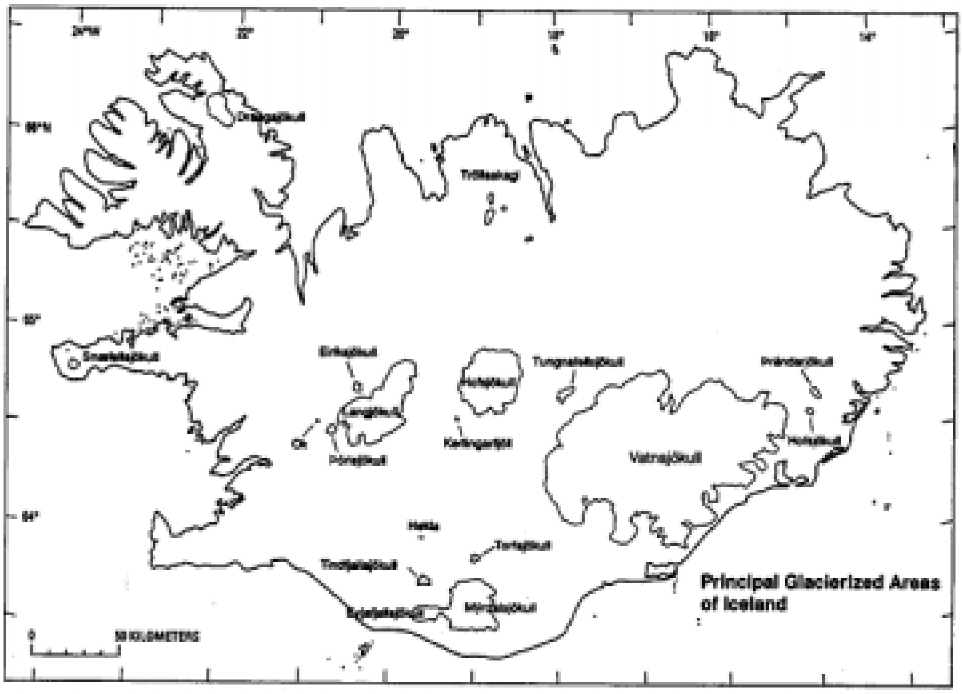


Figure 15. Glacierized Areas of Iceland

The next map shows a close-up of the Vatnajökull region, which is shown in some of the satellite images later in this presentation.

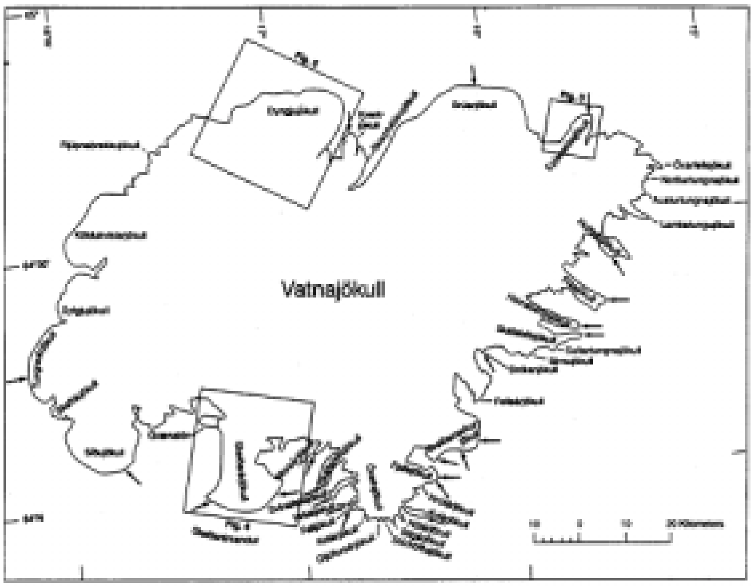
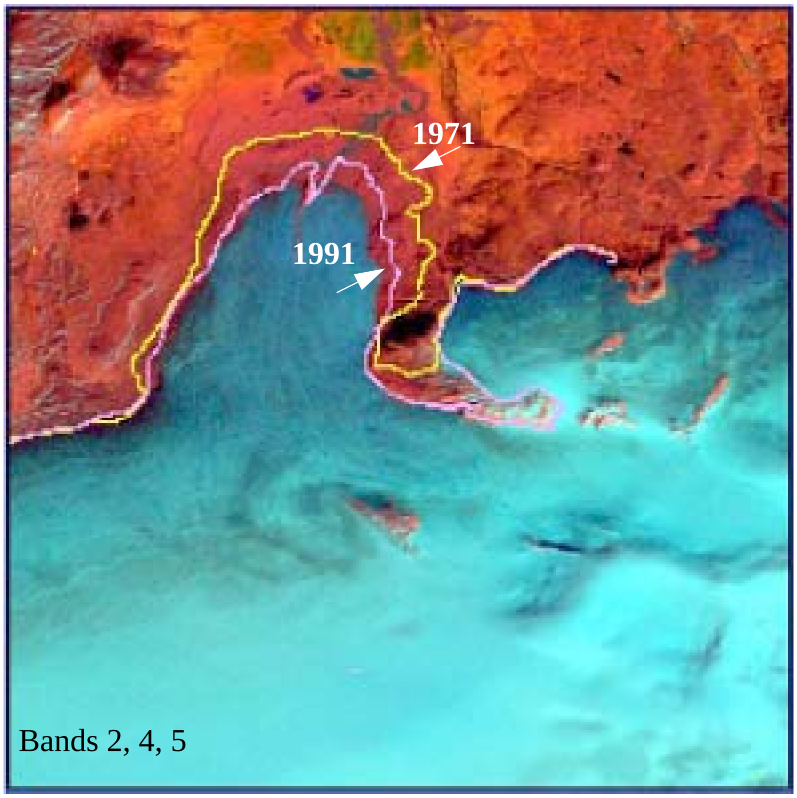


Figure 16. Close-up of Vatnajökull region of Iceland

From Williams (1983) and Williams et al., (1997)

The following image was taken by ETM+ on September 23, 2000. The image shows Eyabakkajökull, an outlet glacier of Vatnajökull ice cap, Iceland, showing 1973 and 1991 positions of the glacier margin.



The glacier front receded ~1.8 km ±136 m from 1973-2000. In late 1972, Eyabakkajökull experienced a 3 km surge (Williams et al., 1974).

Changes from Space

The table in this section shows the unknown errors in different types of satellite imagery.

Map to Satellite	***Unknown error***
MSS to TM*	±136 m**
TM* to TM*	±54 m**
TM* to ETM+	±54 m**
ETM+ to ETM+	±40 m
ETM+ to Ikonos	±40 m
ASTER to ASTER (or to ETM+ band 8)	±21 m
4 m Ikonos to 4 m Ikonos	±5.7 m
1 m Ikonos to 1 m Ikonos	±1.4 m

Table key:

*Not georeferenced (more recent TM data are georeferenced.)
**Includes registration error.
Uncertainty = ±28.52 + 28.52 (from Williams et al., 1997) plus registration error.

There is no registration error when using georeferenced images, e.g., two ETM+ images, or an ETM+ and Ikonos image.

Muir Glacier

The following is an image of Muir glacier in Alaska. The Muir terminus receded >7 km ±136 m from 1973 to 1992:

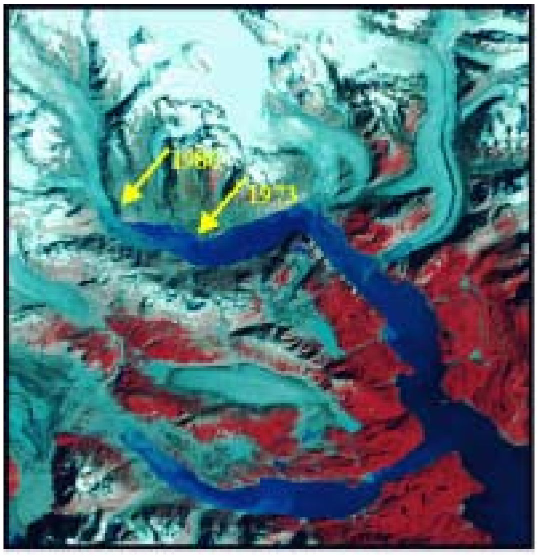


Figure 17. Muir Glacier, Glacier Bay, Alaska, taken September 6, 1986 (Hall et al., 1995)

Pasterze Glacier

The next ETM+ image shows changes in the Pasterze Glacier tongue between 1893-2001:

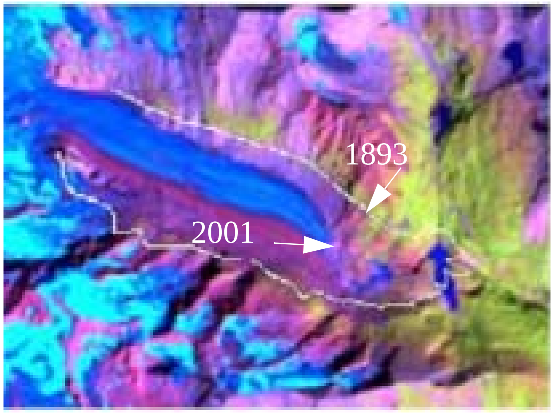


Figure 18. This ETM+ image was taken August 26, 2001

Between 1976 and 2001, Landsat-derived measurements show a recession of the terminus of the Pasterze Glacier of 479 ±136 m while recession on the ground was 428 m ±1 m, a difference of 51 m.

Global Climate and Environmental Changes in Alpine Asia

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Our research focuses on the natural processes and anthropogenic impact responsible for glaciological and hydrological variability on annual to centennial time scales.

This research is being conducted on the glaciers of the Great World Mountain System (Tien Shan, Pamir, Altai, Tibet, Himalayas) that supplies water to regions containing more than 80 percent of the world's human population.

Figure 19. Great World Mountain System Glacier Areas

Our research combines detailed paleo-environmental records from firn-ice cores with the analysis of modern glaciological, synoptic, meteorological, hydrological, snow/ water isotope/ geochemistry and remote sensing data.

This research started in the 1980s at Northern Tien Shan and Pamir. Research continued in the 1990s at Central Tien Shan, southeastern Tibet and the Himalayas and extended to Altai and the southeastern Himalayas in 2001 and 2002. In the summer of 2003 we are planning a deep ice-coring expedition to Altai. We will continue glacio-climatic monitoring at Tien Shan and southeastern Himalayas.

In 2000, two 165 m firn/ice cores from 5120 m above sea level at South Inilchek Glacier, Tien Shan, were recovered after several years of glacio-climatic monitoring and long-term data collection. Three shallow firn cores (49 m apart) were obtained at the Belukha Snow/Firn Plateau (4130 m) in Altai and the Yuolong Glacier snow/firn field (6100 m) at Bomi glaciation in southeastern Himalayas during 2001 and 2002 field reconnaissance.

We are developing a technique that couples large-scale climatology with specific records obtained from a single point at high-mountain glaciers through firn-ice cores and snow sampling. The isotope and major ion data provide a basis for interpreting centennial-scale ice core records and highlight the complexity of time-series isotope and geochemistry records from mid-latitude firn/ice cores.

Regional-scale hydrological conditions, including seasonal changes in moisture source, transport, and recycling in the Caspian/Aral Sea region, are responsible for variability observed in snow/firn and ice-cores. The transfer functions between maximum mean/seasonal air temperature and the highest/seasonal $\delta^{18}O$ content were differentiated by the prevailing synoptic patterns in the accumulated snow of the Tien Shan and the North Atlantic Oscillation and Pacific North America means in the Altai time-series.

The combination of geochemical compositions points to three types of mineral deposits—loess, calcium carbonate, and gypsum—which do not co-vary in a linear fashion. Time-series dust composition variability appears to be linked to changing dust source regions based on rare earth element patterns and element ratios. Differences in the sulfur isotopic composition ($\delta^{34}S$) of a high-dust period (+15.0 ‰) and low-dust period (+5.4 ‰) samples provide strong evidence for two sources of sulfate. The latter composition indicates that a major portion of the atmospheric SO_4^{-2} was derived from anthropogenic emissions.

The Altai glaciers are characterized by abnormally high content of heavy metals compared to world glaciers. They also show significant deviations from natural isotopic ratios (De Bievre and Barne, 1985). The pronounced variable in concentrations of heavy metals from ice core layer dated at the end of 80s is associated with relative contributions from the different sources of heavy metals. High concentrations of heavy metal in stream water is greater in the glacierized basins than in the glacier-free basins.

During 1935-1995, Tien Shan glaciers lost about 27 percent of their mass. During 1952-1998, Altai glaciers lost about 10 percent of their mass. The Altai glaciers retreated by 2-8 m per year. The average rise in air temperature was 0.7°C in Tien Shan/Pamir during the last century. Precipitation increase is greater at low altitudes than at altitudes above 2,000 m.

The annual runoff has decreased in Central Asian rivers. Decrease in snow melt contributes to river runoff, and is compensated by increasing glacier and permafrost melting only in the upper reaches of river basins with large glaciers. The combined effect of increased evaporation and changes in the snow and glacier resources are responsible for the observed reductions in river runoff and increasing water percolation in Central Asia. These changes may partly explain the decline in water levels in Aral and Balkhash lakes and water level rise in the Caspian Sea and Issik Kul Lake.

The Central Asia closed river basins annually stored about 2.5 percent of the total external atmospheric moisture in the glaciers and deep ground water circulation systems for a long period of time. The Tarim river basin appears to be a great sink for atmospheric moisture. Chinese scientists recently discovered huge aquifers under the Takla Makan desert.

There is significant correlation between atmospheric circulation patterns and changes in solute content in precipitation at seasonal and annual time scales. The contribution of vapor from the internal water cycle developed over the arid and semi-arid regions in central Eurasia to snow accumulation occurs partially in winter and autumn seasons, when the peripheries of the Siberian High and southern cyclones bring moisture from the Aralo-Caspian closed drainage basin. Maximum ionic concentration is observed in winter and spring seasons. The main summer precipitation is associated with the external water cycle and is brought from the Atlantic Ocean to central Ten Shan and Altai and from the Pacific Ocean to Altai glaciers. The firn-snow samples characterized by the lowest ionic content among the Tien Shan's glaciers pointing to their marine origination in Atlantic Ocean, Mediterranean Ocean, and the Black Sea. Maximum content of Na+, Cl- and K+ is observed in the summer annual layers of firn core. Significant local NH^4 sources are biomass burning and livestock. We did not find a departure of Na+ and Cl- ions from the seawater ratio in ice core records that point to the marine origination of precipitation. High content of NH_4 and its highest correlation with NO_3- and SO_4^{-2} are consistent with aerosols prevalent in the global troposphere.

Recent Changes in the Extent and Volume of Canadian Arctic Glaciers

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Introduction

The Queen Elizabeth Islands in the Canadian High Arctic contain almost 110,000 km^2 of glaciers and ice caps. This comprises ~5 percent of the Northern Hemisphere’s ice cover, and is the largest area of ice after the Antarctic and Greenland ice sheets.

The glaciers of the Canadian High Arctic likely respond more rapidly to perturbations than the large ice sheets, and are thus potentially sensitive indicators of climate change. A good understanding of their distribution and flow characteristics is therefore important, yet little is currently known about them. This is of particular concern given the enhanced warming (6-8 °C) predicted by general circulation models (GCMs) for the Arctic over the next century.

The aim of this study is to assess changes in the extent of the ice cover in the Queen Elizabeth Islands over the period 1959-1999. An area-volume scaling relationship is used to convert measured area changes to volume changes, which in turn enables an estimate of their contribution to global sea level.

Methods

Digital ice outlines (shapefiles) provided by Geomatics Canada provided the basic information on glacier extent in 1959. These ice outlines were derived from the digitization of 1:250,000 topographic maps, which in turn were created from 1959 stereo aerial photography. At spot locations throughout the study area, the digital ice outlines were checked against the ice extents on the air photos. Few errors were found, and the data sources generally matched each other closely.

The 1999 ice outlines were derived from automatic (unsupervised) classification of orthorectified Landsat 7 imagery. Approximately 15 scenes were required to complete the coverage for our region of interest. To automatically derive the ice covered area in the imagery, the normalized-difference snow index (NDSI) was used (Dozier, 1984):

$$\mathrm{NDSI} = \frac{\text{band } 2 - \text{band } 5}{\text{band } 2 + \text{band } 5}$$

This method utilizes the brightness of snow and ice in the visible band 2 versus the low reflectivity in the near-infrared band 5. Once an image was classified with NDSI, it was passed through despeckle and sharpen filters to remove noise. It was then manually checked against the original Landsat 7 imagery, and changes made where necessary for incorrectly classified areas arising from shadows, etc. Finally, the areas classified as ice were converted to shapefiles in ArcView.

Area changes were derived by subtracting the 1999 ice outlines from the 1959 outlines (see Table 2). A volume-area scaling relationship was used to convert these area changes into estimates of changes in ice volume (Bahr and others, 1997):

Volume = b Area1.25

Extensive airborne radar thickness measurements on Devon Ice Cap allow determination of b = 0.026. By assuming that this value is valid for all the ice caps in our study area, the volume change of each ice cap can be calculated (Table 3). The volume of ice lost was converted to an estimated impact on global sea level by dividing by the area of the world's oceans.

Results and Conclusions

Net loss was recorded for all ice caps in the study area over the period 1959-99 (Table 2). The majority of glacier termini retreated over this period, although advances were also recorded at some locations due to glacier surging. The total area of ice lost was 1844 km^2, or 1.77 percent of the area in 1959.

This area loss equates to an estimated volume change of 635.8 km^3 (Table 3). This would account for an estimated rise in global sea level of 1.45 mm. Total global sea level rise since 1960 has been ~60 mm, of which ~40 mm has been to thermal expansion of the oceans and ~8-16 mm from glacier and ice cap melting outside of Antarctica and Greenland (IPCC, 2001). Thus, the Queen Elizabeth Islands are responsible for 9-19 percent of the global glacier contribution to sea level change over this time, or ~2.5 percent of the total.

Table 2. Change in area of the Queen Elizabeth Islands glaciers over the period 1959-1999

Ice cap	***1959 area***	***1999 area***	***Change km^2***	***Change (%)***
Devon	14342	14004	-338	-2.36
Manson	6255	6124	-131	-2.08
Sydkap	3672	3638	-34	-0.93
Prince of Wales	20500	20337	-163	-0.79
Agassiz	21210	20946	-264	-1.24
N. Ellesmere	26131	25395	-736	-2.82
Axel Heiberg	11978	11819	-159	-1.33
Meighen	93	74	-19	-20.73
TOTAL	104181	102337	-1844	-1.77

Table 3. Change in volume of the Queen Elizabeth Islands ice caps over the period 1959-1999, and their estimated contribution to global sea level

Ice cap	***Volume change 1959-1999 (km^3)***	***Mean elevation change (m)***	***Sea level contribution (mm)***
Devon	65.0	4.5	0.15
Manson	37.8	6.0	0.09
Sydkap	8.6	2.3	0.02
Prince of Wales	63.3	3.1	0.14
Agassiz	103.4	4.9	0.24
N. Ellesmere	303.0	11.6	0.69
Axel Heiberg	54.0	4.5	0.12
Meighen	0.7	7.7	0.00
TOTAL	635.8		1.45

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Glacier Mapping from Historical Data and ASTER Images

Tatiana Khromova, Andrei Glazovsky, Gennady Nossenko, Mark Dyurgerov

A GLIMS Regional Center (RC16) has been established in the Institute of Geography, Russian Academy of Sciences, Moscow. This center is responsible for the glaciated areas in the Russian Arctic, the Urals, the Caucasus, Siberian mountains, Kamchatka, Altay (including the Mongolian section), and mountains in southern Kazakhstan. A wide variety of geographical environment and glacial types allows assessing the applicability of ASTER data for different geographical settings and glaciological tasks. The first object of the project is to create a base of digital maps of current glacier states and glacier margins. Extracting these features from ASTER images is of prime importance. The ASTER mission for the period 2001-2002 covered practically all glaciated regions of Russia. However, unfavorable cloud cover conditions are rather common and increase northward. That greatly reduces the number of suitable images. In addition, the number of images made in the optimal season limits the total useful coverage. Finally, images for some glaciated areas such as the Urals, Suntar-Khayata, and some other mountains, are not yet available. About 10 percent of the total number of images are usable. The multi-band option of ASTER data improves the interpretation of glacial features, such as snow line and glacier surface topography. The preliminary results were obtained from analysis of images for the Caucasus, Kamchatka, Tien-Shan, and the Russian Arctic.

One of the main problems is automatic extraction of individual glaciers from ASTER images. We imagine universal software and automatic processes, but in this case we did manual extraction. Our experience shows that we need to know regional features of the glaciers and to use additional data such as field instrumental data and images with higher resolution (air photos and others).

The high spatial resolution of ASTER images allows us to extract the margins of polar glaciers, which end in the sea. The fronts of cirque glaciers and debris-covered glaciers are identified less confidently, and in some cases require additional ground-truth data. Another problem is shadowing.

Geometrically co-registered Level 1B data are based on orbital parameters without ground control points. As a result, the accuracy we have for Arctic glaciers is only about 200-300 m. It is not enough for GLIMS’ aims. So we need additional correction with the help of ground control points (GCPs) from field studies or topographic maps.

An ASTER image (15 July 2000, Level 1A, with geometric correction) and topographic map (scale 1:200,000) from an aerial photographic survey in 1953 for the Shmidt Island ice cap (Severnaya Zemlya) have been analyzed. Shmidt Island is almost totally covered by ice. It was possible to use only one place with a rock outcrop in the northern part of the island. In this case, values of the glacier outline changes include errors of georegistration, topographic map errors, and glacier changes. As a result, more reliable values of this cap retreat seem to be in northeastern part of the island where the changes are about 600 m in 47 years.

When it was possible to use field data including GCP for georegistration and image interpretation, the accuracy of glacier outline determination may be about 30 m. We compared an ASTER image for Koryto glacier (Kamchatka, Kronotzki peninsula on 4 July 2002) and the map compiled by Dmitri Tzvetkov from a ground photographic survey in 1960. The results show a retreat of the Koryto glacier of 400 m. These results were confirmed by field studies in August of 2002.

A new assessment based on set of ground photogrammetry data and ASTER images shows strong reduction of three Polar Ural Glaciers: MGU, Obruchev, and IGAN from 1953 to 2000. They lost nearly half of their area in this period, and the negative trend in the last decade seems to be accelerating.

The results of earlier studies by Soviet glaciologists in Tien Shan and an ASTER image for September 2001 have been used to calculate changes in area and other features for glaciers in the Akshirak Range over the interval from 1943 to 2001. The overlay of a transformed ASTER image and digital vector outlines for 1943 in ARCView shows the following changes: a decrease in glacier size, the appearance of new glaciers as a result of disintegration of complex ones, the disappearance of small glaciers, an increase in the perimeters of water divides between individual glaciers, and an increase in the area of outcrops (Khromova, et. al., 2003).

A significant loss of glacier area locally has been caused by the direct impact of the exploitation of mineral resources. We estimate the direct impact of exploitation to be ~ 0.7 km^2 of ice, which constitutes about two to four percent of the entire area loss in the Akshirak Range.

The total Akshirak glaciers areas were calculated for 1943 and 2001 in relative units. Area change for 1943-2001 was estimated as 26 percent.

The estimated changes in area need to be examined with respect to various sources of error:

- Errors in the original topographic maps showing glacier outlines
- Errors due to the interpolations used in preparing the DEMS
- Errors in the imagery transformation procedures etc.

Air photos from 1943 and 1980 and topographic maps (1:50,000) were used to examine the boundaries of several glaciers. It was found that the glaciological map by Kuzmichenok (1989) includes in the areas mapped as “glacier” both thin ice cover on slopes adjacent to the glaciers and snow patches abutting the glaciers. We made calculations, both with and without these areas, for the ASTER L1B image transformed in ERDAS software to the UTM projection.

It was shown that the area of ice on slopes amounts to 1-7 percent of the corresponding glacier areas. However, these differences are still small relative to the calculated reduction in area of the Akshirak glaciers. These fields of thin ice and snow patches, together with glacier termini, react first to a change in climatic conditions. Thus, the disappearance of thin ice areas and snow patches represents an essential part of the shrinkage of a glacier system.

To summarize the climatic changes with respect to the glaciers, air temperature, and precipitation from the Tien Shan meteorological station have been calculated for two parts of the glaciological year adapted to the local conditions. The ratio between summer (June-August) and winter (October-May) precipitation was calculated. A strong decrease in precipitation ratio has accelerated since the mid-1970s as well as an increase in summer air temperature. This presents the most unfavorable climatic conditions for glaciers, especially in Central Asia where summer precipitation plays a crucial role in the annual mass balance (Ageta and Higuchi, 1984; Xie Zichu et al., 1999).

The decrease in the Akshirak glaciers area since 1977 is compatible with a 29 percent decrease of glacier area in the Zailisky Alatau, Western Tien Shan, for 1955-1990 (Vilesov and Uvarov, 2001), and a 16 percent reduction in the Pamir for 1957-1980 (Shetinnikov, 1998).

The first results of our studies confirm the clear trend in area loss of glaciers in the Caucasus, Polar Ural, Kamchatka, Tien Shan, and Pamir areas and for some glaciers in the Russian Arctic. The results provide valuable conclusions for worldwide glacier inventorying and monitoring and reveal some technical and conceptual problems which need to be solved.

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Glacier Changes in the Russian Arctic

A.F. Glazovsky

The distribution of glaciers in the Russian part of the Arctic (Figure 20), shows distinctly that glaciation decreases markedly eastward. This reduction clearly relates to a decrease of precipitation and an increase in the continentality of the climate in that direction. The major sites of glaciation in the Russian archipelagos lie along the branches of the atmospheric trough, which originates in the North Atlantic. The eastern end of the trough reaches Severnaya Zemlya, where there is still enough atmospheric moisture to support glaciation; this is also the case in respect of the Taymyr and De Long Islands. An absence of glaciation on the New Siberian Islands results not only from low precipitation but also their low altitude.

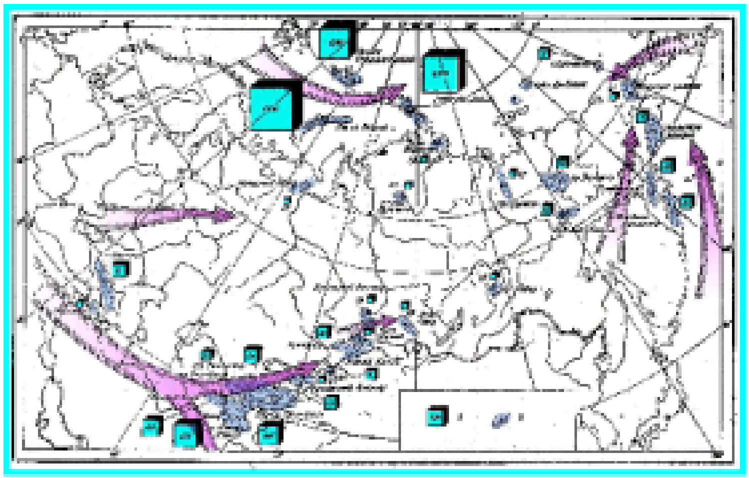

Figure 20. Glacier distribution in Northern Eurasia. Ice volumes (km3 of water) are shown as cubes; arrows show major low pressure tracks (from Krenke, 1982)

The mesoscale distribution of ice masses on the archipelagos is also asymmetric. The larger ice caps, which have numerous outlet glaciers, higher activity indices, and lower equilibrium line altitudes (ELAs), (Table 4), occur in areas located closer to the atmospheric pressure trough (cyclonic activity tracks). The occurrence of ice masses in the Arctic is mainly controlled by a climatic factor. There are, however, two exceptions: the Polar Urals and the Byranga Mountains (in the Taymyr Peninsula), where landscape is also important, being favorable for high snow concentration.

Table 4. Mean summer air temperature (June-August) at mean ELA, mean estimated accumulation, and solid precipitation in the Russian Arctic glaciated areas (Krenke, 1982, modified)

Glaciated region	**Mean ELA (m.w.e.)**	**Accumulation (m.w.e.)**	**Solid precipitation (m.w.e.)**	**Mean T 6-8at ELA * (°C)**
Victoria Island	100	0.38	0.54	-2.2
Franz Josef Land	260	0.30	0.30	-2.6
Novaya Zemlya	480	0.61	0.61	-0.9
Polar Urals	850	1.70	1.06	2.9
Ushakov Island	250	0.31	0.44	-3.1
Severnaya Zemlya	450	0.23	0.20	-2.3
Byrranga Mts.	850	0.33	0.21	-2.9
De Long Islands	200	0.22	0.31	-2.8

* -8 - mean summer air temperature (June-August)

The mean air temperature in January varies from -15°C to -20°C northeast of the Barents Sea to -32°C to -36°C in the Siberian Arctic. The mean air temperature in July is highest in the continental part (+2°C to +3°C) whereas on the archipelagos, it is near zero. The maximum precipitation is in the southern part of the Atlantic sector (as much as 400 mm) but in the Siberian Arctic, precipitation is as little as 150 mm. The precipitation on the glaciers is variable and depends on the glacier morphology and position relative to the prevailing wind directions. The mean differences in the solid precipitation between the leeward and windward sides of glaciation systems are significant, being higher than the differences between particular archipelagos: on Franz Josef Land, 240 mm; Novaya Zemlya, 600 mm; Severnaya Zemlya, 140 mm; and the Polar Urals, 620 mm. The pattern of the ELA shows a general northward decrease of altitude from 600-1000 m above sea level in the Polar Urals and Byrranga Mountains to approximately 150 m on some of the islands in the Franz Josef Land archipelago and Ushakov Island. There are local increases in the ELA on the leeward sides of Severnaya Zemlya, and, especially, Novaya Zemlya and the middle part of the Franz Josef Land archipelago. Regional variations of ELA are shown in Table 4 (Jania, Hagen, 1996).

It is generally believed that the different zones of ice facies on the ice masses of the Russian Arctic show a high ratio of superimposed ice relative to firn (Table 5 and Table 6).

Table 5. Area distribution of different ice facies zones on glaciers in the Russian Arctic (Govorukha, 1989)

Ice facies	**Ablation zone**	**Accumulation zone**		
Glaciated region	(km2)	Total (km2)	Firn zone (km2)	Superimposed ice zone (km2)
Victoria Island	10	1		1
Franz Josef Land	8,430	5,300	3,400	900

Table 5. Area distribution of different ice facies zones on glaciers in the Russian Arctic (Govorukha, 1989)

Ice facies	***Ablation zone***	***Accumulation zone***		
Novaya Zemlya	13,400	10,900	7,600	3,300
Severnaya Zemlya	9,130	9,200	4,750	4,450
De Long Islands	50	27		27
Byrranga Mts.	30	1		1

Table 6. Approximate estimations of internal accumulation on Arctic glaciers by melted water and liquid precipitation which refreeze in snow residual, firn and as a superimposed ice (Krenke, 1982)

Region	***Accum. area and AAR (km^2)/(%)***	***Total accum. (km^3)***	***Net snow residual accum. (km^3)***	***Internal accum. (km^3)***	***Volume of melted water (km^3)***	***Total liquid water input in glaciers (km^3)***	***Loss of total water input for internal accum. (%)***
Franz Josef Land	5,300 /39	4.1	1.0	1.2	2.8	3.5	34
Novaya Zemlya	13000/55	14.4	3.8	4.0	15.9	17.3	23
Severanya Zemlya	9,600 /52	4.3	1.3	1.8	5.3	6.1	30
De Long, Ushakov, Wrangel Islands	154/38	0.12	0.027	0.0	0.1	0.1	-
Total	28,054/50	22.9	6.1	7.0	24.1	27.0	26

Mass balance measurements

The mass balance values of glaciers in the Russian sector of the Arctic relate to different observational periods and have used different methods. The number of direct mass balance measurements is limited. All available long-term reconstructions of mass balance time series indicate negative values for all Russian glaciers during the 20th century.

General Results

1. Available mass balance measurements and reconstruction indicate that the mass balance state of the Russian Arctic glaciers is negative in the 20th century. However, the sparse mass balance data need much more input from remote modem technique studies to be robust in spatial and temporal coverage.
2. The refreezing of melted snow and liquid precipitation water in snow/firn zones and on the ice surface is clearly an important component of the mass balance structure in the High Arctic. Available estimates show that more than half the net accumulation is the result of this refreezing process. On the other hand, internal accumulation reduces the potential run-off by 26 percent. Also, frequent summer snowfalls have a strong impact on the rate of ablation of Arctic ice masses. These processes should be studied much more thoroughly as an important factor in the glacier dynamics, and specifically, in determination of mass balance fluctuation, glacier thermal evolution, and glacier impact on sea level.

3. The iceberg discharge of ice into the sea is also an important factor of glacier dynamics. Nearly one quarter of the flux of Russian Arctic glacier flow is discharged as calving into sea water. Approximately 3.8 km^3 is iceberg flux (1.5 km^3 on Franz Josef Land - 60 percent of glacier run-off; 2.0 km^3 on Novaya Zemlya - 80 percent; 0.2 km^3 on Severnaya Zemlya - 25 percent) Additionally, 2.0 km^3 is lost because of the thermal decay and wave abrasion of the ice cliffs.
4. Marine ice margins reveal the regression trend over the Western Russian Arctic in the second half of 20th century. The largest net recession occurs on Novaya Zemlya (on average –1.5 km, maximum –5.56 km). In second place is Franz Josef Land (on average –0.82 km, maximum –3.6 km) and the last one is Severnaya Zemlya (in average –0.13 km, maximum –2.1 km).
5. Because of the general recession of marine ice margins, the ice-covered area on archipelagos has diminished by 725 km^2 (-375 km^2 on Franz Josef Land, -284.2 km^2 on Novaya Zemlya, and -65.4 km^2 on Severnaya Zemlya). The positive effect of the minor advance of some ice shores (29.1 km^2 on Franz Josef Land, 0.3 km^2 on Novaya Zemlya, and 22.6 km^2 on Severnaya Zemlya) is significantly below the overriding regression of the ice shores (-404.4 km^2 on Franz Josef Land, -284.5 km^2 on Novaya Zemlya, and –88.0 km^2 on Severnaya Zemlya). The average net rates of the glacier front changes are -30 m/yr on Novaya Zemlya, -17 m/yr on Franz Josef Land, and -3 m/yr on Severnaya Zemlya.

Glacier Dynamics in the Future

Recently the problem of polar glacier sensitivity was studied in the ICEMASS project (the response of Arctic ice masses to climate changes). It shows that the variation of glacier sensitivity to climate change across the Arctic depends on how global warming will be distributed in space and time. For the dry glaciers summer temperature dominates the picture, but for wetter regions fall and spring temperatures are just as important.

Severnaya Zemlya, Franz Josef Land, and in a lesser extent, Novaya Zemlya, belong to the dry-type region. Therefore, summer temperature changes might strongly influence their mass balance state and dynamics in the future.

Additional Factors

Now most of ice bodies on Severnaya Zemlya, Franz Josef Land, and Novaya Zemlya are cold enough to refreeze a substantial part of the melting water and liquid precipitation that percolates in cold snow and firn layers in summer. As a result of refreezing, the net melting losses decrease by 20-30 percent. In the case of long-term warming, the cold capacities of ice bodies might decrease enough to be unable to recapture the part of melting water in summer, that will accelerate glacier recession without additional climate forcing.

Secondly, the warming of cold ice bodies that now dominates the archipelagos might result in a transition from a cold-type regime to a polythermal type (with upper cold and lower warm layers), or even to a temperate one (with ice temperature is at melting point throughout the ice body). Such deep changes in the hydrothermal state might increase the glacier instability manifested in surge behavior. Now the surge-type glaciers are abundant on Svalbard. Meanwhile, there are only few on Novaya Zemlya and Severnaya Zemlya. Further penetration of warming deep into the high Arctic might change the state drastically.

The third factor is the positive feedback between ice-covered area and regional air temperature. Shrinking of ice-covered area and a corresponding increase of ice-free area (which has different summer albedo and other physical properties) results in regional summer temperature rise, that, in turn, nonlinearly accelerates ablation. A similar effect might result from a slight variation in sea water temperature and sea-ice conditions around the archipelagos in summer time.

The fourth specific feature is the calving activity of the glaciers that end in the sea with a grounded ice cliff from which icebergs are discharged. These so-called tidewater glaciers dominate in the archipelagoes, while floating ice tongues or ice shelves are much more rare. Numerical modelling shows (Vieli, Funk, and Blatter, 2001) that for the slowly retreating or advancing glaciers, the linear relationship between calving rate and water depth at the ice front is rather satisfactory. But rapid changes are mostly controlled by the bedrock topography and are in a lesser degree a direct reaction to mass balance variation. It suggests better knowledge of glacier bedrock topography is required to be able to reliably predict future glacier front and ice shore changes.

These peculiarities should be kept in mind, especially if the long-term or local forecast scenarios developed for glacier dynamics where required for safety and protection needs of some specific technical projects.

What Next?

The following topics should be considered as the major points of glaciological investigations in Russian Arctic in the near future.

- 2D and 3D glacier geometry
- Glacier velocity fields
- Monitoring of transient snow line
- Radio-echo sounding studies
- Deep ice core drilling
- Ground truth observations
- Special studies in poorly known regions (for example Central and Eastern Siberia)

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Assessment of Glaciers Change on Polar Urals from ASTER Imagery

Gennady Nossenko, D. G. Tzvetkov

The Polar Ural area is a support region of the Russian Subarctic glacier monitoring system. In spite of the small sizes (up to 1 km^2) of present-day glaciers, the research on Polar Ural glaciers has fundamental scientific importance for understanding climatic changes.

In 1958-1981 the Institute of Geography of the Russian Academy of Sciences (RAS) carried out surveys and research on Polar Ural glaciers. According to the Glacier Inventory of the USSR comprising materials of air surveys from 1953 to 1960, there were 47 glaciers in the common area (14 km^2).

Between 1953 and 1981, 10 glaciers were covered by new ground topographical and air photogrammetric surveys of fluctuations of the glaciers' form and size (IGAN, MGU, Obrucheva, Chernova, Karsky, Anuchina, MGG, MIIGAIK, B.Usinsky, and Oleny).

The periodic ground phototheodolite surveys of glaciers were made at scales of 1:2,000 to 1:5,000 and annual geodetic (theodolite) measurements of coordinates of marked glacier surface points. Data from the air surveys from 1953, 1960, 1968, and 1973 (M 1:15,000 to 1:30,000) were also used. The mass balance measurements were conducted annually from 1958 to 1981 on the IGAN and Obrucheva glaciers. Now the Institute of Geography of the RAS has a unique database of different observations of glaciers in the Polar Urals up to 1981.

The remote sensing data from the Terra satellite have allowed us to prolong this series of observations and to receive new data about the modern condition of glaciers. The ASTER images taken 12 July 2000 and14 July 2001 were used for these studies (Figure 21). Unfortunately, they cover only the western part of the Polar Urals, including MGU, Chernova, and Obrucheva glaciers. Images were transformed to a geographical projection with usage of topographical sheets (M 1:200,000) and they were used to extract modern glacier boundaries and estimate changes. The determination of the glacier body was done manually. The comparison of the results to the observational data of the last years has allowed conclusions about the continuing degradation of all three glaciers and possible full disappearance of them in the coming decades (Figure 22, Table 7).

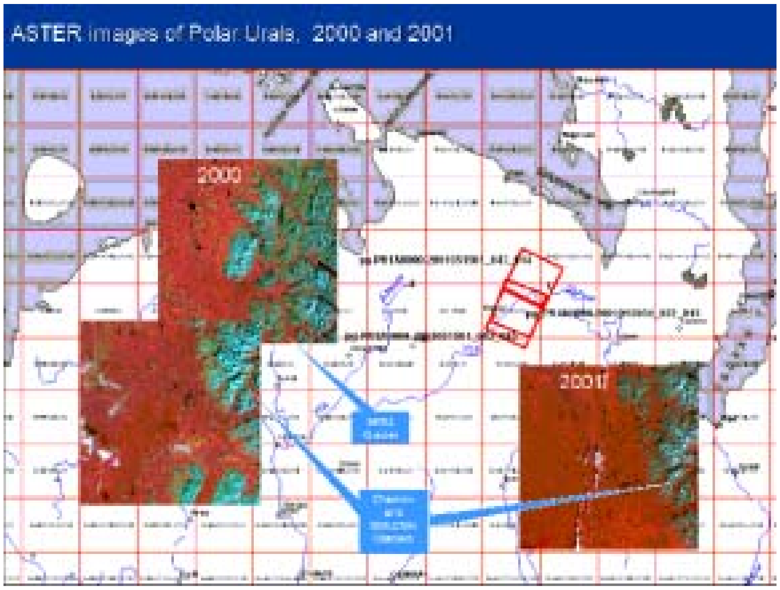
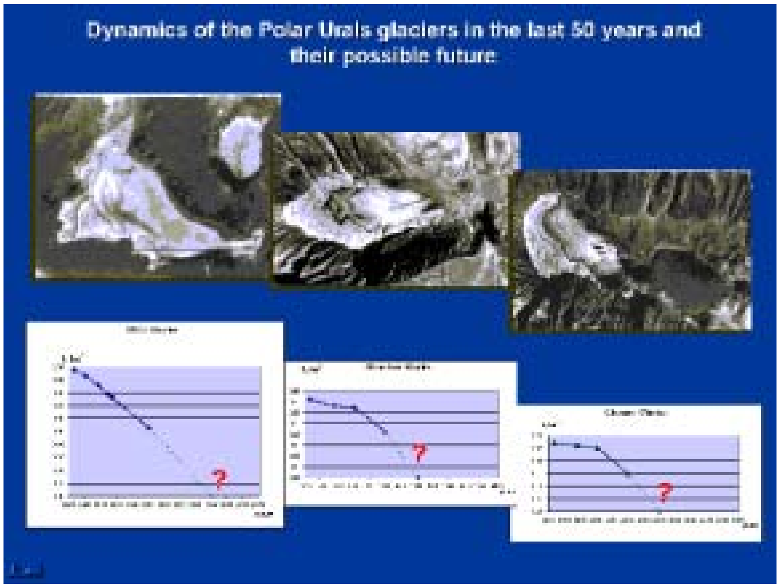


Figure 21. ASTER images of the Polar Urals, 2000 and 2001



Dynamics of the Polar Urals glaciers in the last 50 years and their possible future

Figure 22. Polar Ural glacier dynamics

The studies have shown the real possibility of using of ASTER images for a quantitative assessment of long-term changes of small glaciers. It was possible to obtain such estimation of changes in Polar Ural glaciers using ASTER images over the last 20 years.

Table 7. Assessment of the current size of Obruchev and Chernov Glaciers from ASTER images with the aid of air photos and topographic maps

Years of observation		1953	1968	1981	2000
Glacier area (km^2)	Obruchev	0.36	0.33	0.32	0.21
	Chernov	0.27	0.26	0.25	0.25

Workshop Attendees

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A HISTORY OF GLACIER INVENTORIES

Mark F. Meier

Studies of glaciers and monitoring their changes began at least as early as the 18th century. This became an organized international effort in 1894 with the formation of the International Commission on Glaciers, now the International Commission on Snow and Ice (ICSI). Through the first half of the 20th century the emphasis was on recording glacier variations. By the time of the International Geophysical Year (1957-59), the need for an expansion of the science to glacier mass balances and glacier/climate relations was noted, as was a need to document the existence, areas, and characteristics of glaciers on Earth.

Action to meet these objectives was taken by the ICSI during the International Hydrologic Decade and the ensuing International Hydrological Programme, beginning in 1965. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) supported the development of these new programs. A Permanent Service on the Fluctuations of Glaciers (PSFG), headed by Engineer. Peter Kasser, was formed, and allied with the Federation of Astronomical and Geophysical Analysis Services (FAGS). ICSI/UNESCO working groups also published technical manuals on Glacier Inventory (Dr. Fritz Müller), Combined Heat-Ice and Water-Balances at Selected Glacier Basins (Dr. Mark F. Meier), the monitoring of Seasonal Snow and Avalanches (Dr. Marcel deQuervain), and other glaciological subjects, and began educational programs on these subjects in underdeveloped countries. As a result, glacier monitoring and research activity around the world increased enormously; for instance, the number of long-term mass balance programs increased from 2 to more than 80 during the mid-1960s.

A Temporary Technical Secretariat for the glacier inventory program, under Dr. Müller's direction, was established in 1973, cosponsored by UNESCO and the Global Environmental Monitoring System (GEMS) of the United Nations Environmental Programme (UNEP). The goal of this effort was to produce a World Glacier Inventory by 1985 or soon thereafter. This effort was impeded by several factors, including a recommendation for complete documentation of each glacier, which was more than most countries could handle, a general economic recession, and the death in 1980 of Dr. Müller. This phase of the program concluded with the publication of *World Glacier Inventory: Status 1988*, by ICSI/UNESCO/UNEP. However, the majority of glaciers in the world have not yet been inventoried according to the original guidelines, and new, less labor-intensive, methods such as remote sensing are now at the forefront.

One outgrowth of the IGY was the formation of a World Data Centre System, with centers by discipline in the United States (A), the USSR (B), and in other countries (C). This system served the glaciological community well, providing free exchange of data during the Cold War. In the USA, World Data Center for Glaciology, Boulder is now co-located with the National Snow and Ice Data Center (NSIDC) and directed by Dr. Roger Barry.

The PSFG began publication of the volumes *Fluctuations of Glaciers* (FoG*)* at 5-year intervals beginning in 1976, with the support of ICSI, UNESCO, FAGS, and the Federal Institute of Technology in Zürich (ETH), and later, UNEP. These volumes included more than just advance/retreat information; for instance mass balances and thickness changes.

In 1987, the struggling World Glacier Inventory and the active publication of glacier fluctuation data were incorporated in a new World Glacier Monitoring Service (WGMS), considered part of GEMS, at ETH under Dr. Wilfried Haeberli. The five-year FoG book was continued, and annual publication of the new *Mass Balance Bulletin* speeded the distribution of data to the users. The bulk of the data were presented as tables, graphs, and maps. Under pressure from ICSI and the user community, WGMS has joined with NSIDC to publish digital fluctuation and mass balance data and to digitize the glacier inventory data.

Now the challenge – and the opportunity – is to incorporate, standardize, and determine the accuracy of remote sensing information.

LIST OF GLACIER INVENTORIES AND WORLD MAP

Prepared by H. Jiskoot

The table in this section lists countries in alphabetical order and shows the glacier inventory status (1=no glaciers, 2=complete inventory, 3=incomplete inventory, 4=no inventory.

Table 8. Status of Worldwide Glacier Inventories

Country name	***Sovereign***	***Status***
Aruba	Netherlands	1
Antigua and Barbuda	Antigua and Barbuda	1
Afghanistan	Afghanistan	3
Algeria	Algeria	1
Azerbaijan	Azerbaijan	2
Albania	Albania	1
Armenia	Armenia	1
Andorra	Andorra	1
Angola	Angola	1
American Samoa	United States	1
Argentina	Argentina	3
Australia	Australia	1
Austria	Austria	2
Anguilla	United Kingdom	1
Antarctica	Antarctica	4
Bahrain	Bahrain	1
Barbados	Barbados	1
Botswana	Botswana	1
Bermuda	United Kingdom	1
Belgium	Belgium	1
Bahamas The	Bahamas The	1
Bangladesh	Bangladesh	1
Belize	Belize	1
Bosnia and Herzegovina	Bosnia and Herzegovina	1
Bolivia	Bolivia	2
Myanmar (Burma)	Myanmar (Burma)	1
Benin	Benin	1
Byelorus	Byelorus	1

Table 8. Status of Worldwide Glacier Inventories

Country name	***Sovereign***	***Status***
Solomon Islands	Solomon Islands	1
Brazil	Brazil	1
Bhutan	Bhutan	2
Bulgaria	Bulgaria	1
Bouvet Island	Norway	1
Brunei	Brunei	1
Burundi	Burundi	1
Canada	Canada	3
Cambodia	Cambodia	1
Chad	Chad	1
Sri Lanka	Sri Lanka	1
Congo	Congo	1
Zaire	Zaire	2
China	China	2
Chile	Chile	3
Cayman Islands	United Kingdom	1
Cocos (Keeling) Islands	Australia	1
Cameroon	Cameroon	1
Comoros	Comoros	1
Colombia	Colombia	3
Northern Mariana Islands	United States	1
Costa Rica	Costa Rica	1
Central African Republic	Central African Republic	1
Cuba	Cuba	1
Cape Verde	Cape Verde	1
Cook Islands	New Zealand	1
Cyprus	Cyprus	1
Denmark	Denmark	1
Djibouti	Djibouti	1
Dominica	Dominica	1
Jarvis Island	United States	1
Dominican Republic	Dominican Republic	1
Ecuador	Ecuador	3

Table 8. Status of Worldwide Glacier Inventories

Country name	***Sovereign***	***Status***
Egypt	Egypt	1
Ireland	Ireland	1
Equatorial Guinea	Equatorial Guinea	1
Estonia	Estonia	1
Eritrea	Eritrea	1
El Salvador	El Salvador	1
Ethiopia	Ethiopia	1
Czech Republic	Czech Republic	1
French Guiana	France	1
Finland	Finland	1
Fiji	Fiji	1
Falkland Islands (Islas Malvinas)	United Kingdom	1
Federated States of Micronesia	Federated States of Micronesia	1
Faroe Islands	Denmark	1
French Polynesia	France	1
Baker Island	United States	1
France	France	2
French Southern & Antarctic Lands	France	1
Gambia	Gambia	1
Gabon	Gabon	1
Georgia	Georgia	1
Ghana	Ghana	1
Gibraltar	United Kingdom	1
Grenada	Grenada	1
Guernsey	United Kingdom	1
Greenland	Denmark	3
Germany	Germany	1
Glorioso Islands	France	1
Guadeloupe	France	1
Guam	United States	1
Greece	Greece	1
Guatemala	Guatemala	1

Table 8. Status of Worldwide Glacier Inventories

Country name	***Sovereign***	***Status***
Guinea	Guinea	1
Guyana	Guyana	1
Gaza Strip	Gaza Strip	1
Haiti	Haiti	1
Heard Island & McDonald Islands	Australia	1
Honduras	Honduras	1
Howland Island	United States	1
Croatia	Croatia	1
Hungary	Hungary	1
Iceland	Iceland	3
Indonesia	Indonesia	2
Man Isle of	United Kingdom	1
India	India	3
British Indian Ocean Territory	United Kingdom	1
Iran	Iran	4
Israel	Israel	1
Italy	Italy	2
Ivory Coast	Ivory Coast	1
Iraq	Iraq	1
Japan	Japan	1
Jersey	United Kingdom	1
Jamaica	Jamaica	1
Jan Mayen	Norway	1
Jordan	Jordan	1
Johnston Atoll	United States	1
Juan De Nova Island	France	1
Kenya	Kenya	2
Kyrgyzstan	Kyrgyzstan	2
North Korea	North Korea	1
Kiribati	Kiribati	1
South Korea	South Korea	1
Christmas Island	Australia	1

Table 8. Status of Worldwide Glacier Inventories

Country name	***Sovereign***	***Status***
Kuwait	Kuwait	1
Kazakhstan	Kazakhstan	2
Laos	Laos	1
Lebanon	Lebanon	1
Latvia	Latvia	1
Lithuania	Lithuania	1
Liberia	Liberia	1
Slovakia	Slovakia	1
Liechtenstein	Liechtenstein	1
Lesotho	Lesotho	1
Luxembourg	Luxembourg	1
Libya	Libya	1
Madagascar	Madagascar	1
Martinique	France	1
Macau	Portugal	1
Moldova	Moldova	1
Mayotte	France	1
Mongolia	Mongolia	3
Montserrat	United Kingdom	1
Malawi	Malawi	1
Macedonia	Macedonia	1
Mali	Mali	1
Monaco	Monaco	1
Morocco	Morocco	1
Mauritius	Mauritius	1
Midway Islands	United States	1
Mauritania	Mauritania	1
Malta	Malta	1
Oman	Oman	1
Maldives	Maldives	1
Montenegro	Montenegro	1
Mexico	Mexico	2
Malaysia	Malaysia	1

Table 8. Status of Worldwide Glacier Inventories

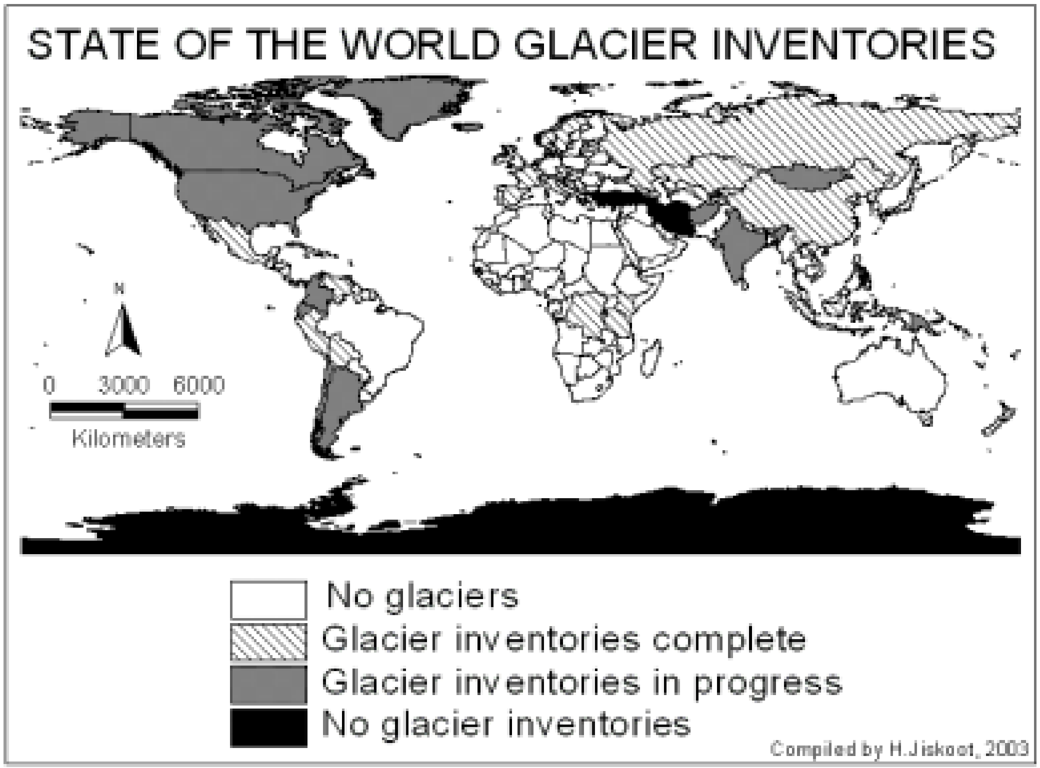
Country name	***Sovereign***	***Status***
Mozambique	Mozambique	1
New Caledonia	France	1
Niue	New Zealand	1
Norfolk Island	Australia	1
Niger	Niger	1
Vanuatu	Vanuatu	1
Nigeria	Nigeria	1
Netherlands	Netherlands	1
Norway	Norway	2
Nepal	Nepal	2
Nauru	Nauru	1
Suriname	Suriname	1
Netherlands Antilles	Netherlands	1
Nicaragua	Nicaragua	1
New Zealand	New Zealand	2
Paraguay	Paraguay	1
Pitcairn Islands	United Kingdom	1
Peru	Peru	2
Paracel Islands	Paracel Islands	1
Spratly Islands	Spratly Islands	1
Pakistan	Pakistan	1
Poland	Poland	1
Panama	Panama	1
Portugal	Portugal	1
Papua New Guinea	Papua New Guinea	3
Pacific Islands (Palau)	United States	1
Guinea-Bissau	Guinea-Bissau	1
Qatar	Qatar	1
Reunion	France	1
Marshall Islands	Marshall Islands	1
Romania	Romania	1
Philippines	Philippines	1
Puerto Rico	United States	1

Table 8. Status of Worldwide Glacier Inventories

Country name	***Sovereign***	***Status***
Russia	Russia	2
Rwanda	Rwanda	1
Saudi Arabia	Saudi Arabia	1
St. Pierre and Miquelon	France	1
St. Kitts and Nevis	St. Kitts and Nevis	1
Seychelles	Seychelles	1
South Africa	South Africa	1
Senegal	Senegal	1
St. Helena	United Kingdom	1
Slovenia	Slovenia	1
Sierra Leone	Sierra Leone	1
San Marino	San Marino	1
Singapore	Singapore	1
Somalia	Somalia	1
Spain	Spain	2
Serbia	Serbia	1
St. Lucia	St. Lucia	1
Sudan	Sudan	1
Svalbard	Norway	2
Sweden	Sweden	2
South Georgia and the South Sandwich Is	United Kingdom	1
Syria	Syria	1
Switzerland	Switzerland	2
United Arab Emirates	United Arab Emirates	1
Trinidad and Tobago	Trinidad and Tobago	1
Thailand	Thailand	1
Tajikistan	Tajikistan	2
Turks and Caicos Islands	United Kingdom	1
Tokelau	New Zealand	1
Tonga	Tonga	1
Togo	Togo	1
Sao Tome and Principe	Sao Tome and Principe	1

Table 8. Status of Worldwide Glacier Inventories

Country name	***Sovereign***	***Status***
Tunisia	Tunisia	1
Turkey	Turkey	4
Tuvalu	Tuvalu	1
Taiwan	Taiwan	1
Turkmenistan	Turkmenistan	1
Tanzania, United Republic of	Tanzania, United Republic of	2
Uganda	Uganda	1
United Kingdom	United Kingdom	1
Ukraine	Ukraine	1
United States	United States	3
Burkina Faso	Burkina Faso	1
Uruguay	Uruguay	1
Uzbekistan	Uzbekistan	2
St. Vincent and the Grenadines	St. Vincent and the Grenadines	1
Venezuela	Venezuela	2
British Virgin Islands	United Kingdom	1
Vietnam	Vietnam	1
Virgin Islands	United States	1
Namibia	Namibia	1
West Bank	West Bank	1
Wallis and Futuna	France	1
Western Sahara	Western Sahara	1
Wake Island	United States	1
Western Samoa	Western Samoa	1
Swaziland	Swaziland	1
Yemen	Yemen	1
Zambia	Zambia	1
Zimbabwe	Zimbabwe	1


STATE OF THE WORLD GLACIER INVENTORIES
N
0
3000
6000
Kilometers
No glaciers
Glacier inventories complete
Glacier inventories in progress
No glacier inventories
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Glaciological Data Series

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