Report GD-30

GLACIOLOGICAL DATA

TWENTY-FIFTH ANNIVERSARY

Monitoring an Evolving Cryosphere

Summary of the NSIDC Special Session at the American Geophysical Union Fall Meeting, December 10-14, 2001

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

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NSIDC
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Foreword

This issue of Glaciological Data contains material relating to the celebration of the 25th Anniversary of the transfer of the WDC for Glaciology from the U.S. Geological Survey to the University of Colorado at Boulder. The celebrations included a workshop in Boulder held on 11 October 2001, and a special session “Monitoring an Evolving Crysophere” at the Fall 2001 AGU meeting in San Francisco. The Boulder workshop participants were addressed by Mr. Greg Withee, Assistant Administrator, National Environmental Satellite, Data, and Information Service; Dr. Susan Avery, Director, Cooperative Institute for Research in Environmental Sciences; and Dr. Jerry Peterson, Interim Vice Chancellor for Research, University of Colorado at Boulder. A panel discussion entitled “Cryosphere in the Balance: NSIDC’s Role for the Next Quarter Century” followed, with four invited participants and chaired by Dr. Mark Anderson, Department of Geosciences, University of Nebraska. The panel members were Dr. Don Cline, Head of Operations at the National Operational Hydrologic Remote Sensing Center; Dr. Judy Curry, Professor of Aerospace Engineering Sciences at CU; Dr. Ted Habermann of NOAA’s National Geophysical Data Center; and Dr. Konrad Steffen, Associate Director for the CIRES Cryospheric and Polar Processes Division and Professor of Geography at CU. A summary of the panel discussions is included here, together with a history of WDC for Glaciology/NSIDC. The issue also contains a summary of publications authored by NSIDC staff since 1990.

The special session at the Fall 2001 AGU was organized by NSIDC’s Dr. Ann Nolin and Dr. Ted Scambos and comprised two oral sessions and two poster sessions. A selection of these presentations is included in this issue, together with the abstracts of all of the other oral and poster presentations. We acknowledge the kind permission of the AGU to reproduce these abstracts here. I thank the staff of NSIDC who participated in organizing the workshop and compiling this publication including Cindy Brekke, Teresa Mullins, Laura Naranjo, and Lyne Yohe. We also thank our current funding agencies: NASA, NOAA, and NSF, and our user community. The Center looks forward to the challenges of the next quarter century of service to cryospheric scientists and the science community at large.

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

Citation

NSIDC wishes to thank the American Geophysical Union (AGU), which has generously allowed us to reproduce presentation and poster abstracts that appeared in NSIDC’s Special Session, “Monitoring an Evolving Cryosphere,” at the AGU Fall Meeting, December 10-14, 2001.

When citing any of the papers or abstracts within, please use the following citation:

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The History of World Data Center for Glaciology, Boulder, and the National Snow and Ice Data Center at the University of Colorado, 1976-2001

Roger G. Barry
Director, NSIDC/WDC for Glaciology, Boulder

Background

The World Data Center (WDC)-A for Glaciology was established, along with other WDCs for the geophysical sciences, during the International Geophysical Year (IGY), 1957-58 (Shapley, 1987). There were also World Data Centers for Glaciology in Moscow (WDC-B) and in Cambridge, England (WDC-C). WDC-A for Glaciology was directed by Dr. William O. Field of the American Geographical Society in New York from 1957 to 1970, with support from the U.S. National Committee for the IGY through the National Science Foundation (Field, 1987). In 1970, the responsibility for the WDC-A for Glaciology was transferred to the U.S. Geological Survey, Glaciology Project Office, Tacoma, WA, under Dr. Mark Meier (Meier, 1987). Funding difficulties later led to inter-agency discussions and an agreement in 1976 with the National Oceanic and Atmospheric Administration (NOAA) Environmental Data and Information Service (EDIS) to assume responsibility for the Center. Alan H. Shapley, Director of the National Geophysical Data Center in Boulder, approached Dr. Jack D. Ives, Director of the Institute of Arctic and Alpine Research, to propose that the Center be operated at the University of Colorado on behalf of NOAA (Shapley, 1987). A proposal for the Center's operation in Boulder was presented to the Committee on Glaciology of the Polar Research Board (PRB), together with other proposals from the Ohio State University and from the Arctic Environmental Information and Data Center (AEIDC) in Alaska. The Committee endorsed the University of Colorado proposal, and Dr. Herbert Friedman, Chairman of the Geophysics Research Board, formally approached NOAA and the University on behalf of the World Data Centers. Dr. Robert M. White, NOAA Administrator, and University President Roland Rautenstraus agreed to the proposed transfer and the WDC-A for Glaciology was formally transferred effective 14 October, 1976. Dr. Roger Barry assumed directorship of the Center in Boulder. The WDC name was changed in 1999 to remove the letter designation, WDC-A for Glaciology, that originally corresponded to a geographical grouping of the World Data Centers. The World Data Center-A for Glaciology is now called the World Data Center for Glaciology, Boulder.

Formative Years

The Center began operation in Boulder, CO, in 1976 with two staff members (Marilyn Shartran and Ann Brennan) overseeing a library of glaciological literature and a collection of glacier photographs. Limited funds were available to support visiting scientists in their use of the Center's holdings. WDC- A for Glaciology had published a series of Glaciological Notes (beginning in 1960) that provided bibliographic information and (from 1971) a listing of available glacier aerial photographs. These Notes were replaced by Glaciological Data Reports (starting in 1977), of which this issue is number 30. The Glaciological Data Reports include not only disciplinary bibliographies but also reports on data products and meeting reports on data issues and cryospheric science. Taking into consideration the mandate and scope of NOAA's environmental data concerns, the Center also held workshops and developed inventories of sea ice and snow cover map products. In 1978, with NOAA Environmental Data Services support, the Center recruited additional staff to prepare an ice core inventory, and attempted to assemble selected ice core data. The latter endeavor had limited success due to difficulties in acquiring data from researchers. Nevertheless, the inventory proved a valuable planning tool for Advisory Panels of the NSF Office of Polar Programs (OPP).

The WDC-A for Glaciology archived its first remote sensing data set in 1979. The Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) film archive was about to be discarded by the University of Wisconsin. Through the efforts of Dr. Ed Zipser, National Center for Atmospheric Research

(NCAR), the positive transparency archive of 600,000 images dating from 1973 was shipped to the Center. The collection was cataloged and organized by student labor supervised by Greg Scharfen. The OLS archive provided inexpensive copies of imagery of snow and ice features and meteorological phenomena, mosaics of the polar regions, and imagery of nighttime urban lights and fires. These images were used for many research projects on cryosphere-climate interactions, and also to assess lightning occurrence. Later (1992-99), the 1.3 million pieces of OLS imagery were transferred to the Federal Records Center, after the DMSP products became digital and NOAA NGDC took over their management.

During this same period, the WDC-A for Glaciology acquired several data sets from the Great Lakes Environmental Research Laboratory, NOAA, including aerial photography, mosaics of freshwater ice reconnaissance, and lake ice breakup dates. The Center also received and archived numerous hard-copy charts of snow cover and sea ice from operational agencies; these were gradually replaced by digital versions in the 1980s-90s.

Establishment of NSIDC and Program Expansion

Roger Barry became a Fellow of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado in 1981. The WDC-A operation was transferred to CIRES, and this provided a further link with NOAA by virtue of the cooperative agreement between the University of Colorado and the NOAA Environmental Research Laboratory.

In June 1978, Dr. Thomas S. Austin, Director NOAA EDS, contacted Dr. Barry concerning the possibility of establishing a national center for glaciology. Discussions followed with Dr. Pembroke Hart, Executive Secretary of the Geophysics Research Board; Dr. Linc Washburn, Chairman of the Polar Research Board; and Dr. Colin Bull, glaciology representative of the CDIDC Review Committee. A proposed program and structure were developed, and on March 20, 1982, on the recommendation of the Panel on Glaciological Data of the PRB, and the Committee of Geophysical and Environmental Data of the National Research Council, the Center received the title of National Snow and Ice Data Center (NSIDC). This laid the basis for a widened disciplinary scope and increased focus on U.S. cryospheric data.

Until 1981, NOAA provided the sole source of funding for the WDC-A for Glaciology, but contacts with other agencies were subsequently developed through the efforts of the NSIDC Director. Dr. Robert Crane and then graduate student Dr. Mark Anderson facilitated an assessment of passive microwave data products for sea ice research for NASA in 1982. This led to the selection of NSIDC (in 1983) as the archival point for the planned NASA sea ice products from the DMSP Special Sensor Microwave Imager (SSM/I). Plans were made for a NASA-funded Cryospheric Data Management System (CDMS) to be installed on a VAX-750 at NSIDC using software developed at the Pilot Ocean Data System at NASA's Jet Propulsion Laboratory. The first SSM/I sensor was launched in 1987, and NSIDC began producing satellite brightness temperature data and sea ice products. In March 1989, NSIDC produced the first volume in a series of CD-ROMs for the Nimbus-7 SMMR brightness temperature grids for the polar regions. The volume became the prototype for the popular "SSM/I Brightness Temperature Grids for Polar Regions" CD-ROM set, which NSIDC began distributing in 1991.

Building on the data management undertaken in 1986-88 for the Marginal Ice Zone Experiment (MIZEX) project (led by Claire Hanson, User Services, NSIDC), the Center took on similar responsibilities for data from the Land-Atmosphere-Ice Interactions (LAII) and Greenland Ice Sheet Project (GISP) programs of the NSF OPP. CD-ROMs were prepared for the Greenland ice sheet data and for the LAII program, as well as an educational CD developed by Dr. David McGinnis. This activity culminated in the establishment of the Arctic System Science Data Coordination Center (ADCC) in 1994. The role of the ADCC has expanded since 2000 under the leadership of Rudy Dichtl. A parallel effort to manage Antarctic information and data was begun in

1996 by Greg Scharfen, with the assembly of metadata for all U.S. Antarctic programs. This was followed in 1999 by the designation of an Antarctic Glaciological Data Center (AGDC); both efforts are supported by the NSF.

Following a successful proposal to NASA-EOSDIS, NSIDC was awarded a contract to operate a Distributed Active Archive Center (DAAC) for Snow and Ice in 1991. This resulted in a rapid increase in technical staff at NSIDC. One of the first tasks of the DAAC was the cross-DAAC collaborative development of the Version 0 Information Management System. The NSIDC contribution was lead by Vince Troisi. The DAAC-wide V0-IMS tied together the data catalog and ordering systems of the newly formed DAACs. This effort eventually won the "Golden Hammer" award from the Clinton Administration for its innovation.

During this period, the NSIDC DAAC strove to stabilize existing digital remote sensing data sets and to ingest other appropriate data for snow and ice research. The NOAA/NASA Pathfinder Program was initiated in 1993 to assure that certain key remote sensing data sets important to global change research were scientifically validated, consistently processed, and made readily available to the research community. The Polar Pathfinder Program identified three long time-series data sets for reprocessing: AVHRR, TOVS, and Special Sensor Microwave Imager (SSM/I), and later Scanning Multichannel Microwave Radiometer (SMMR). Under this program, NSIDC has produced a 24-year, consistently processed time series of gridded satellite passive microwave data in a common format called the Equal Area Scalable Earth Grid (EASE-Grid). This data set was developed using SMMR data for 1978-1987 and SSM/I data for 1987-2002. Three other data sets (AVHRR at 4 km and 1.1 km resolution, and TOVS data) were also processed to a similar grid for the polar regions, using archived raw data, to create an 18-year record. The grids reflected the greater or lesser resolution of the sensors relative to SSM/I, but used identical projections and coordinate axes, so that the data sets can easily be used together. AVHRR grids were prepared at NSIDC, and TOVS at the University of Washington and Rutgers. Together, the TOVS, AVHRR, and polar passive microwave grids are known as the ‘Polar Pathfinder’ data, and they are managed by NSIDC. The DAAC subsequently built graphical user interfaces (GUI) to aid scientists with search, subsetting, and ordering of these data.

Collaborative data center and basic research by NSIDC-affiliated scientists have led to global gridded snow-cover-extent data sets, Northern Hemisphere snow cover and sea ice integrated extent gridded data, and experimental passive-microwave-based snow water equivalent products.

In preparation for the launch of Terra, the DAAC staff expanded in the mid-1990s to include operations, technical documentation, user services, and systems engineering expertise. As the launch of Terra approached in 1999, the DAAC hired Team Leaders for MODIS snow and ice data products, and also for the near-future launch of the AMSR and GLAS instruments. The EOS Core System, a complex suite of computing hardware and software, was delivered to NSIDC in May 1997.

A Polar DAAC User Working Group (PODAG) was established by NASA, and Dr. Konrad Steffen served as its chair for 1991-2000, succeeded by Dr. David Bromwich of the Ohio State University. The User Working Group has been a mainstay of scientific guidance to the DAAC over the past decade.

In the 1990s, NSIDC realized that the World Wide Web and Internet explosion was a technology that could be used to advertise and deliver data sets to science users, and to provide information explaining the cryosphere and monitoring of global cryospheric elements. NSIDC began offering data via the Web in February 1994. NSIDC has incrementally upgraded its Web presence over the decade to where the current NSIDC website contains about 3,500 pages and averages 14,000 hits per day.

NOAA at NSIDC

The WDC library continues to acquire and archive new materials and maintains an electronic catalog for use inhouse. The library also contributes holding information to other databases.

In the early 1990s NSIDC collaborated with the National Ocean Survey, Navy-NOAA-USCG National Ice Center, and the NOAA Global Change Program on an effort to build and deploy a DIFAS: Digital Ice Forecasting and Analysis System. This system was envisioned to provide digital sea ice products to the NIC, and retrospective digital archive products to NSIDC. While the effort was not deployed to operational state, it provided invaluable training to both NSIDC and JIC staff on the design of networked computing systems.

In the spring of 1993, the NOAA Earth Science Data and Information Management (ESDIM) Initiative funded an NSIDC-led workshop to assess and prioritize snow and ice data. The conclusions of this workshop have guided NSIDC data acquisitions over the past decade. Subsequent to this workshop, NOAA and NSIDC upgraded the archival standards for high-priority NSIDC-held and NOAA-owned data sets. Later in the decade, the ESDIM program provided data rescue funds for key Russian snow cover and sea ice historical records, and for the development of a digital world glacier inventory.

Also in 1993, NSIDC produced the Historical Arctic Rawinsonde Archive (HARA) CD-ROMs. This compilation, funded jointly by NSF, NOAA, and NASA, is a baseline data set of atmospheric soundings for the Arctic.

International Contacts and Affiliations

The WDC-A for Glaciology initiated contacts with Russian and Chinese glaciologists at a 1978 workshop on the World Glacier Inventory. In 1979, Roger Barry and Dr. Colin Bull (Ohio State University) made the first visit to the WDC-B for Glaciology in Moscow on behalf of the PRB's Panel on Glaciological Data and the WDC Coordination Office. The trip included visits to the Institute of Geography in Moscow, the Arctic and Antarctic Research Institute in Leningrad, the Institute of Geography in Almata, and the Central Asian Hydrometeorological Institute (SANIGMI) in Tashkent.

In 1981, Roger Barry was invited to visit glaciological facilities and field stations in western China in the company of Professor J.D. Ives and Dr. Gordon Young, University of Waterloo, Ontario. The group visited Urumchi, Glacier No.1, and the avalanche field station (near Ining in the Tien Shan), and Lanzhou accompanied by Professor Shi Yafeng and Dr. Kang Ersi from the Lanzhou Institute of Glaciology and Cryopedology, and Dr. Qui Jiachi from Urumuchi (who had studied in Boulder). This laid a solid basis for subsequent collaboration following the establishment by China of WDC-D for Glaciology in Lanzhou in 1988. The representative for the WDC-D for Glaciology, Chen Xianzhang, spent six months at NSIDC in 1995 learning about our operations, and there was a shorter return visit by Mr. Chen and Dr. Li Xin in 1998.

In 1988, Roger Barry was a speaker at the Fifth International Permafrost Conference in Trondheim, Norway, and organized a pre-conference workshop (attended by nearly 50 scientists from nine countries) on the need for inventories and catalogs of permafrost data. As a result, the International Permafrost Association (IPA) set up a Working Group on Data and Information, which over the next decade developed a Global Geocryological Database (GGD) and produced a Circumpolar Active-layer Permafrost System CD-ROM (CAPS) of permafrost maps, data, and information for the 1997 International Permafrost Conference. A CAPS version 2 CD-ROM is being prepared for the 2003 International Permafrost Conference. This work is being supported by the International Arctic Research Center (IARC) at the University of Alaska and by the IPA through a new Frozen Ground Data Center established at NSIDC in 2001.

Beginning in the 1990s, strong links were forged with groups in Russia and the former Soviet republics, and with others in Switzerland and Germany. NATO Linkage grants supported exchanges of personnel with the Institute of Geography in Moscow and SANIGMI in Tashkent. Collaboration on the WMO Global Digital Sea Ice Data Bank and the Environmental Working Group Arctic atlases for sea ice and for climate and meteorology led to joint projects with the Arctic and Antarctic Research Institute in St. Petersburg. Dr. Barry was a visiting professor at the Institute of Geography, ETH, Zurich, in 1990 and 1997, and at the Alfred Wegener Institute for Polar and Ocean Research in 1994. In 2001, he was a Fulbright Scholar at Moscow State University Department of Cryolithology and Glaciology. Links with China were strengthened in 1999 when Dr. Barry gave invited lectures on climate and the cryosphere in Beijing (Institute of Atmospheric Physics and the WDC for Remote Sensing), Lanzhou (Institute of Glaciology and Cryopedology) and Shanghai (Polar Research Institute). NSIDC's Richard Armstrong and Tingjun Zhang have made other visits to Lanzhou, as well as to Tibet and Mongolia, concerning snow cover mapping and frozen ground data.

NSIDC Research Staffing

The NSIDC staff expanded from 6-7 between 1979 and 1983 to 16 in 1987. In 1980 Ron Weaver, who had earlier conducted research on sea ice and glaciers in Baffin Island, was appointed Scientific Manager of the WDC. Dr. Richard Armstrong, a specialist in glaciers, snow cover, and avalanches, was hired as manager for the Marginal Ice Zone Experiment (MIZEX) project. Following the transfer of NSIDC into CIRES, the activities were enhanced through the appointment of a number of CIRES Visiting Fellows with cryospheric interests. These included: Dr. S. Munro (glacier modeling), Dr. K. Stewart (freshwater ice), Dr. K. Steffen (remote sensing), Dr. D. McGinnis (downscaling), Dr. A. Frei (snow cover in climate models) and Dr. S. Sokratov (snow cover modeling). Other long-term visitors were supported by Fulbright scholarships: Dr. A.N. Krenke (snow cover) and Dr. O. Solomina (mountain glacier fluctuations).

The Visiting Fellow appointment of Konrad Steffen was prolonged through NASA research support, and he later joined the University of Colorado as a faculty member in CIRES and Geography. This faculty addition, and a University Research Initiative award for research on Arctic Ocean – Atmosphere-Ice System Studies to Dr. Barry, A.S. McLaren, and R. C. Schnell led to the intake of several graduate students who played a key role in the expansion of cryospheric research at NSIDC. Key among these were Jim Maslanik, Jeff Key, Mark Serreze, and M.W. Miles. A new Division of Cryospheric and Polar Processes was designated in CIRES, including Fellows who were faculty (Barry and Steffen) and researchers (U. Radok, R.C. Schell). Dr. Barry served as Associate Director for the Cryospheric and Polar Processes Division from 1991-98, and was succeeded by K. Steffen.

In the 1990s, the affiliated research staff at NSIDC expanded as former graduate research assistants Jeff Key, Jim Maslanik, Fred McLaren, and Mark Serreze obtained grant support. The Center recognized the necessity for in-house expertise to provide quality assurance for its data and information products, and guidance on new directions. A conscious decision was made to recruit personnel with skills in the main areas of cryospheric data analysis and modeling and in remote sensing techniques and applications. The additions to NSIDC during the 1990s were Ted Scambos, Anne Nolin, Tingjun Zhang, and Julienne Stroeve. Funding was provided by NOAA-NESDIS to recruit a NOAA liaison staff member, and Florence Fetterer joined NSIDC from the Naval Research Laboratory. Further appointments of Martyn Clarke, Andrew Barrett, and Christoph Oelke were made possible by successful research proposals in hydroclimatology.

The current staff numbers over 70 individuals, including part-time student and staff appointments.

Scientific Program Planning

NSIDC staff have made important contributions to scientific research and science data management program planning. Dr. Barry has endeavored to raise awareness of data management issues in committees of the National Research Council on which he has served. These included ad-hoc committees of the Polar Research Board on The Role of the Polar Regions in Climatic Change (1979-83), and the Panel on Remote Sensing of Snow and Ice (1985-87). He was also a Member of the Polar Research Board from 1987 to 1991. Richard Armstrong served on the NRC Panel on Snow Avalanches, of the Committee on Ground Failure Hazards (1986-1991).

Subsequently, NSIDC became increasingly involved in international science and data activities. Richard Armstrong was a member of the Working Group on Snow Classification of the International Association of Hydrologic Sciences (IAHS) / International Committee on Snow and Ice (ICSI) which produced the International Classification for Seasonal Snow on the Ground. In 1992, Dr. Barry and Vince Troisi participated in the WMO Global Digital Sea Ice Data Bank (GDSIDB) development with the Arctic and Antarctic Research Institute in St. Petersburg, and Dr. Barry became co-Chair of the GDSIDB and Sea Ice Working Group of the WMO Commission on Maritime Meteorology. Later, Florence Fetterer took part in the GDSIDB meetings and joined the International Ice Charting Working Group to represent research interests.

Dr. Barry became a member of the Global Climate/ Global Terrestrial Observing System (GCOS/GTOS) Terrestrial Observation Panel for Climate in 1995, and was a member of the World Climate Research Programme (WCRP) Arctic Climate System project from 1995 to 2000. He was co-Chair of a WCRP Task Group on Climate and the Cryosphere (CliC), responsible for developing the CliC Science and Coordination Plan, and is currently co-Vice Chair of the CliC Scientific Steering Group. Also for ACSYS/CliC, Konrad Steffen is Chair of the Observation Products Panel, Mark Serreze chairs the ad hoc Panel on Products from Polar Reanalysis, and Richard Armstrong is a member of the Data Management and Information Panel.

Greg Scharfen serves on the Scientific Committee for Antarctic Research (SCAR) Council of Managers of National Antarctic Programs (COMNAP) Joint Committee on Antarctic Data Management (JCADM) dealing with Antarctic data issues.

Ron Weaver served on the NASA Data Information System and Services (NEWDISS) core committee. In 2000, the DAACs formed an Alliance to promote intra-DAAC collaboration, and to promote sound science data management practices. Ron Weaver served as the interim Vice-Chair, and is currently the second Chairman of the DAAC Alliance. Vince Troisi and Michelle Holm have both contributed to the NASA Earth Science Information Partner (ESIP) Federation as the NSIDC representative. Other NSIDC DAAC staff have served as members of Federation working groups and standing committees.

Current Organization and Programs at NSIDC

The organizational structure of the Center has evolved reflecting its growth. The functional units of NSIDC are operations, communications, programmers, user services, systems, administration, and scientists. Teams and committees have been formed, such as the Managers Team, the DAAC Management Team, and an Outreach Committee. The important links with CIRES are maintained through representation on the Fellows Council, the Members Council, and CPP Seminars and Coffee meetings. NSIDC is involved in the new research themes of CIRES in the areas of Advanced Observations and Modeling, Climate System Variability, and Regional Processes.

The Center's primary activities are structured in terms of their funding source and mandate; namely

- The Distributed Active Archive Center (DAAC) for Snow and Ice (NASA)
- NOAA data sets and ESDIM projects
- The World Data Center for Glaciology, Boulder (1976) (NOAA)
- The NSF Antarctic Data Coordination Center (1996) and Antarctic Glaciological Data Center (1999)
- The NSF Arctic System Science (ARCSS) Data Coordination Center (1994)
- The Frozen Ground Data Center (2001) supported by the International Arctic Research Center (IARC) at the University of Alaska.

Details of each of these activities are available on the NSIDC Web site (http://nsidc.org).

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NSIDC 25th Anniversary Panel Discussion
October 11, 2001
Hosted by the National Snow and Ice Data Center
University of Colorado, Boulder, CO

Welcoming Address

Dr. Roger G. Barry, Director NSIDC, welcomed attendees in honor of the NSIDC's 25th anniversary. He presented a short history of the NSIDC. The NSIDC was founded in 1976 with a staff of two and a library collection of glacier photos. Initially, NOAA was the sole source of funding. The Distributed Active Archive Center (DAAC) started in 1991 and has grown since then to a current staff of just under 70. Important aspects of the NSIDC are its connection to the University and its large complement of scientists. Current Programs at the NSIDC include:

1. NASA Distributed Active Archive Center (DAAC)
2. NOAA at NSIDC
3. NSF Antarctic Data Coordination Center (ADCC) and Antarctic Glaciological Data Center (AGDC)
4. NSF Arctic System Science (ARCSS) Data Coordination Center (ADCC)
5. World Data Center for Glaciology, Boulder
6. Frozen Ground Data Center

After finishing with an informative chronological chart describing the main historical events pertinent to the NSIDC, Dr. Roger Barry introduced Mr. Greg Withee for the opening comments.

Opening Comments

Mr. Greg Withee, Assistant Administrator of the National Environmental Satellite, Data, and Information Service, gave a warm welcome to the attendees and thanked the NSIDC as one of many NOAA collaborative data centers. Currently NOAA supplies about five percent of the NSIDC's budget, and Mr. Withee acknowledged that the return on the investment for NOAA is excellent. Mr. Withee described other anniversaries coinciding with the 25th anniversary of the NSIDC. The World Meteorological Organization held its 50th anniversary last year, NOAA celebrated 30 years last year as well, and the National Climatic Data Center had its 50th anniversary celebration this year. Along with these celebrations, Mr. Withee said that 2003 will be the International Year of Fresh Water and, as such, will be an indirect celebration of the NSIDC due to the fact that ninety percent of the earth's fresh water is frozen.


Mr. Greg Withee

Aside from celebrations, new satellite and in situ programs will be important to the NSIDC, including the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

Mr. Withee commented that there is much the NSIDC is doing to help people get the data they need in order to assess the environmental impact of any course of action.

Dr. Susan Avery, Director of the Cooperative Institute for Research in Environmental Sciences (CIRES), spoke next and recognized the NSIDC for its contributions to various institutions. First, the NSIDC has meant a great deal to CIRES and to the University of Colorado (CU). The NSIDC is the only NOAA data center hosted at a university. Also, the NSIDC data is important for research in regional process studies, snow and snowmelt components of the Water in the West initiative, and climate variability. For CU in particular, the NSIDC has become a nucleus for polar research, physical geography, geology, atmosphere and climate research, and for attracting faculty and students. There is a synergy between the NSIDC scientists and the data center since NSIDC scientists use the data and become familiar with how to present and improve the data products. Dr. Avery commented on how Dr. Barry has a passion for data and has managed to assemble an impressive team at the NSIDC.

Panel Discussion

- Moderator: Mark Anderson, Associate Professor at the University of Nebraska at Lincoln
- Dr. Don Cline, Head of Operations at the National Operational Hydrologic Remote Sensing Center
- Dr. Judy Curry, Professor of Aerospace Engineering at CU
- Dr. Ted Habermann, NOAA's National Geophysical Data Center
- Dr. Konrad Steffen, Associate Director for the CIRES Cryospheric and Polar Processes Division; Professor of Geography at CU

The focus for the panel discussion was "Cryosphere in the Balance: NSIDC's role for the next quarter century." Moderator Mark Anderson posed questions about the pertinent issues in data preservation and access and information dissemination for NSIDC. Panelists were also asked what role the NSIDC should play in archiving model output, and how GIS and other visual imaging software will affect data products and dissemination.

Left to right: Mark Anderson, Dr. Koni Steffen, Dr. Ted Habermann, Dr. Don Cline, and Dr. Judy Curry.

Konrad Steffen began by stating that there is a need for researchers to obtain polar subsets of model output, and other data sets need to be available for polar regions. Besides having been done for NSEP, it could be broadened to other data sets such as AMIP and CMIP. Leading in a different direction, Ted Habermann commented on GIS and visual imaging software, saying that there is a growing need to bring together scientific data and GIS information. There was some discussion as to how data should be stored; should it be stored in a form suitable to GIS, or remain in a basic ASCII format for translation when needed and appropriate. Questions were asked as to what data should be made available in a GIS format and how, and if certain data would need or even lend itself to a visual format. Panelists agreed that the NSIDC could be a leader in the merger between scientists and traditional GIS users. The main conflict between archiving data in either a GIS or ASCII format is the user. Physical scientists most often need data in a ASCII basic format, while the general public and educational organizations could have better use of the data in some sort of visual representation. Of main importance is that data needs to be available in some format to begin with. Data portability traditionally has been via ASCII representations; however, it would be beneficial to ease access and usability over the long term. As of now there are many tools that do not require ASCII data. The transfer of data from one format to another could end up being the most important ability that the NSIDC could have in increasing all types of users. As more users will want to do queries in the future, deciding on how to get the users the data and in which format(s), could ultimately decide the user base. This was seen as one of the NSIDC's core strengths, that in most DAACs the data is archived and only the people who originally produced it use the data. NSIDC uses data in house and as such is constantly being reviewed by a third party. Panelists agreed that the connection to the University is very important if for this reason alone. One potential problem raised was that data center scientists could have access to data that is not available to outside users and would raise a perception that the data center existed solely to support its own scientists.

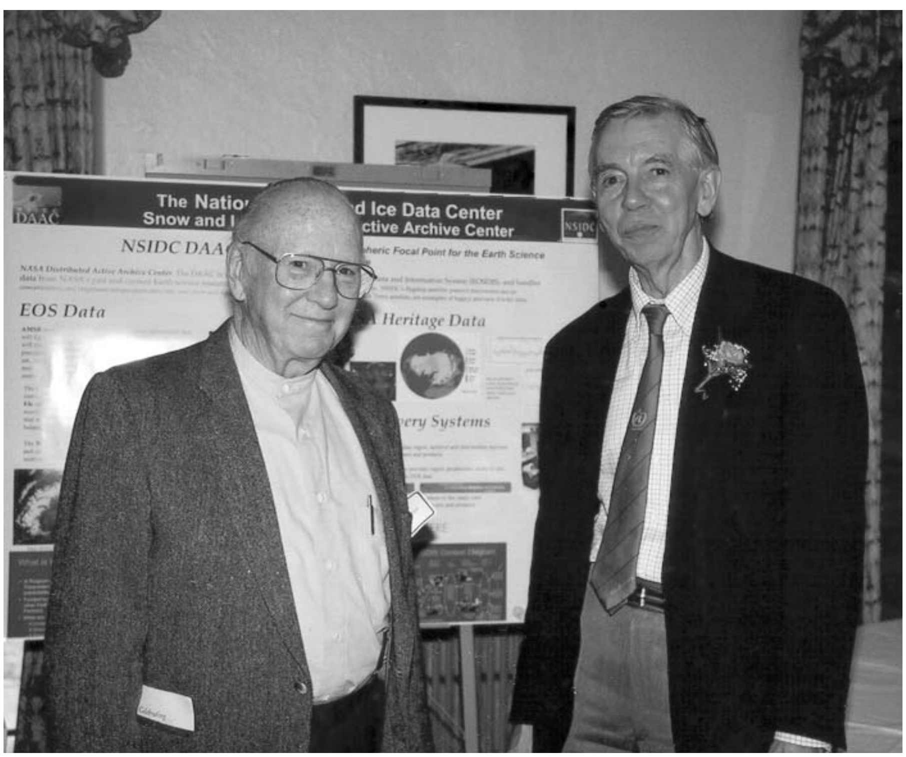
Archiving model output was a topic that most panelists though to be problematic. Archiving transient model code would most likely not be useful, as models are constantly changing and being updated. Also, the code is hard to decipher and often tens of thousands of lines long. The fact that documentation is often non-existent can make reading or understanding any particular model tough to impossible. Given that enough original documentation exists when changing models, it is often just as hard to find good documentation concerning a switch. "Frozen" models might be more valuable as frequently they are better documented and more useful. As pointed out by Don Cline, archiving forcing data used in models might be important. Unfortunately a data center can't archive everything. However, the NSIDC could be used as a "pointing" center helping people locate different places where they can find the specific data or models they require.

What to archive was also as important as how to archive it. Currently most of the data collected and distributed by the NSIDC is data from satellite projects and large-scale data sets. There seems to be a need for data centers to collect smaller data sets from scientists. One main problem that the NSIDC faces is that both data centers and scientists have different ideas on information storage. Data centers focus on a standard format that they can put all their data into, while scientists often use whichever format best suits them on any particular project. Along the same lines, the timeframe that each group relates to are in opposition. While conservation of data over the long haul is the primary concern of data centers, scientists often have a much shorter attention span, often corresponding to the funding cycle for their project. This is a main cause for data centers not getting individual scientists' data. Other factors include the lack of documentation, making data useless to anyone other than the original scientist. Solutions include requiring scientists to submit data, including corresponding metadata, to a data center in order to be provided with funding by a funding agency. As scientists are often required to submit their data to a data center already, policing these requirements could be the biggest problem. The panel mentioned that the NSF and NASA are already demanding that new data sets be in standard formats, making it easier to archive the data in data centers. Another main problem and determining factor in getting data from scientists into data centers is funding. Often data analysis gets shorted in proposals. Data archiving is often considered the twenty percent of funding sacrificed if less than one hundred percent is approved for any project. There is a need for data centers to develop formulas for the amount of resources needed for data management to aid scientists in this proposal writing.

How can the NSIDC best serve the needs of its diverse user communities? Possible answers include web-based tools at data centers to aid proposal writers in setting up a data submission strategy. Data centers are again being recognized as a very important tool. Data centers are once again seen as providing additional value over self-publishing and distribution of data by individual scientists. The Internet originally made it easier to disseminate information, and interest in data centers decreased. However, security issues like hacking are causing problems with FTP servers and the dissemination of data from individual servers. This has caused an increase in the demand for data centers and their services. This increased demand and the corresponding connection with a diverse user community has increased benefits. Constructing standard metadata descriptions seems like a burden on the NSIDC, but users are seeing the benefits in terms of being able to perform searches on catalogs. Referring back to the format that the data is collected in, in order to help serve a diverse user community, it might be necessary to at least offer conversion of data into whichever format is required by the users.

The user diversity is currently skewed heavily in the direction of research scientists, reaching around 88 percent. The remaining 12 percent of users constitutes the general public, and K-12 schooling. Don Cline made an important comment saying that the cryospheric community is relatively small and, as such, we cannot afford to turn anyone away. By incorporating a more flexible data ordering environment (e.g., GIS tools), the cryospheric community and data centers in particular can serve a broader user base. The NSIDC is unique because it has a higher percentage of researchers then other DAACs. There is constant pressure to find new interest in the sciences; however, the problem is just getting the information to them in a format that they find easy to use and understand. Interests in the weather data come from a broad range of users and potential users. Examples of requested data include ski trails maps that include road maps. Currently that cannot be handled; however, to include this data or make it available together would certainly raise the user base. It seems important to let the user determine what he or she wants. Using the same idea for outreach could have very good results. It could be possible to use students to determine the number of people and scientists that want data packaged in any particular way. Also critical is to find partners who can communicate well with the general public. Many people who teach graduate level students are not able to teach fifth graders and increase their desire to learn about the cryospheric sciences. Other examples of outreach programs could include self-service web pages. If there is to be an interest in cryospheric scientists in the future there has to be time dedicated now toward generating the interest. Importantly, to gather funding in the future it is beneficial to show the public what can be done with the data and how it is helpful to them. This brings up the point that it is not just K-12 and the public but also Congress that needs to be shown the usefulness of the data.

Dr. Jerry Peterson, Interim Vice Chancellor at CU, gave the closing remarks. Both praise for the NSIDC's work to date and some ideas for the future were made. Evironinformatics was coined as a phrase for getting human wisdom out of data. The NSIDC should look forward to continuing its progress in archiving and disseminating data.



Mark Meier and Roger Barry at NSIDC's 25th Anniversary Reception, 11 October, 2001.

Arctic Ocean Snow Melt Onset Dates Derived From Passive Microwave, A New Data Set

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Abstract

Snow melt onset is defined as the point in time when the appearance of liquid water in the snow pack changes the crystalline structure within the pack. Owing to the associated increase in surface albedo during melt, surface energy absorption increases rapidly after the onset of snow melt. Monitoring interannual variations in snow melt onset is therefore useful for accurately modeling surface conditions, and it is also valuable for validating climate models and detecting climate change. Since microwave emission changes rapidly when liquid water appears in the snow pack, passive microwave remote sensing techniques can monitor melt onset. Passive microwave satellite data from the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I) are indispensable for this task because they represent an all-season, all-weather, diurnally consistent, and reasonably continuous data set for more than 20 years in length (1979-1998). The microwave data time series is created from a blended brightness temperature record generated from different satellite platforms through linear regression analysis to ensure consistency in the data set. The melt onset date is calculated by monitoring the difference between the 18-GHz (SMMR) or 19-GHz (SSM/I) horizontal brightness temperatures and 37-GHz horizontal brightness temperatures. Results indicate both regional and annual variations exist in the melt onset dates. The melt onset dates are generated annually and are available via ftp from the National Snow and Ice Data Center (NSIDC). This new data set provides a valuable addition to researchers for seasonal-to-interannual and long-term climate studies, and it is hoped that others will find the data set useful.

Introduction

The discussion of global warming in recent decades has caused increased interest in year-to-year climate variations in the polar regions. The sensitivity of the polar regions to climate variations and change is believed to result from the complex exchange mechanisms operating between the oceans, ice, and atmospheric systems. The significance of sea ice in the polar regions is particularly emphasized during the spring transition period from winter conditions to summer conditions. For example, during the melt period, the surface albedo can vary from values greater than 0.9 for fresh dry snow to values less than 0.3 for wet-snow covered sea ice. With lower albedos, more shortwave energy is absorbed, further warming the air and ice surfaces. Therefore, determination of the melt onset is an important event in the polar region and this new data set produces a 21-year time series of individual melt onset dates. Understanding the energy variations that take place during the spring transition through the determination of melt onset can help determine the effects of climate variations, and therefore climate change in the polar region.

Microwave emissivity of snow increases dramatically as the snow melts and liquid water appears. Surface scattering dominates over volume scattering, resulting in a sharp increase in the brightness temperature signature. Lower microwave frequencies (19.3 GHz for the SSM/I instrument, and 18.0 GHz for the SMMR instrument) are more responsive to melt onset in the firn than are higher frequencies (37.0 GHz for both SSM/I and SMMR), due primarily to the change in emission depth associated with melt. The difference between 19.3 (or 18.0) GHz and 37.0 GHz brightness temperatures changes from positive to near-zero or negative. The increase in brightness temperatures associated with melt is frequency- and polarization-dependent; horizontal channels reflect a stronger dependence on snow conditions during melt.

Data

25 km^2 daily-averaged brightness temperature data from the Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imagers (SSM/I) were obtained from the National Snow and Ice Data Center (NSIDC) archive. Since the passive microwave data originated from four different radiometers, all data were converted to be consistent with the SSM/I F8 data using regression analysis during overlap periods. Brightness temperature from SMMR were converted to F8 using the slope and intercept values provided by Jezek et al. (1991), and the F11 to F8 with values from Abdalati et al. (1995). The brightness values from F13 were first converted to F11 values using the slope and intercept from Stroeve et al. (1998), and then converted to F8 with the values from Abdalati et al. (1995). These conversions are essential in determining variability in the melt onset, and not changes in the radiometers.

Mean Melt Onset Pattern

The 20-year mean melt onset map indicates the spatial melt pattern is roughly radial in nature, beginning along the southern ice edges and progressing northward (Anderson Figure 1, page 115). Melt onset typically starts prior to Julian Day 70 in the Bering Sea, the Sea of Okhotsk, and along the Labrador coast. From Julian Days 70-90, melt onset usually occurs in most of the Bering Sea and the Sea of Okhotsk, and some melt onset is noticeable in Hudson Bay, the South Greenland coastline, and the eastern Arctic Islands. Through Julian Days 90-110, the melt onset area expands to include the Hudson Bay coastline, and southern portions of Davis Strait. Melt onset also appears in the East Siberian Sea and along the Russian coastline. From Julian Days 110-130, melt is typically detectable in most regions of the Arctic Basin, and throughout all of Hudson Bay. The next 20 days (Julian Days 130-150) are marked by melt onset covering the Davis Strait and most of the southern Canadian Arctic Archipelago Islands. At this point, the melt onset pattern begins to rapidly expand northward, and from Julian Days 150-170 the total melt onset area nearly doubles. The latest melt onset dates are located in the Lincoln Sea north of Greenland, consistent with the fact that the minimum summer temperatures are located on the Greenland ice sheet. Superimposed upon the roughly radial melt onset pattern are significant regional patterns. For instance, it is evident that melt onset begins near coastal regions and islands. The former can clearly be seen in Hudson Bay, while the latter is noticeable along the larger islands of the central Arctic region.

There also appears to be regional differences in the variability of melt onset over the 20-year study period. The range in melt onset (Anderson Figure 1, page 115) at a given location, defined as the latest melt date minus the earliest melt date, shows a definite geographic pattern. The vast majority of points in the Arctic basin have a range of one to two months, while the range in the more southerly latitudes, such as Hudson Bay and along the continental coastlines, often exceeds two months. The smaller variability in the central Arctic suggests the annual melt onset date is influenced mainly by the spring transition in incoming solar radiation. In contrast, the larger variability along the ice edges hints that synoptic atmospheric conditions play a more significant role in influencing the melt onset date in these areas. The one-standard deviation map (Anderson Figure 1, page 115) displays a similar pattern to the range map. Variations of 7-14 days are found mainly in the central Arctic, while areas with a standard deviation of 14-21 days are found in the western Arctic, the Bering Sea, and the Sea of Okhotsk. Most of the regions with standard deviations of 21-28 days are located either in Hudson Bay, or along the coastal regions. Variations larger than 28 days are visible along the eastern Arctic ice edge.

Annual Melt Onset Pattern

In order to better understand interannual variations in the melt onset dates, the distribution of the annual melt pattern (Anderson Figure 2, page 115) are displayed. It is clear that the distribution of melt in any given year rarely follows the mean melt distribution (Anderson Figure 1, page 115). 1981 best resembles the mean melt distribution, but it still exhibits areas where the melt occurs either earlier or later than average. For instance, earlier melt is seen in the Siberian and Chukchi Seas, and the west-central Arctic Ocean. In contrast, later than average melt is observable in the Kara and Barents Sea regions.

In two of the years, 1979 and 1987, the melt distribution is greater than average in March and April, but then melt is delayed, and from May through July the spatial area of melt is less than average. In 1979 earlier melt occurs in the Bering Sea, along the Alaskan coast, and in portions of Hudson Bay, explaining the enhanced melting noted in March and April. Similarly, melt onset is delayed in much of the central Arctic, explaining why the melt distribution is below average from May through July. In 1987, earlier melt is seen in Hudson Bay and the Sea of Okhotsk, while later melt is observed from the Siberian Sea northward in to the Arctic Ocean.

Several years, including 1988, 1993, 1994, and 1998, show an opposite pattern to 1979 and 1987. In theses cases, the spatial melt area is below normal in March and April, but quickly increases such that from May through July the spatial area of melt onset is greater than average. In 1988, the vast majority of area that melts on average in March and April is delayed several weeks, with the exception of southern Hudson Bay. The enhanced melting seen from Julian Days 160-190 is due to earlier melt in the Arctic Ocean north of the Laptev Sea. In comparison, during 1993, delayed melt is observable throughout all of Hudson Bay, and most of the other southern ice regions, with the exception of a small band of earlier melt along the southern edge of the East Siberian Sea and the Laptev Sea. The enhanced melt later in the season is due to earlier melt in the Arctic Ocean north of the Chukchi Sea. It is also clear that deviations from the average are stronger in 1993 than 1988, and that even though the melt is enhanced from Julian Days 150-180, there are sections of later than average melt noticeable in the central Arctic during this time. In 199, the spatial melt pattern is similar to 1988, with earlier than average melt seen in southern Hudson Bay, set against delayed melt in much of the remaining southern ice regions. Enhanced melt from Julian Days 160-190 is caused by earlier melt in the Arctic Ocean north of the Canadian Arctic Archipelago. In comparison with the other three years that have a similar melt distribution, 1998 displays a much more hemispherically- based melt pattern. For instance, very early melt is seen over vast portions of the Western Hemisphere, especially in the Arctic Ocean. In contrast, later than average melt is noticeable in the Kara and Barents Seas, as well as the Arctic Ocean directly north of these seas. Enhanced melting towards the latter stages of the melt period are also noted for 1989, 1991, and 1995. In 1989, large sections of Hudson Bay experience later than average melt, while parts of the Sea of Okhotsk, the Laptev Sea, the Kara Sea, and the central Arctic Ocean experience earlier than average melt. Similarly, in 1991, Hudson Bay experiences later melt, while the Beaufort Sea, the East Siberian Sea, the Chukchi Sea, and the Laptev Sea all experience early melt. In 1995, an average melt pattern is seen for most of Hudson Bay, but earlier than average melt is observable in the Beaufort, Kara, and Barents Seas. The melt pattern in 1990 stands out as a very abnormal melt season.

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Summary

This study presented an improved snow melt onset-date detection algorithm for Arctic sea ice surfaces. The new Advanced Horizontal Range Algorithm (AHRA) utilizes temporal information in the brightness temperature difference between 19 GHz (18 GHz for SMMR) and 37 GHz to determine melt onset over sea ice locations in the Arctic. From 1979 through 1998, snow melt onset began in the Bering Sea and Sea of Okhotsk in the first week of March, and progressed northward towards the central Arctic by the middle of July. The latest melt onset dates were observed in the Lincoln Sea, north of Greenland, in accordance with the minimum in air temperatures located over Greenland. In comparison with the roughly radial northward melt progression of the annually averaged melt onset map, specific years showed a high degree of spatial variability. Most years typically have some regions of earlier than average melt, and other regions with later than average melt. However, 1990 appeared to be an extraordinarily early melt onset year, with later than average snow melt onset predominately occurring in the Beaufort Sea.

There is considerable opportunity to use this new melt onset data set for climate studies, including the development and validation of general circulation model outputs, and for the detection of climate change. Currently, work is underway to examine the interannual trends in melt onset at the regional level. In addition, the large interannual variability in melt onset data, especially in the southern regions, suggests an atmospheric influence.

Data Availability

The Arctic snow melt product is titled Snow Melt Onset Over Arctic Sea Ice from SMMR and SSM/I Brightness Temperatures, and the data and documentation are available from the National Snow and Ice Data Center on their Web page at http://nsidc.org/data/nsidc-0105.html.

Acknowledgments

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State of the Cryosphere: Response of the Cryosphere to Global Warming

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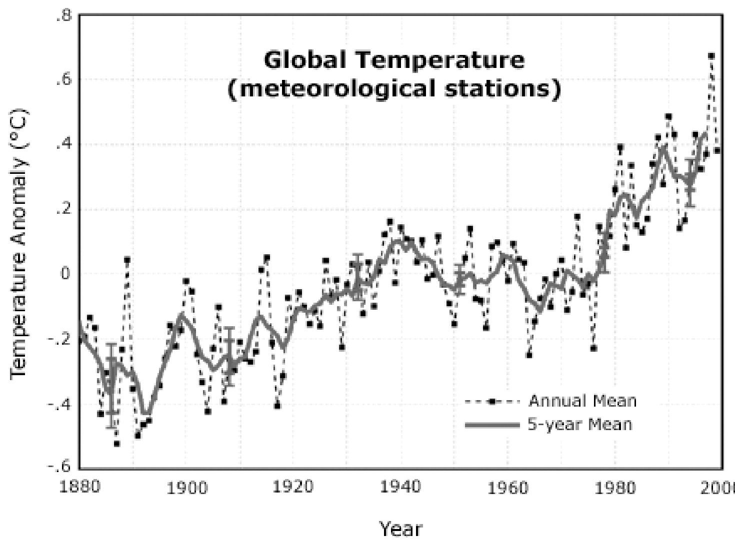
Introduction

The cryosphere, the regions of the Earth where water is found in solid form, is extremely sensitive to temperature change. Average temperatures in snow- and ice-covered areas typically remain below 0 degrees Celsius throughout much of the year. Unlike other substances found on Earth, ice and snow exist relatively close to their melting points, and frequently change phase from solid to liquid and back again. Consequently, consistent and prolonged warming trends should result in observable changes to the Earth's cryosphere. Water changing from solid to liquid and back often results in dramatic visual changes across the landscape as snow and ice masses shrink or grow.

Global mean temperatures have risen over the past 100 years by about 0.6 degrees Celsius. Over half of this increase has occurred in the last 25 years. Temperatures vary from year to year and from decade to decade, superimposed on the longer upward trend. The range of natural variability in global temperature appears to be about plus or minus 0.2 degrees Celsius, so that it is only after the late 1970s that global mean temperatures emerge from the noise of natural variability (see Armstrong Figure 1). In some regions, however, extreme warming has been detected. For example, winter temperatures in some locations in Alaska and northern Eurasia have warmed by nearly 6.0 degrees Celsius over the past 30 years (Serreze et al. 2000).



Armstrong Figure 1. Global temperature trend expressed as both the annual and five-year departure (anomaly) from the long-term mean temperatures, measured over 120 years. Image courtesy of NASA Goddard Space Flight Center, supplied by Hansen et al. 1999.

In the following sections, snow cover, glaciers, permafrost, sea ice, ice shelves, and the related parameter sea level are discussed. In all cases scientists attempt to monitor both the areal extent and mass of these snow and ice bodies. Certainly areal extent is easier to determine than mass. Various forms of remote sensing, from both aircraft and satellite, allow us to look down on surfaces at varying spatial scales and over time to determine if the snow- or ice-covered area is expanding or contracting. Long-term monitoring includes looking at the areal extent of snow cover and sea ice as well as changes in area and mass of mountain glaciers. In all cases shown here, regardless of parameter or measurement method, the amount of snow and ice has been decreasing over the past several decades.

Northern Hemisphere Snow Cover

Snow cover is an important climate change variable due to its influence on energy and moisture budgets. Snow cover presence accounts for the large differences between summer and winter land surface albedo, both annually and interannually. Snow may reflect as much as 80 to 90 percent of the incoming solar energy, whereas a snow-free surface such as soil or vegetation may reflect only 10 to 20 percent. A warming trend results in decreased snow cover. With the resulting decrease in reflected energy, absorption of solar radiation increases, adding heat to the system, thereby causing even more snow to melt. A classic positive temperature-albedo feedback mechanism ensues, which is a key component in climate models. Surface temperature is highly dependent on the presence or absence of snow cover, and temperature trends have been shown to be related to changes in snow cover (Groisman et al. 1994).

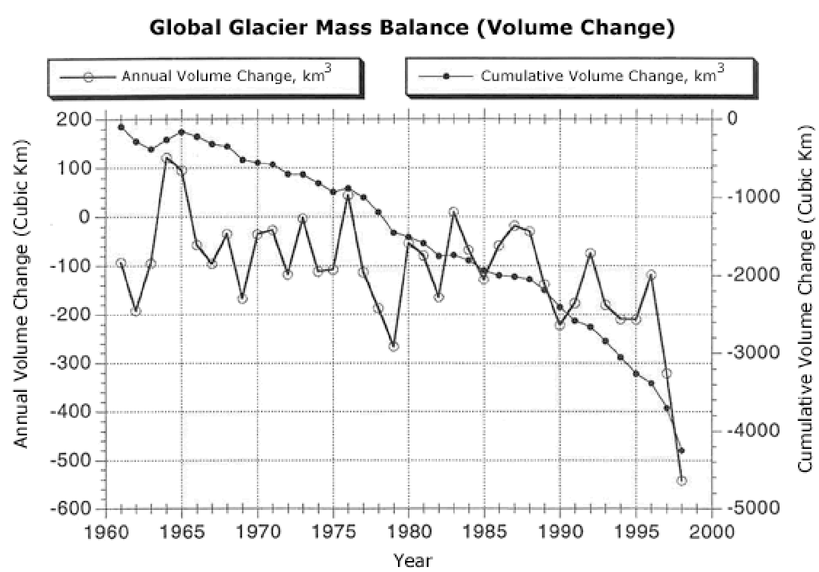
During the past three decades, satellite remote sensing has provided important information on hemispheric scale snow extent. Since 1966 the National Oceanic and Atmospheric Administration (NOAA) has produced weekly snow extent maps for Northern Hemisphere land surfaces using visible-band satellite imagery (Robinson 1993). Because snow has such a high albedo compared to other surfaces on Earth, snow-covered areas appear much brighter in satellite imagery than most other surface types.

The 20-year trend in mean annual snow extent derived from visible and passive microwave satellite data indicates a decrease of approximately 0.2 percent per year (Armstrong and Brodzik 2001). Precipitation in regions of seasonal snow cover appears to have been increasing slightly over this time period, which leads us to conclude that diminishing snow cover is the result of increasing temperatures.

A detailed account of the spatial and temporal variability of Northern Hemisphere snow extent can be found in Frei and Robinson 1999.

Glaciers

Over long periods of time, a clear picture of how glaciers respond to climate change may be seen. Unlike snow cover and sea ice extent, scientists cannot use short-term changes in the areal extent of small glaciers as an index of current climatic conditions. Glaciers continually move, transporting mass from higher to lower elevations, somewhat like a conveyer belt. If the combination of climate and ice dynamics determines that the glacier is advancing, the effect of the advance of the terminus is to increase the overall glacier area. However, because glaciers move slowly, a significant time lag occurs between the occurrence of the climatic conditions that caused the advance, or retreat, and the actual advance or retreat. This lag may amount to several years or even longer, and is determined by the complicated and sometimes uncertain processes that control how fast the glacier moves.



Armstrong Figure 2: Global glacier mass balance. Image courtesy of the Mark Dyurgerov, Institute of Arctic and Alpine Research, University of Colorado, Boulder.

For glaciers outside Antarctica or Greenland, referred to here as subpolar and mountain glaciers, considerable compilation and analysis of existing mass balance measurements have occurred (Haeberli et al. 1998; Dyurgerov and Meier 1997a; Dyurgerov and Meier 1997b). Glaciers involved in mass balance studies are sparsely distributed over all mountain and subpolar regions with about 70 percent of the observations coming from the mountains of Europe, North America, and the former Soviet Union. Mass balance on more than 280 glaciers has been measured at one time or another since 1946, although we only have a continuous record from about 40 glaciers since the early 1960s. These results indicate that in most regions of the world, glaciers are shrinking in mass. For the period 1961-1998 "small" glaciers lost approximately 7 meters in thickness, or the equivalent of more than 4,000 cubic kilometers of water.

Permafrost

Permafrost underlies approximately 22.8 million square kilometers (about 24 percent of the exposed land surface) of the Northern Hemisphere. It occurs as far north as 84^{o}N in Greenland, and as far south as 26^{o}N in the Himalayas (Zhang et al. 1999). See Armstrong Figure 3, page 116.

Geologists and geocryologists have mapped permafrost regions for at least 50 years. In 1990, the International Permafrost Association (IPA) recognized the need for a single, unified map to summarize the distribution and properties of permafrost and ground ice in the Northern Hemisphere. The IPA map shows the distribution of permafrost and ground ice for the continental landmasses, areas of mountain and plateau permafrost, sub-sea and relict permafrost, relative abundance of ice wedges, massive ice bodies and pingos, and ranges of permafrost temperature and thickness (Brown et al. 1998).

Much of the Northern Hemisphere permafrost is overlain by evergreen boreal forest. These boreal forests comprise both a source and a sink of carbon. In fact, the Arctic itself contains nearly one-third of the Earth's stored soil carbon. If the high northern latitudes were to undergo a significant temperature increase, the regional soils would begin to release carbon into the atmosphere. An increase in carbon could lead to increased plant growth, resulting in increased carbon absorption and possibly a temperature drop or stabilization. Alternately, it could simply lead to higher temperatures, fueling the cycle of carbon release and temperature rise (Environmental News Network 1999 and Goulden et al. 1998).

Permafrost's widespread distribution—nearly 24 percent of the Northern Hemisphere land surface, compared with perennial ice and snow, which covers only 3 percent of the Earth's surface—make it a substantial component of the cryosphere (Zhang et al. 1999 and Williams and Smith 1989). Likewise, its role in the storage and release of carbon makes it a major factor in future global change. However, because of the difficulty involved in assessing the location and extent of permafrost, the kinds of time series data available for other aspects of the cryosphere are less abundant for permafrost.

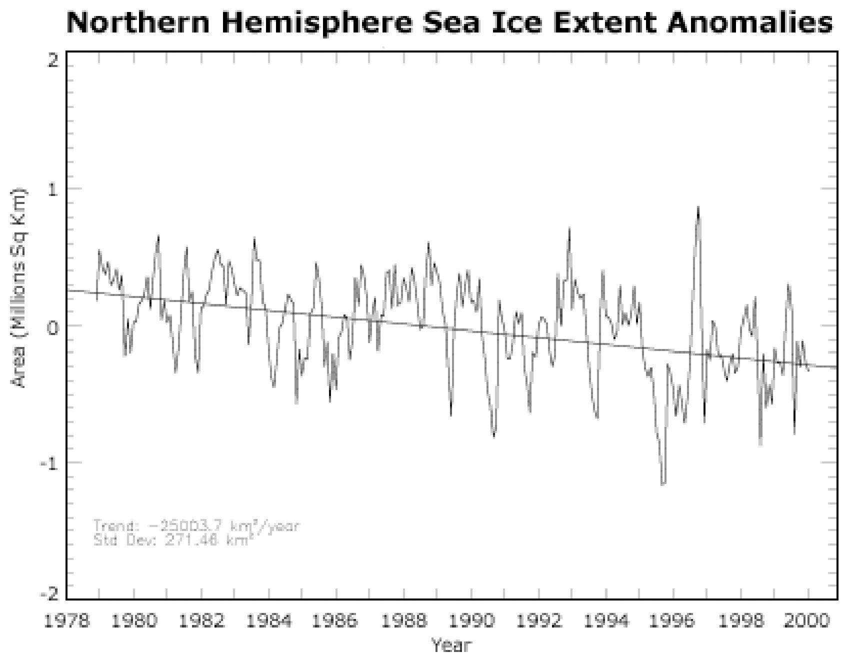
Sea Ice

Sea ice is important because it regulates exchanges of heat, moisture, and salinity in the polar oceans. It insulates the relatively warm ocean water from the cold polar atmosphere, except where cracks, or leads, in the ice allow exchange of heat and water vapor from ocean to atmosphere. The number of leads determines where and how much heat and water are lost to the atmosphere, which may affect local cloud cover and precipitation.

Ice thickness, its spatial extent, and the fraction of open water within the ice pack can vary rapidly and profoundly in response to weather and climate. Sea ice typically covers about 14 to 16 million square kilometers in late winter in the Arctic, and 17 to 20 million square kilometers in the Antarctic's Southern Ocean. The seasonal decrease is much larger in the Antarctic, with only about three to four million square kilometers remaining at summer's end, compared to approximately seven to nine million square kilometers in the Arctic.

Satellite data provide the best means of observing ice pack coverage and variability. A variety of remote sensing instruments have been used successfully to map sea ice conditions. However, due to frequent cloud cover in the polar regions and the fact that the sun remains below the horizon for continuous periods in winter, microwave sensors are the most commonly used instruments for ice-cover mapping. Passive microwave instruments such as the Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR), the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I), and radar such as RADARSAT and the European Remote Sensing Satellites ERS-1 and ERS-2 provide the main data sets used for sea ice studies because of their nighttime and all-weather capabilities.

Observations of polar oceans derived from passive microwave instruments have become essential for tracking ice edges, estimating sea ice concentrations, and classifying sea ice types. In addition to the practical use of this information for shipping and transport, these data add to the meteorological knowledge base required for a better understanding of global climate. Passive microwave imagery are available in a consistent form from late 1978 through the present, with earlier but less reliable data from ESMR. The satellite data from the SMMR and SSM/I instruments have also been combined with earlier observations from ice charts and other sources to yield a time series of Arctic ice extent from the early 1900s onward. See Armstrong Figure 4.



Armstrong Figure 4. Passive microwave-derived (SMMR/SSMI) sea ice extent departures from monthly means for the Northern Hemisphere, 1978-2000.

While the quality of these data vary over time, the resulting time series provides a reasonable summary of hemispheric ice extent. These data suggest greater variations in recent years, with 6 of the 10 years of minimum Arctic ice extent having occurred since 1990.

Trends estimated from satellite data suggest a net decrease in Arctic ice extent of about 2.9 percent per decade, while Antarctic ice extent increased by 1.3 percent per decade (Cavalieri et al. 1997). Due to regional variability, changes in ice cover can be different in different regions (e.g., Parkinson 1995).

Ice Shelves

Ice shelves are thick platforms of ice that are connected to land and float on the ocean. They gain mass primarily through flow from grounded ice sheets and glaciers; they lose mass through iceberg calving and melting. Most of the world's ice shelves, including the largest, are in Antarctica.

Ice shelves respond more quickly to warming temperatures than do ice sheets or glaciers. Examination of meteorological records has revealed atmospheric warming on the Antarctic Peninsula over the past several decades, and the northernmost ice shelves on the peninsula have retreated dramatically (Vaughan and Doake 1996). In fact, since 1974, seven ice shelves have retreated by a total of approximately 13,500 square kilometers.

The most pronounced ice shelf retreat has occurred on the Larsen Ice Shelf, located on the eastern side of the Antarctic Peninsula's northern tip. The shelf is divided into three regions from north to south: A, B, and C. In January 1995, two events on the Larsen Shelf attracted considerable public attention: (1) the calving of a 70 by 25 kilometer iceberg from the Larsen B (the last large iceberg to calve from this shelf), and (2) the disintegration of the remainder of the Larsen A, which began retreating in the 1980s. Although the iceberg received more media attention, the disintegration may have been more closely related to climate change. While iceberg calving is a natural occurrence, the sudden breakup of approximately 2,000 square kilometers of ice shelf into small icebergs was unprecedented.

In 2002, satellites recorded an even larger disintegration of an ice shelf. Between January 31 and March 5, 2002, approximately 3,250 square kilometers of the Larsen B shattered, releasing 720 billion tons of ice into the Weddell Sea. It was the largest single disintegration event in 30 years of ice shelf monitoring. Preliminary studies of sediment cores suggest that it may have been this ice shelf's largest collapse in 12,000 years. See Armstrong Figure 5, page 116.

Because ice shelves already float on the ocean, their disintegration does not raise global sea level, but related effects cause concern. Both modeling and observation suggest that glaciers feeding ice shelves will increase in speed and possibly discharge continental ice into the ocean should ice shelves disintegrate. The retreat of the Larsen Ice Shelf provides evidence that disintegration can happen more quickly than was previously thought. Other ice shelves in Antarctica are being closely monitored. Currently, there is no evidence of a strong warming trend on the Ross Ice Shelf, located further south in Antarctica. However, the Ross Ice Shelf is the main outlet for several major glaciers from the West Antarctic Ice Sheet, and contains enough above-sea-level ice to raise global sea level by 5 meters. At present, the Ross Ice Shelf's mean annual temperature is well below freezing; however, summer temperatures in the warmest part of this shelf are currently just a few degrees below that needed for the formation of melt ponds. Other ice shelves appear to be stable at this time, although they are closer to their climatic limit than previously believed.

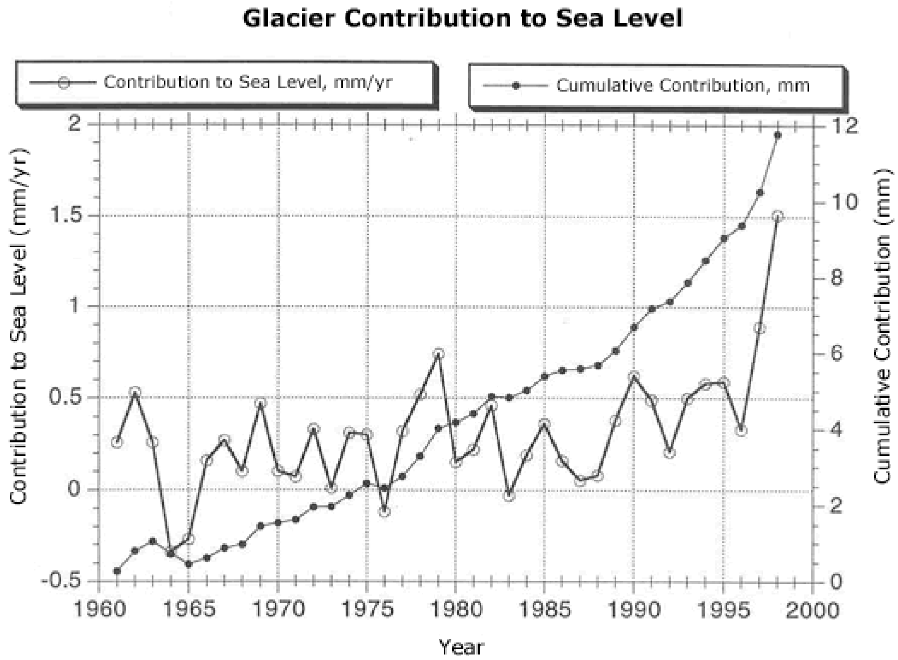
Global Sea Level

Global sea level is currently rising, mainly as a result of ocean thermal expansion and glacier melt, both caused by recent increases in global mean temperature. Antarctica and Greenland, the world's largest ice sheets, make up the vast majority of the Earth's ice. If these ice sheets melted entirely, sea level would rise by more than 70 meters.

Current estimates, however, indicate that mass balance for these ice sheets is in approximate equilibrium, and therefore they are not currently affecting sea level to any significant extent.

The network of small glaciers described in the Glaciers section of this paper have a total area of only 680,000 square kilometers, making up about four percent of the total land ice area (Meier and Bahr 1996). However, these lower latitude glaciers may have contributed as much as 30 percent of the total sea level change in the 20^{th} century.

Global mass balance data are transformed to sea-level equivalent by multiplying annual average mass balance (approximately -150 millimeters for the period 1961-1998) by the surface area of these "small" glaciers (680 thousand square kilometers). When dividing this value by the surface area of the oceans (361.6 million square kilometers), the final result comes to 0.28 millimeters of sea level rise per year. The contribution to sea level rise from melting glaciers began increasing at a faster rate starting in the mid-1970s. This is in agreement with high-latitude air temperature records.



Armstrong Figure 6. Glacier contribution to sea level. Image courtesy of Mark Dyurgerov, Institute of Arctic and Alpine Research, University of Colorado, Boulder.

Over the past 100 years, sea level has risen by 1.0 to 2.5 millimeters per year; thus the contribution from melting of smaller glaciers would be approximately 10 to 30 percent of the total. However, climate models based on the current rate of increase in greenhouse gases indicate that sea level will rise at a rate of about two to five times the current rate over the next 100 years as a result of the combined effect of ocean thermal expansion and increased glacier melt (IPCC 1996).

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Monitoring the Antarctic Ice Sheet: The Antarctic Glaciological Data Center's Compiled Products THERMAP and VELMAP

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Understanding trends in the climate and mass balance of the Antarctic ice sheet is crucial to understanding current global climate change. Mean annual surface temperature is a significant environmental factor that directly indicates short-term Antarctic climate change. Ice flow speed is a component of the overall mass balance, and changes indicate a response to longer-term shifts in climate and basal conditions. Data sets compiling past and current information on these parameters contribute to understanding the mass balance and overall stability of the Antarctic ice sheet.

In an effort to better understand past, present, and future temperatures and mass balance of the ice sheet, the Antarctic Glaciological Data Center (AGDC) at the National Snow and Ice Data Center (NSIDC) is compiling two data sets:

Antarctic "10-meter" Temperature Data (THERMAP):
Firn temperature at a depth of around 10 meters gives a close estimate of the mean annual surface temperature at that location. However, recent field and remote sensing work suggests that the temperature field over the ice sheet may be modified by local topography, i.e., the undulation field. The "10-meter" temperature data set is a compilation of measurements dating back prior to the IGY. THERMAP data are represented with a map showing the traverse route, station location, and temperature measurement. Data can also be viewed in tabular form, which includes data sources, information on data acquisition techniques, and additional measurements made at each site; i.e., density and accumulation.

Antarctic Ice Velocity Data (VELMAP):
This data set is a compilation of recent ice motion data for the Antarctic ice sheet, from a variety of sources. Landsat and SPOT image pairs, GPS, and Synthetic Aperture Radar (SAR) interferometry data have contributed over 100,000 velocity vector points. The data are presented in tabular form, containing latitude, longitude, speed, bearing, and error ranges , and are supported by satellite image maps summarizing the data. See Bauer Figure 1, page 117.

For more VELMAP information and imagery, visit http://nsidc.org/data/velmap/index.html. For more THERMAP information and imagery, visit http://nsidc.org/data/antarctic_10m_temps/index.html.

Historical Digital Sea Ice Data from the National Ice Center Now Available to the Research Community

Kyle R. Dedrick
Marine Information Resources Corporation, Ellicott City, MD

After an extensive digitization and quality control process spanning four years, weekly digital sea ice charts produced by the National Ice Center (NIC) from 1972 through 1994 are now available to the public in support of environmental research. These charts were originally intended as navigation aids for vessels operating in Northern Hemisphere sea-ice-infested waters. However, the data now represent a unique resource for Arctic researchers, adding significantly to sea ice data sets compiled by Walsh (1978) and others.

Ice concentration records derived from satellite passive microwave data are similar to the NIC data set in terms of resolution, extent, and period of record, but the data contained in the ice charts in many instances include more detail, available only through manual interpretation and integration of higher-resolution satellite and airborne sources. The completeness, consistency, and reliability of the NIC data reflect gradual changes, experienced over 23 years, in technology related to remote sensing and computer-based analysis of satellite imagery and other environmental data sources. Moreover, sea ice chart generation was (and still is, for the most part) carried out by a manual form of data fusion, which is inevitably subject to error on the part of analysts and cartographic technicians. Most inconsistencies and errors have been removed during quality control of the data in digital form; however, some errors remain and there is insufficient information available to truly validate the historical analyses.

Although the NIC digital sea ice data set has limitations, it spans a longer period than the passive microwave record and avoids some of its inherent biases. Additionally, the NIC data contain information on sea ice stage of development (related to thickness) and form (such as land-fast ice). Such information has not been reliably obtained from the passive microwave record. In its current, quality controlled, digital form, the NIC data set is easily processed, reduced, and analyzed in a computational environment, which makes it a powerful resource for sea ice modeling, climate modeling, and historical sea ice trend analysis.

Initial analysis of the data reveals that sea ice concentration patterns in the Atlantic and Pacific sectors of the Arctic vary in response to changes in the North Atlantic Oscillation. This result is consistent with the findings of other researchers, who used other data sets. More rigorous analysis of the data set is currently underway, in cooperation with the National Ice Center, at NASA (D. Cavalieri) and Vexcel Corporation (K. Partington), and these studies are already revealing trends in the Arctic ice cover not previously examined in other long-term data sets.

Researchers interested in analyzing the NIC data set should consider that the mission of the National Ice Center is to provide the best possible sea ice analyses in as timely a manner as is operationally feasible to support its operational customers. NIC ice charts are based on in situ observations, as well as data from a constantly evolving suite of space-borne sensors. Given this mandate, and the constant changes in technology, the weekly charts have steadily improved both in resolution and fidelity over the years. While this improvement is important for operational users, it can introduce trends or biases into the long-term sea ice record.

The NIC historical data set provides a superb general picture of the Arctic sea ice conditions. It is anticipated that NIC will continue an extensive quality control process on its digital ice charts for years 1995 and beyond, with subsequent publication of these data.

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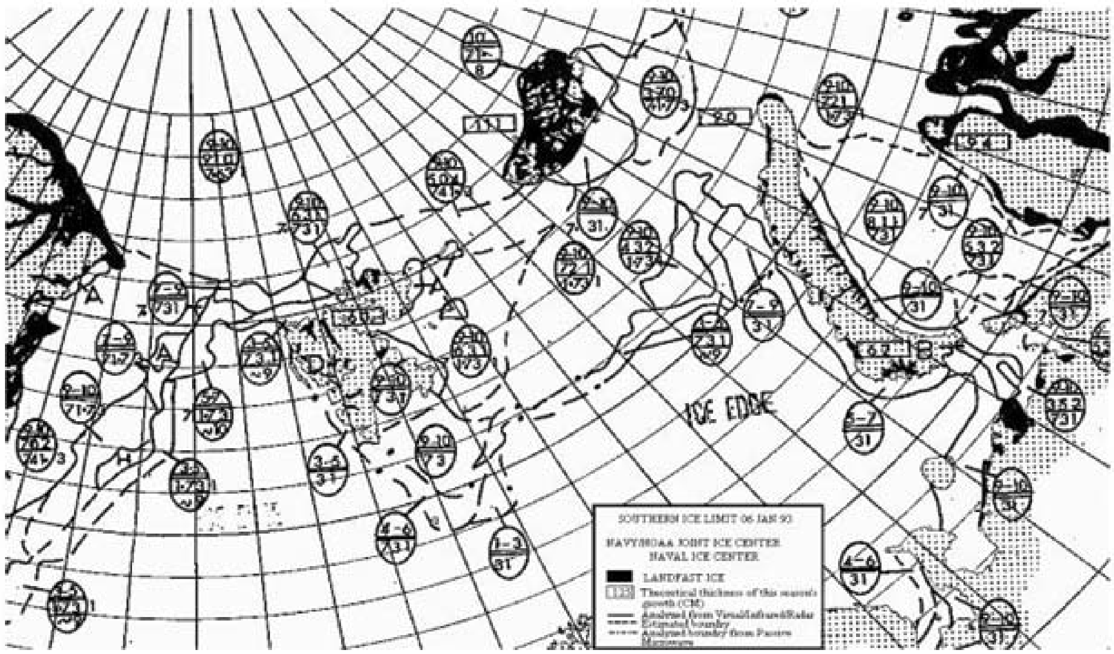

Dedrick Figure 1a. An example of a late 1980s/early 1990s era NIC Sea Ice Chart. During the 1980s and beyond, NIC reported total ice concentration, ice stage of development and ice form in accordance with the WMO "Egg Code" standard, which facilitated direct translation to SIGRID ASCII code during digitization.

See Dedrick Figure 1b and Dedrick Figure 2 on page 118.

Assessment of a Combined SMMR and SSM/I Derived Snow Water Equivalent Time Series for Western Canada, 1978 – 1999

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Abstract

When Special Sensor Microwave/Imager (SSM/I) and Scanning Multichannel Microwave Radiometer (SMMR) data are combined, the time series of dual polarized, multichannel, spaceborne passive microwave brightness temperatures extends from 1978 to the present. The Meteorological Service of Canada (MSC) has developed an operational snow water equivalent (SWE) retrieval algorithm for western Canada that can be applied to both SMMR and SSM/I data. This dataset now provides the potential to investigate climatological research questions that demand a time series of significant length. Attention must be given, however, to the impact of the slightly different spatial, temporal, and radiometric characteristics between SMMR and SSM/I data on SWE algorithm performance, and time series continuity and consistency.

An assessment of potential sensor bias on SWE retrieval is performed in this study by evaluating nine winter seasons of SMMR (1978/79 – 1986/87) and nine winter seasons of SSM/I (1987/88 – 1995/96) derived SWE estimates. These data are compared to a distributed network of in situ measurements taken from the MSC digital archive of Canadian station data. Mean bias error (MBE) and the relative frequency of microwave measurement errors (over- versus underestimation of SWE) are used to assess algorithm consistency between the two microwave time series. MBE results indicate that in some areas the microwave SWE estimates are more accurate during the SMMR seasons, while for other regions the SSM/I estimates are more accurate. Potentially problematic is a bias in the direction of error: microwave underestimation dominates the SMMR time series, while no consistent direction of error is evident in the SSM/I time series.

Introduction

Snow cover is a dynamic variable, subject to synoptic scale changes in extent, depth, and water equivalent. This variability has strong impacts on both atmospheric energy exchange, and the terrestrial water balance. Synoptically sensitive, spatially continuous, and temporally repetitive snow cover data are therefore required to monitor snow cover over time, and subsequently identify any spatial and temporal trends in snow cover parameters.

The Meteorological Service of Canada (MSC) has developed a suite of land-cover sensitive, snow water equivalent (SWE) algorithms for western Canada (Goodison and Walker 1995, Goita et al. 1997). Weekly SWE maps of the Canadian prairie and boreal forest regions are provided to water resource management agencies each winter. The spaceborne passive microwave brightness temperatures from which the operational product is derived are now available in a common gridded projection from 1978 to the present. When combined, Scanning Multichannel Microwave Radiometer (SMMR: 1978–1987) and Special Sensor Microwave/Imager (SSM/I: 1987–present) data provide a dataset of suitable length to which rigorous time series analysis can be applied. Attention must be given, however, to the impact of the slightly different spatial, temporal, and radiometric characteristics between the SMMR and SSM/I data on SWE algorithm performance, and therefore, time series continuity and consistency. The specific purpose of this study is to evaluate time series of five-day averaged (pentad) winter season (December, January, February) SWE imagery derived from first SMMR, then SSM/I brightness temperatures using the MSC algorithms. The objective is to determine if these two datasets can be combined seamlessly for future applications.

Data

Combining the SMMR and SSM/I time series is facilitated by the availability of the brightness temperatures in a common gridded product: the Equal-Area Scalable Earth Grid (EASE-Grid; see Armstrong and Brodzik 1995). Each EASE-Grid pixel has a spatial resolution of 25 km by 25 km; however, as summarized in Derksen Table 1, there are a variety of orbital, spatial, and radiometric differences between the two sensors that can potentially bias the EASE-Grid brightness temperatures.

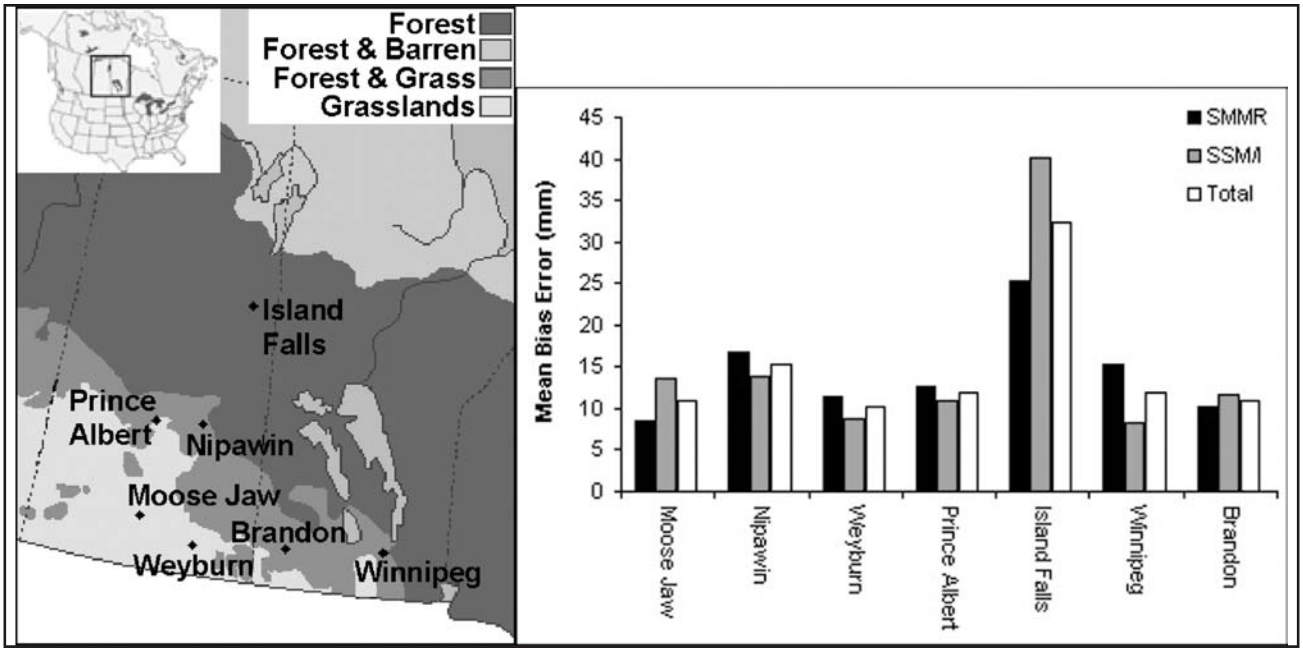
Derksen Table 1. Comparison of SMMR and SSM/I sensors.

	SMMR	SSM/I
Platform	NIMBUS-7	DMSP F8; F11; F13
Time Series	26 Oct 1978 - 20 Aug 1987	9 Jul - Present
Channels	6.6, 11, 18, 21, 37 GHz	19, 22, 37, 85 GHz
Polarization	V and H, all channels	V and H, except 22 GHz (V only)
Data Acquisition	Every other day	Daily
Swath Width	780 km	1400 km
Approximate Orbital Timing	Ascending - noon equatorial crossing Descending - midnight equatorial crossing	F8: Ascending - 0600 equatorial crossing F11/13: Ascending - 1900 equatorial crossing

The MSC algorithms were developed through ground, airborne, and satellite data acquisition programs (Goodison and Walker 1995, Goita et al. 1997). For each EASE-Grid pixel, SWE is derived as an area-weighted average of four separate algorithms that estimate SWE for open prairie environments, and coniferous, deciduous, and sparse forest cover. The open environment algorithm utilizes the brightness temperature gradient between the 37V and 19V (18V for SMMR) channels (37V-19V/18.0), while the forest algorithms are based on unique linear relationships in brightness temperature difference (37V-19V) for the three forest types. Land cover for each pixel is taken from the International Geosphere-Biosphere Programme (IGBP) 1-km global land cover classification, resampled to the EASE-Grid by the National Snow and Ice Data Center (NSIDC). The 17 IGBP land cover classes are aggregated into the four land cover types associated with the SWE algorithms. For additional information on the MSC algorithms, and more detailed descriptions of recent evaluation and application studies, see Derksen et al. (2000) and Derksen et al. (in press).

Results

Passive microwave SWE values, derived with the MSC land-cover-sensitive algorithms, were compared to surface SWE estimates for the stations shown in Derksen Figure 1. The surface SWE estimates are taken from the MSC digital archive of Canadian station snow depth data. The daily snow depth values for each pentad period were averaged, and converted to SWE using regionally and seasonally averaged snow density values provided in Brown (2000). It would have been preferred to use snow course data as the in situ dataset because these data provide direct SWE measurements; however, the sparse temporal coverage of snow course data at most stations (often only one measurement per month) seriously limits the use of snow course data for algorithm evaluation.



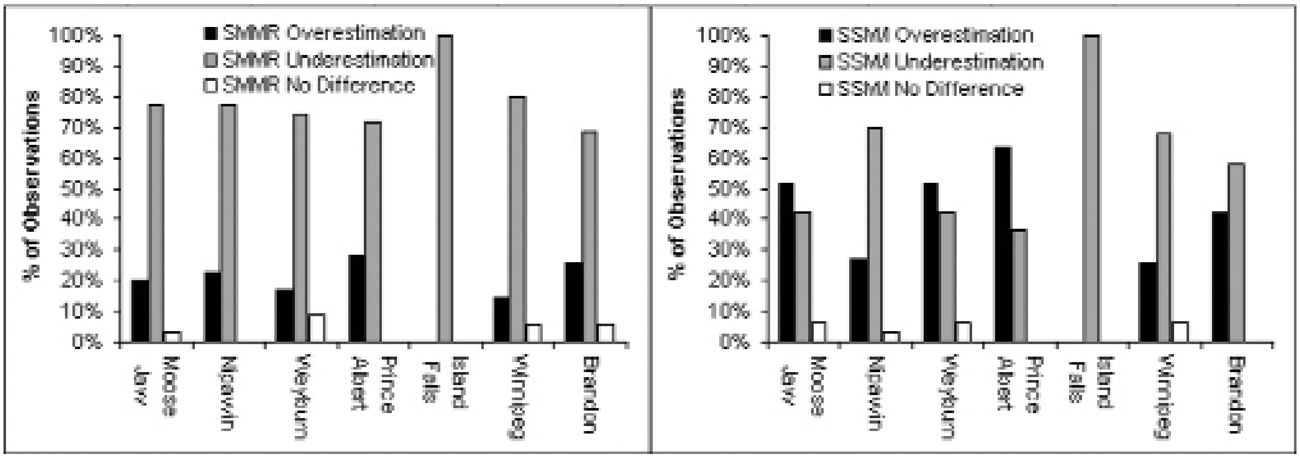
Derksen Figure 1. MBE results for in situ and microwave SWE comparison.

Four dates through the winter season were compared: the first pentads of December (Dec. 2-6), January (Jan. 1-5), and February (Jan. 31-Feb. 4), and the final pentad of the winter season (Feb. 25-March 1). Nine SMMR seasons and nine SSM/I seasons were investigated, with mean bias error (MBE) calculated for each of the four dates through the 18 seasons in the form

$$MBE = \frac{\Sigma \mid SWE_{SSM/I} - SWE_{Surface} \mid}{n}$$

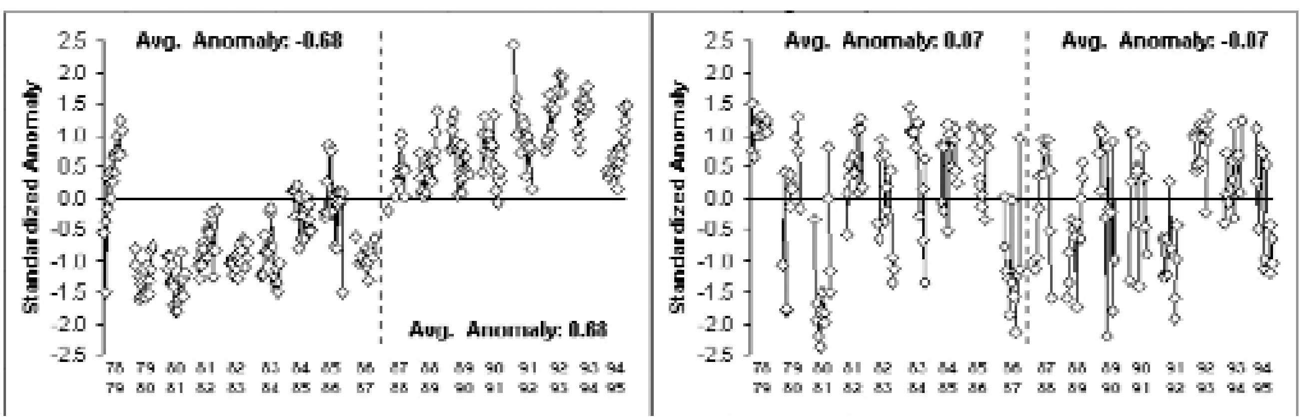
where n is the number of pentads. This provides a simple assessment of the agreement between the in situ and microwave SWE estimates. The MBE results are summarized for the SMMR seasons, SSM/I seasons, and complete time series in Figure 1. The microwave estimates are typically within 15 mm of surface estimates except at Island Falls, which is located in a heavily forested area. The SMMR time series shows stronger agreement with in situ SWE estimates for three stations (Moose Jaw; Island Falls; Brandon), while the SSM/I time series exhibits stronger agreement for four stations (Nipawin, Weyburn, Prince Albert, Winnipeg). There appears to be no mean error bias between the two microwave time series relative to the in-situ SWE estimates.

The MBE results, however, do not provide insight on the direction of disagreement between the two datasets, and don't indicate whether the microwave estimates are typically too high or too low relative to the surface data. To illustrate this, the frequency of microwave under- and overestimation, relative to the surface estimates, is shown in Derksen Figure 2. These results indicate that SWE underestimation dominates the SMMR time series (Derksen Figure 2a), while the SSM/I derived SWE exhibits a mix of over- and underestimation through the time series (Derksen Figure 2b). The exception to this is Island Falls, where the SMMR and SSM/I derived SWE are consistently lower than the in-situ estimates. This may be a consequence of the high-volume conifer forest and numerous small lakes in the region, which combine to strongly influence microwave emissivity. Finally, the regional density values used to convert in situ snow depth to SWE may not be representative of a high-density forest environment due to the measurement site location. Regardless, it is evident that algorithm performance is anomalously poor in the heavily forested environment characterized by Island Falls.



Derksen Figure 2. The frequency of microwave under- and overestimation relative to the in situ SWE estimates for the SMMR time series (a) and SSM/I time series (b).

The impact of the consistently lower SWE estimates produced with the MSC algorithm during the SMMR seasons is illustrated clearly by examining the standardized, total study area, SWE anomaly sequence for the winter seasons of 1978/79 through 1994/95 (Derksen Figure 3a). The transition from SMMR to SSM/I clearly corresponds to a shift from predominantly negative anomalies to largely positive anomalies. Because the anomaly break occurs exactly at the transition point between sensors, it cannot be attributed simply to a climatological shift. A climatological explanation is further discredited by the NOAA snow extent anomaly time series produced for the same period (Derksen Figure 3b). Assuming that SWE and snow extent anomalies are positively correlated, the passive microwave derived SWE anomaly trend in Derksen Figure 3a cannot be explained given the optically derived snow extent trend shown in Derksen Figure 3b.



Derksen Figure 3. Standardized total study area anomalies produced from passive microwave SWE imagery (a) and NOAA optical snow extent charts (b). The study area is outlined in Derksen Figure 1.

Discussion

The growing time series of operational, satellite derived, geophysical datasets have great potential for addressing research problems that require a spatial dataset of significant length. Before utilizing these datasets, however, this study has shown that it is important to ascertain the level of consistency of the derived variable through time, especially if there is a change in sensor. With the case of passive microwave derived SWE imagery, there is evidence of a difference in SWE magnitude in estimates derived from SMMR versus SSM/I brightness temperatures. A focus on applications that remove the influence of any potential bias is therefore required at this time.

Acknowledgments

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Mapping Global Snow Cover using Moderate Resolution Imaging Spectroradiometer (MODIS) Data

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Abstract

Moderate Resolution Imaging Spectroradiometer (MODIS) global snow and ice products are produced at NASA/Goddard Space Flight Center and archived and distributed through the National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (DAAC). The snow-mapping algorithms are automated, which means that a consistent data set may be generated for long-term climate studies that require snow-cover information. Implementation of product enhancements is ongoing, and ultimately reprocessing of the entire data stream will occur in order to achieve consistency in the snow products.

Introduction

On December 18, 1999, the Earth Observing System Terra spacecraft was launched with a complement of five instruments, one of which is the Moderate Resolution Imaging Spectroradiometer (MODIS). Global snow-cover products at 500-m and 0.05^{o} (~5.6-km) resolution are produced from MODIS data using automated algorithms at Goddard Space Flight Center in Greenbelt, Maryland. The products are transferred to the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, where they are archived, and distributed via the EOS Data Gateway (http://nsidc.org/~imswww/pub/imswelcome/index.html). In this paper, we describe the current state and availability of the MODIS snow products (http://modis-snow-ice.gsfc.nasa.gov/modis.html) as well as some of the planned enhancements and outstanding issues relating to the products.

Background

MODIS is an imaging spectroradiometer that provides global imagery of the Earth's surface and clouds in 36 spectral bands from ~0.4 to 14.0 mm (http://modis.gsfc.nasa.gov/). Key land-surface objectives are to study global vegetation and land cover, global land-surface change, vegetation properties, surface albedo, surface temperature, and snow and ice cover on a daily or near-daily basis (Justice et al. 1998).

In many ways, the MODIS snow maps are complementary to the National Oceanic and Atmospheric Administration (NOAA) operational maps. Analysts at NOAA National Environmental Satellite, Data, and Information Service (NESDIS) produce the Interactive Multisensor Snow and Ice Mapping System (IMS) snow maps daily at a spatial resolution of about 25 km (Ramsay 1998). NOAA's National Operational Hydrologic Remote Sensing Center (NOHRSC) also provides operational snow maps, but at 1-km resolution, for the coterminous United States, Alaska, and portions of southern Canada (Carroll 1995). While the NOAA maps are produced every day by specially-trained analysts, the MODIS snow maps are automated which permits a consistent product to be produced; necessary for long-term climate studies. Also, ephemeral snow cover – snow that may be on the ground for only a few hours or snowfall in regions that rarely receive snow – is often shown on the MODIS maps. This contrasts with NOAA operational snow maps which may or may not map those occurrences of snow cover. Also, the MODIS maps are 500-m resolution in contrast to the 1-km resolution of the NOHRSC maps of North America, and the 25-km resolution NOAA NESDIS maps which cover most of the globe.

Description of the MODIS snow-mapping products, algorithms and distribution

The MODIS snow products are provided as a sequence of products beginning with a 500-m resolution swath product. Inputs to the swath snow-cover product are: the MODIS calibrated radiance data, the MODIS cloud mask (Ackerman et al. 1998), and a land/water mask. The daily data are gridded into the Integerized Sinusoidal Projection to produce the daily snow tile product, which is generated by selecting the observation that was acquired nearest nadir and that has the greatest coverage of the grid cell from the many observations acquired during a day. This product also has 500-m resolution. An eight-day composite maximum snow-cover product is produced for each tile by compositing eight days of the daily 500-m resolution products. The daily global snow-cover climate-modeling grid (CMG) product is presented in a geographic projection, by assembling MODIS daily tiles to include all land areas of the daily 500-m snow product and binning the 500-m cell observations into the 0.05^{o} resolution of the CMG cells (Riggs et al. 2000, Hall et al. in press). The eight-day composite CMG products (Hall Figure 1, page 119) may be downloaded from http://modis-snow-ice.gsfc.nasa.gov/MOD10C2.html, or ordered through NSIDC.

The automated MODIS snow-mapping algorithm uses at-satellite reflectances in MODIS bands 4 (0.545-0.565 mm) and 6 (1.628-1.652 mm) to calculate the normalized difference snow index (NDSI), and MODIS bands 1 (0.620-0.670 mm) and 2 (0.841–0.876 mm) to calculate the normalized difference vegetation index (NDVI) (Hall et al. in press). The NDVI and NDSI are used together to improve snow mapping in dense forests as described in Klein et al. (1998).

Threshold tests, including a "thermal mask" (which uses MODIS infrared bands 31 [10.78-11.28 mm] and 32 [11.77-12.27 mm]) are also employed. Quality assurance (QA) information is available in the data products to help the user determine the usefulness of the snow-cover data (Riggs et al. 2000).

All of the MODIS snow (and ice) products are stored at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. The NSIDC is one of eight NASA Data Active Archive Centers (DAACs), and is part of the Earth Observation System Data and Information System (EOSDIS). The EOSDIS utilizes the EOSDIS Core System (ECS) for data management across the DAACs, and the EDG, which facilitates online Web-based user access to data (Scharfen et al. 2000). Users can search and order data via the EDG client at NSIDC (http://nsidc.org/imswelcome), and can access information about the MODIS snow products with links to related MODIS web pages (http://nsidc.org/NASA/MODIS/).

Issues and Limitations

The current version of the snow algorithm uses only the most "cloud conservative" test of the MODIS cloud-mask product, which leads to cloud obscuration of some snow cover. There are many cloud spectral tests (Ackerman et al. 1998), and identification of alternative spectral tests built into the MODIS cloud mask product that may be better suited to snow mapping has been accomplished (Riggs and Hall, submitted), and is in the process of being incorporated into the snow products.

Problems arise in some situations where snow is falsely detected due to a feature having reflectance characteristics similar to snow. Many of those situations were eliminated by the use of the thermal mask; however, some erroneous mapping of snow remains, especially when selective cloud-mask spectral tests are used to maximize mapping of snow cover. Resulting "false snow" generally occurs due to ice in high clouds which are most problematic during the summer.

It is hoped that sub-pixel snow cover mapping will become part of the MODIS 500-m resolution products within the next couple of years. Several algorithms are under development for mapping sub-pixel snow cover using MODIS data (Barton et al. 2000, Kaufman et al. in press, Appel and Salomonson in press).

Errors of omission are known to occur in the eight-day composite products under the following conditions. Snow may be deposited and melt while the region is cloudy. If the clouds then clear after the snow has melted, the MODIS eight-day composite maps will not show that there was any snow cover during that eight-day period. This error of omission has not been estimated yet for the global scale, but appears to be rather minor. However, there are notable examples where snow cover deposited from a large storm may be missed due to persistence of storm-related clouds near the end of an eight-day period. Usually, however, the snow cover is then seen on the following eight-day composite.

Conclusions

Strengths of the MODIS snow-cover products are that they are provided at improved resolution relative to existing snow maps, and are produced by automated algorithms globally and on a daily basis. Following reprocessing of the entire MODIS data stream, a consistent data set will be created, permitting longer-term climatology studies to be conducted.

The MODIS snow algorithm displays great sensitivity in the detection of snow cover, and good snow/cloud discrimination has been achieved. However, cloudcover and darkness preclude mapping snow cover using MODIS data alone. In the future, passive-microwave data will be combined with the MODIS data to develop improved snow maps that will not be restricted by weather conditions or darkness, and that will also contain information on snow depth (Chang et al. 1987, Armstrong and Brodzik 1999).

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Glacier Monitoring: Opportunities, Accomplishments, and Limitations

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Glacier monitoring has a long history. The relation between glacier changes and climate was pointed out as early as 1772. In 1894, the International Commission on Snow and Ice (ICSI) was formed to promote an international program of glacier monitoring; mainly advance/retreat observations. The 20th century saw the International Geophysical Year (IGY), the World Data Centers, the International Hydrological Decade/Programme (IHD/IHP), and the World Glacier Monitoring Service, as well as the NSIDC in the United States, all of which supported expanded programs of glacier monitoring. Emphasis turned to inventories, mass and energy balances, glacier hydrology, studies of the great ice sheets, growth of data exchange systems, and standardization of national and international monitoring programs

So, why do we monitor glaciers?

- Glaciers are sources of beauty in the mountain and polar landscape.
- Glaciers supply water with unique and often useful runoff characteristics; they contribute to the headwater sources of major rivers supplying large populations.
- Glaciers are important influences on mountain ecosystems.
- Glaciers are sources of paleoclimate data, and of information on high-mountain meteorology and hydrology.
- Glaciers are major contributors to global sea-level rise.

Glacier mass balance information has been available since about 1961(Haeberl 1996, Dyurgerov 2002), and these results have been used to calibrate glacier/climate change models since the 19th century for a number of glaciers (M. Meier Figure 1, page 119, see Dyurgerov and Meier 2000). These results show that glacier wastage has been pervasive during the last century. The volume of ice in the European Alps and in the Caucasus has decreased by half, and major changes have occurred in other areas (Meier et al. 2002). The large glaciers of southeastern Alaska and adjacent Canada have lost mass, without much relative shrinkage, contributing significantly to sea-level change (Arendt et al. 2002). Small glaciers and those in marginal environments are disappearing, especially in the tropics. Spatial and regional differences abound; large arctic glaciers and ice caps are changing slowly, but warming. In those few cases where we have data, the retreats of the last century exceed any seen in the last several millennia.

M. Meier Table 1. Detailed examination of the mass balance data of the last 40 years show several interesting changes related to climate.

Table 1. Globally-averaged mass balance components, for three periods.

Component	**1961-76**	**1977-87**	**1988-98**
<b> (mm/yr)	-82	-125	-217
$\mathbf{b_{20}}$ (mm/yr)	-93 (33)	-208 (39)	-400 (36)
$\mathbf{b_w}$ (mm/yr)	1480 (40)	1430 (58)	1700 (51)
$\mathbf{b_s}$ (mm/yr)	-1650 (40)	-1680 (58)	-1890 (51)
a (mm/yr)	1540 (40)	1430 (58)	1780 (51)
AAR (%)	55 (23)	51 (32)	46 (34)

<b> is net balance, area-weighted by large regions, and including all available time series; $\mathbf{b_{20}}$ is net balance for time-series of 20 years or more, $\mathbf{b_w}$ is winter balance, $\mathbf{b_s}$ is summer balance, **a** is turnover = $(b_w - b_s)/2$; numbers in ( ) are numbers of glaciers used in each calculation.

Is existing knowledge sufficient to predict the future contribution of glaciers to sea-level rise, as in the recent IPCC Scientific Assessment (Church et al. 2001)? Several problems exist:

1. The total-area problem: IPCC 2001 used a total glacier area of 680,000 km^2; newer guesses raise the area of small glaciers in Antarctica alone up to perhaps 700,000 km^2 and some of this ice will be contributing to sea-level rise with future warming.
2. The diminishing-area problem: IPCC 2001 assumed decreasing total area based on studies of small glaciers, and did not consider the major contribution of large glaciers (e.g., in Alaska) that are not shrinking appreciably in area.
3. The big- and small-glaciers problems: Small ice patches and glaciers are missing from most inventories, and no big glaciers are being monitored with mass balance observations; there is reason to believe that this sampling imbalance introduces bias.
4. The sensitivity problem: Glacier sensitivity to global warming (m of ice per degree warming) may be increasing; if this continues, sea-level rise will be more than projected.

Looking into the 21st Century, we see several opportunities for improvement in glacier monitoring science. We need to

- create proper regional and global syntheses
- overcome glacier-size bias in surveys
- develop new understanding and technology (e.g., repeated laser altimetry, remote-sensing imagery) to cover large areas, monitor large glaciers, and to incorporate these results in an international glacier-monitoring strategy
- emphasize inventory work to develop sufficient size, altitude, etc. distributions and use scaling relations to extend to probability distribution functions of pertinent variables for synthesis, i.e., avoid the "you-must-measure-every-glacier" mentality.

Perhaps even more importantly, there are political and resource problems that need to be solved. Of first importance is the decreasing support for monitoring (the "it's only data" criticism often expressed in science proposal reviews). This decrease in support is partly due to the fact that people involved in expansion of programs and support during the IGY/IHD are now retiring; where is the new generation of people willing to promote and fight, at all levels, for the value of long-term monitoring programs? Some of the most valuable of these have been reduced, imperiled, or abandoned. These include those in the United States (US Geological Survey) and Canada; in Russia, the long-term programs in Severnaya Zemlya and the Polar Ural Mountains, and in Central Asia the Abramov, Shumskiy and Fedchenko Glacier stations. Time-series of unique meteorological and glaciological observations at high altitudes, some extending for more than 60 years, have terminated, with little hope for restoration. Our understanding of climate, hydrology, and glaciology in these important regions suffers.

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Near Real-Time Microwave Sea Ice Products for Operational Sea Ice Analysis

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The U.S. National Ice Center (NIC) provides operational ice analyses for all ice-covered regions. These analyses are created from available high- and low-resolution imagery (including AVHRR, OLS, and Radarsat), reconnaissance data, ice forecasts, and climatology. Recently, the NIC has transitioned from weekly analyses to biweekly analyses for the Arctic and Antarctic.

Daily operational SSM/I ice concentration products supplement these biweekly analyses. The current product in the Arctic is from the NIC Hybrid Algorithm, a combination of the NASA Team algorithm, the NASA Team Thin Ice algorithm, and the Cal/Val algorithm. The Antarctic product employs the enhanced NASA Team 2 algorithm. In addition to these two operational algorithms, a variety of experimental products are posted daily on the National Ice Center Science Team Web Page (http://www.natice.noaa.gov/science/). These include several other SSM/I concentration products (e.g., original NASA Team, Bootstrap, Cal/Val), a QuikScat ice extent product, and model sea ice concentration forecasts (from 1 to 5 days). Additional products are also planned, including an ice motion product and a polynya detection product.

The goal of these experimental products is to provide improved operational ice analyses more efficiently. Here we present examples of the NIC products as well as the latest results from ongoing evaluation studies. These products are consistent with and complementary to the NSIDC sea ice products, but the focus is on the NIC mission of operational support.

Introduction

The U.S. National Ice Center (NIC) is a joint NOAA/U.S. Navy/U.S. Coast Guard operational center. Its mission is to provide high-quality global and tactical analyses of ice-covered regions. To accomplish this goal, a wide variety of satellite imagery is employed, including AVHRR, DMSP OLS, and Radarsat. DMSP SSM/I passive microwave imagery is also an important source for NIC because it provides complete daily coverage of the polar regions in all sky conditions. However, the benefits of SSM/I for operational ice analyses are limited because of its relatively coarse spatial resolution (25 km) and higher errors, particularly in areas of operational importance such as thin ice regions and near the ice edge. Thus, the most commonly used SSM/I sea ice concentration algorithm, the NASA Team algorithm, is often insufficient for operational analyses. Several other algorithms (Cal/Val, Bootstrap, Bristol, NASA Team 2, NIC Hybrid, etc.) have been developed that may be more or less accurate than the NASA Team, depending on ice conditions. At this time, there is not a single algorithm that has been proven overall more effective for operational applications.

NIC has begun evaluating these algorithms in an operational context. Each of these algorithms are being produced in near real-time and are published daily on the National Ice Center Polar Science Team web page (http://www.natice.noaa.gov/science/). In addition to the passive microwave sea ice products, higher-resolution QuikScat scatterometry imagery, 85-GHz brightness temperature fields are also being produced, as well model ice concentration forecast fields.

Sea Ice Concentration Products

Several sea ice concentration fields are produced operationally by NIC; they are listed below and sample imagery is provide in W. Meier Figures 1 and 2, page 120. Each passive microwave product is derived from algorithms using combinations of the SSM/I 19-GHz and 37-GHz channels, except for the NASA Team 2 algorithm, which also employs the 85-GHz channels. The NIC Hybrid algorithm was originally developed by K. Partington at NIC; a combination of the Cal/Val, the NASA Team, and the NASA Team Thin Ice (Cavalieri, 1994) algorithms, it is designed to improve performance near the ice edge and in thin ice regimes in the Northern Hemisphere.

Passive Microwave Sea Ice Concentration Products

NASA Team, NT (Cavalieri et al, 1984)
Cal/Val, CV (Ramseier et al., 1988; Hollinger et al., 1991)
NIC Hybrid, NH (Meier et al., 2001) (Arctic only)
Bootstrap, BS (Comiso et al., 1997)
NASA Team 2, N2 (Markus and Cavalieri, 2000)
Bristol, BR (Smith, 1996) (available soon online)

The algorithms are run on 24-hour composite SSM/I brightness temperatures gridded to the NSIDC 25-km polar stereographic projection; the format is consistent with the NSIDC NASA Team and Bootstrap products. The NASA Team weather filter, using ratios of the 19-, 22-, and 37-GHz channels is employed for all algorithms.

A summary of many of the algorithms is provided in Meier et al. (2001). Details on the individual algorithms can be found in the listed references. The near real-time products have been produced since October 2000. Online access to archived products is planned; in the interim they are available upon request.

High-Resolution Microwave Sea Ice Products

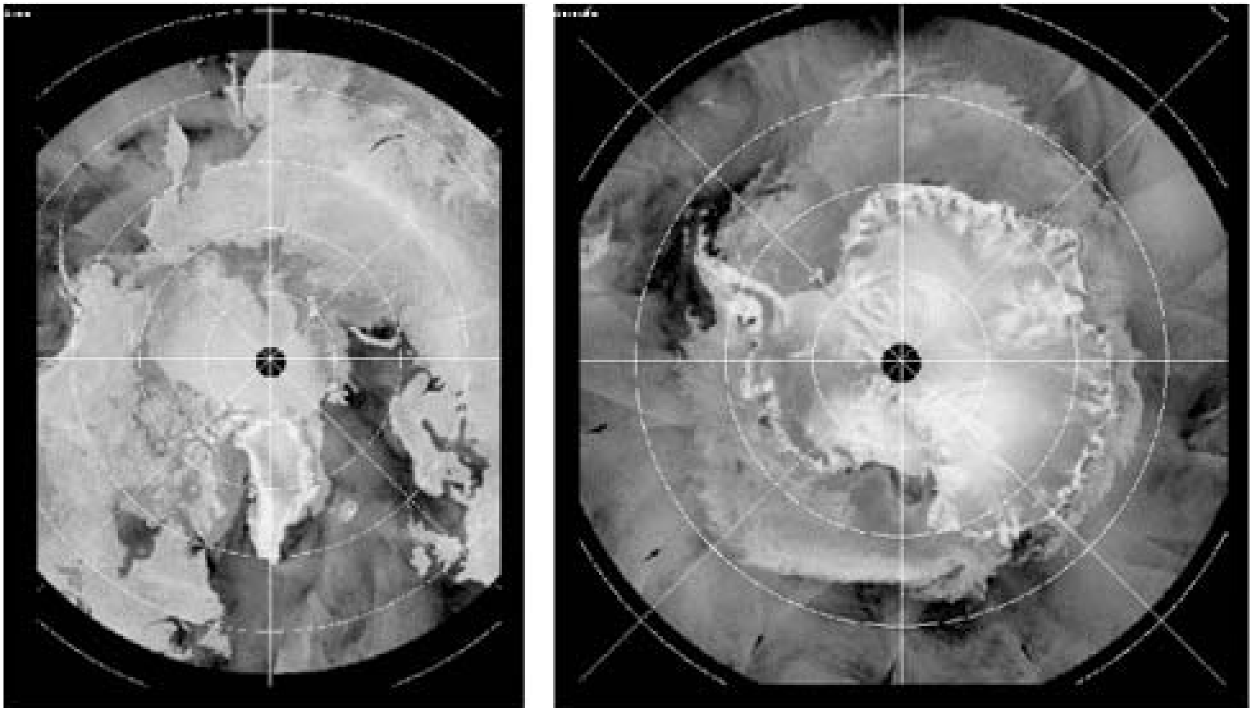
In operational sea ice analysis, spatial and temporal resolution is crucial. Ideally, leads on scales of 1 km or less would be analyzed daily. Thus, a major drawback of microwave products is low spatial resolution. To supplement the SSM/I ice concentration products, two higher-resolution microwave sea ice extent products have been implemented.

85-GHz Polarization Difference

The 85-GHz channel of SSM/I is gridded to a 12.5-km resolution (on the NSIDC polar stereographic grid). Sea ice is clearly distinguishable from open water at this frequency because emission from sea ice is basically unpolarized, while water is highly polarized (W. Meier Figure 3, page 121). This allows the ice edge to be determined at potentially twice the precision of the lower-resolution SSM/I channels. A drawback of using the 85-GHz channel is that atmospheric interference is a major issue. This has limited the use of the 85-GHz channel in ice concentration algorithms. To alleviate the effects of the atmosphere, NIC produces a polarization difference image, subtracting the horizontal channel from the vertical channel. This removes much of the atmospheric contribution and yields clear delineation of ice and open water in most cases; as an additional check, the NASA Team weather filter is used to screen out regions of clearly open water.

QuikScat Imagery

Scatterometer data from the SeaWinds sensor on QuikScat has a raw spatial resolution of 25 km. However, using resolution-enhancement techniques developed by D. Long and others at Brigham Young University (Long et al., 1993; Remund and Long, 1999), 36-hour composite images are produced with a spatial resolution of 2.225 km. These high-resolution images are a valuable resource for NIC analyses because scatterometer data is unaffected by clouds or solar illumination. The QuikScat product on the NIC web site is created by averaging 5 x 5 pixel regions and then interpolating to the 12.5-km NSIDC polar stereographic grid for consistency with the other products (W. Meier Figure 4).



W. Meier Figure 4. Quikscat imagery for Arctic (left) and Antarctic (right) for 6 December 2001.

Sea Ice Concentration Forecast Products

NIC also relies on the Polar Ice Prediction System (PIPS) sea ice forecast model (Preller and Posey, 1989; Preller, 1992) for guidance in analyses and short-term forecasting. The model was developed at NRL Stennis Space Center and runs operationally at the U.S. Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, CA.

PIPS 2.0 is a coupled ice/ocean model forced by atmospheric forecast products. The sea ice component is a standard viscous-plastic (Hibler, 1979) two-layer ice model with seven thickness subcategories (Walsh et al., 1985). It is coupled to a variation of the Cox (1984) ocean model. The sea ice concentration field in PIPS is initialized daily using the SSM/I Cal/Val concentration fields. An analysis field and 24-, 48-, 72-, and 120-hour forecast fields are produced daily. An example is provided in W. Meier Figure 5, page 121.

The daily forecast ice concentration fields are available on the NIC Science web site. Ongoing assessment of the utility of PIPS forecasts is being conducted at NIC (Van Woert et al., 2001). While these products are an important supplementary tool for NIC analyses, they have not yet proven reliable enough for route planning and other operational guidance. Development of an improved sea ice forecast model, PIPS 3.0, is currently underway.

Case Study Evaluation

In addition to producing the SSM/I concentration fields for analysts and the scientific and operational community, NIC is conducting in-house evaluations of the products through comparisons with higher-resolution imagery. Earlier in-house evaluations have indicated that the NASA Team 2, Bootstrap, and NIC Hybrid

(Northern Hemisphere only) are the most accurate. Since July 2001, whenever particularly useful imagery (primarily AVHRR and OLS) was found, it was saved for case-study comparisons with SSM/I.

Here, we present one example case study from the Kara Sea region from 23 July 2001, using an OLS image (W. Meier Figure 6, page 122). This is the summer melt period when SSM/I products are generally less accurate. However, it is an important time period for operations. While ice concentration fields are less reliable, simple ice edge and compact ice thresholds may still be fairly accurate. The ice edge is defined here as SSM/I concentrations greater than 10 percent; the compact ice threshold is defined by SSM/I concentrations greater than 85 percent. On the imagery for 23 July shown here, the contour lines toward the top of the image represent the compact ice boundary, and the lower contour lines represent the ice edge boundary. The lines are color coded by algorithm, as indicated on the image; the Bristol algorithm has not yet been included in these evaluations.

While there is not much difference between the algorithms, the NASA Team 2 contours appear to match up most closely with the OLS image in the example shown here. This has been borne out in most case studies examined to date. Occasionally, the NIC Hybrid has been found to be most accurate in the Arctic. This is not surprising, since it was developed specifically to obtain better performance discriminating the ice edge. In earlier studies, the NIC Hybrid was found to be quite accurate as well. However, in the case studies discussed here, the NIC Hybrid has often been found to be much less accurate.

Thus, from the results to date, the NASA Team 2 appears to be the best overall algorithm for operational applications in either hemisphere. However, these case studies have encompassed only a short time period and the conclusions can only be preliminary at this point. Because the performance of the algorithms can vary by season, at least a full year of case studies will be necessary for a final assessment.

Conclusion

The U.S. National Ice Center uses all available imagery to provide as accurate sea ice analyses as possible. This is currently a labor-intensive process and analyses are produced only biweekly. To supplement these analyses, NIC is now producing near real-time microwave imagery. These images are lower resolution and less accurate for operational applications, but they are an important resource because they provide complete daily coverage of all ice-covered regions.

These products are continually being evaluated in the hope of determining the best overall product (or combination of products) for operations, as well as seeking improvements to increase accuracy. The ultimate goal is to provide automated daily products useful for routine operational guidance.

NIC is also developing an operational passive microwave ice motion product and a polynya detection algorithm, the Polynya Signature Simulation Method (PSSM), developed by Markus and Burns (1995). Other products are also being investigated.

Acknowledgements

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Sea Ice Datasets At NSIDC: From Yearbooks To Digital Catalogs

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During the past 25 years, and especially during the past decade, the sea ice datasets available to researchers have expanded dramatically. The National Snow and Ice Data Center (NSIDC) began its Boulder era in the mid-1970s, when the available sea ice information consisted primarily of copies of paper charts, usually of hand-drawn analyses from national ice agencies (the U.S., U.K., Canada, and Denmark). The storage media were the boxes and file drawers that arrived in Boulder with NSIDC. The utility of sea ice information for diagnostic and monitoring information has advanced in three phases, with NSIDC playing a central role in each. First, historical ice charts, extending back to the 1800s in some cases, were digitized by national centers (the U.S. Navy/NOAA National Ice Center, and its Canadian counterpart) as well as by research scientists. NSIDC became the digital archive for these datasets in the late 1970s and early 1980s. Second, digital satellite imagery was processed and synthesized by other agencies and delivered retrospectively to NSIDC. The widely used ESMR/SMMR/SSMI data products from NASA are prime examples. Third, as NSIDC assumed its role as a NASA Distributed Active Archive Center (DAAC), real-time availability of satellite products was achieved. Today NSIDC's and other websites provide such information to users around the world. In addition, new sea ice products such as sea ice motion fields, submarine-derived ice thickness datasets, and complementary atmospheric and ocean products in digitized form now serve as a basis for interdisciplinary studies of sea ice as part of the broader polar system. Several such studies are highlighted in this presentation.

Walsh Table 1. Ice Data at NSIDC: The 25-Year Evolution.

1976 -- NSIDC User Survey ("Primary field of Interest")

17%	Mountain glaciers
14%	Climatology
11%	Ice sheets
11%	Glacial Geomorphology
9%	Snow/ice physics
8%	Snow hydrology
8%	Avalanches
7%	Remote Sensing
7%	SEA ICE
5%	Permafrost
4%	Freshwater ice

2001 -- NRC Committee Survey ("Primary research focus" of users)

38%	SEA ICE/OCEAN
18%	Ice sheets/sea level
14%	Terrestrial hydrology, physics
10%	Terrestrial biology, biogeochemistry
10%	Atmospheric variables
2%	Glaciers
2%	Snow cover
10%	Cross-variable interactions

Processing of Ice Draft Measurements From Submarine Upward Looking Sonar

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Introduction

Suppose someone had said to you that they had a fifty-year record of an important and almost unknown climatic variable, and that you were free to examine and utilize it to study climate change. This has happened to the polar science community.

The U.S. Navy has acquired raw data on the draft of the arctic ice pack from every cruise under the arctic pack since they began in 1958. These data were collected for operational purposes and the fact that they have been preserved over many decades is remarkable and fortunate. Still more fortunate, the Navy has agreed to make the data available to the scientific community.

The 43-year record, from 1958 to the present, covers a large portion of the Arctic Ocean. Royal Navy data complement the U.S. data, covering the area from the Greenland Sea to the North Pole. All told, the U.S. and U.K. submarine draft data provide an invaluable look at the interdecadal behavior of the arctic sea ice pack.

To date, drafts from some 18 cruises have been processed and are now available through the National Snow and Ice Data Center (NSIDC). Data from over 40 more cruises are being processed and should become available over the next few years.

The release of these data has been pursued by projects involving the custodian of the U.S. data, the Arctic Submarine Laboratory in San Diego, California, and several institutions:

- Cold Regions Research and Engineering Lab (CRREL), Hanover NH
- Applied Physics Lab at the University of Washington, Seattle, WA
- Scott Polar Research Institute at Cambridge University, Cambridge, U.K.
- Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI.

These institutions have been involved in a massive effort to process, analyze, and release heretofore classified data for general distribution. Here we focus on projects supported by the National Science Foundation (NSF) to provide data from U.S. Navy submarines.

Data Being Released

Draft data have been collected on all U.S. arctic submarine cruises, beginning with the cruise of the first nuclear-powered submarine USS Nautilus in 1958. Before 1976, data were recorded only on analog paper charts. After 1976, paper charts continued to be collected, but the ice draft was also digitally recorded on a Digital Ice Profiling System (DIPS). Data from many of the cruises with DIPS have been already been processed and released. Summary statistics have been produced for a few of the analog data.

Data release area: Currently data declassified by the U.S. Navy are all located within a specified release area, sometimes referred to as the “SCICEX box,” an area in the Arctic Basin outside the exclusive economic zones of foreign nations (Wensnahan Figure 1, page 122). Each cruise tended to cross the Arctic Ocean once; some cruises being shorter, some considerably longer. Wensnahan Figure 2, page 123, shows four typical cruise tracks including some data from a Royal Navy cruise. There are many areas of interest to the science community that are not currently included in the release area and about which we know little. It is hoped that draft data in areas outside of the "Box" may also be released at some point in the future—perhaps as optimally interpolated winter and summer mean fields.

Distribution in time and space: The temporal distribution of the data is not uniform (Wensnahan Figure 3, page 123). There are years with no data and times of year with no data. Additionally, cruises covered different regions in different years. As a result, this is not a record from which one can construct, among other things, an annual map of ice thickness.

Data products: The original draft measurements were recorded approximately six times per second. The data are edited and processed to produce profiles of draft-versus-distance evenly spaced at 1-m intervals. Summary statistics are computed from the profiles for 10- to 50-km segments of the submarine track. Computed statistics include histograms of ice draft, with means, variance, etc.; spatial autocorrelation; keel spacings and depths; level ice segment lengths and slopes; lead spacings and widths; undeformed ice segment spacings; lengths; and mean drafts.

Availability: The draft data are available from NSIDC (http://nsidc.org/data/sea_ice.html). Much of the data can be downloaded directly (http://nsidc.org/data/g01360.html). Additional data are available as part of the Environmental Working Group Joint U.S.-Russian Arctic Sea Ice Atlas CD, which can be ordered from NSIDC (http://nsidc.org/data/g01962.html).

Processing

The raw data exist in two distinct formats: analog charts and, from 1976 on, digital recordings (DIPS). The analog charts (Wensnahan Figure 4, page 124) must be scanned and digitized; this is a major part of our current effort. Both the DIPS data and the digitized charts go through a sequence of steps to ensure data quality and accuracy. The original data are in most cases classified, and the final step in processing is for the U.S. Navy's Arctic Submarine Lab to clear the processed data for public release.

Scanning and digitizing analog charts.

Our current project involves digitizing more than 1,600 charts from early cruises. Each analog chart is about 75 feet long and represents about 16 hours of data.

Scanning: Each chart is fed through a wide-format form-feed scanner, producing a ~800-MB image. The image is then burned onto CDs by a robotic CD duplicator and printer. The entire process takes about 30 minutes per chart.

Digitizing: The scan is turned into a digital time sequence of drafts using custom-built image processing software. This involves a) rectifying the curvilinear chart, b) recognizing the data trace vs time marks and draft grid, and c) scaling the trace to draft versus time (Wensnahan Figure 4, page 124).

Because the chart speed is usually slow (1 in/min) the best temporal resolution that can be achieved from charts is usually about one data point per second.

Processing outline

Both the digital and scanned and digitized analog data undergo a number of steps before the data are ready for public release. These steps are:

1. Initial editing: Bad data are identified by thresholding, operator inspection, and comparison with the original analog chart.
2. Zero Offset: Open water is identified in the record and used to calibrate the drafts.
3. Segment the data: Incorporate navigation data and eliminate portions when the submarine was maneuvering (turning or changing depth).
4. Interpolate to 1m: Data are recorded initially as drafts vs time. Data are converted to draft vs distance (spatial profiles) at 1-meter intervals.
5. Compute Statistics: As outlined above.
6. Clear data for release: The final products must be reviewed and cleared for public release.

Data Quality

The ice draft is calculated using the two-way travel time from the sonar to the ice and back, and the depth of the sonar, as measured by a pressure sensor in the submarine.

Errors:

Errors arise from several sources:

- Sound speed: The sound speed profile between the sonar and the sea ice is not incorporated into the computation of draft. The profile in the Arctic Ocean is not highly variable (4700 to 4750 ft/s), but the error from this source can be on the order of a meter.
- Sonar depth: The measured depth of the sonar is subject to the variability of the surface atmospheric pressure and inaccuracy in the ship's pressure sensor. This error can also be about a meter.
- Adjustment of system to “0”: During operation, the ice draft recorder is manually set to read within the scale limits of the system. As such, open water often does not register as having a draft of 0 but some small positive value.
- In-water reflections: Returns may come from things other than the ic,e such as fish or air bubbles in the water column.
- System noise: Additional noise can be produced by electronic and acoustic interference.
- Beam width: The ice draft profile is smeared by the finite width of the sonar beam, which gives a return from the deepest ice within the beam.

Remedies: The first three errors are corrected by the identification of open water in the draft record, which allows the record to be properly calibrated to zero draft. In-water reflections and system noise are effectively dealt with by a combination of automated and human screening (see the previous section). The beam width error is depth dependent. To date, depth has not been reported or archived with the draft data.

Numbers: Overall, the relative error from ping to ping is estimated to be 0.3 m (McLaren et al. 1994); the overall accuracy of a 50-km mean draft is estimated to be 0.6 m by Wadhams (1990) and 0.15 m by McLaren et al. (1994).

Intercomparability: Finally, the comparability of analog chart and digitally recorded data is important to studies of long-term change in the ice cover, because data before 1976 were only recorded on paper charts, and after 1976 they were recorded digitally. This issue has not received much attention but is now under study.

Summary

This is a valuable dataset in the process of being constructed.

Processing involves converting some chart data to digital data, combining navigation data with draft data, interpolating to lat/long, declassification, and archiving.

Uncertainties in the data are thought to be in the range of 15 to 30 cm.

For the purpose of capturing all the variability in the arctic ice cover, these data are rather sparsely distributed in season, year, and space. They can, however, give us insights into interdecadal and regional changes that have occurred, providing us with information never before available.

Research Based on These Data

Draft data lend themselves to studies of many aspects of climatology, climate model comparisons and improvement, interannual and regional variability of the ice pack, and ice morphology. A growing body of literature exists based on the data. The following is a small sample.

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Abstracts prepared from NSIDC's Twenty-fifth Anniversary Session at the American Geophysical Union Fall Meeting, December 10-14, 2001

Elevation Changes of Some of Canada's Major Ice Caps

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In an effort to understand the current mass balance of the major Canadian ice caps, we conducted precise airborne laser surveys in spring of 1995 and 2000 using NASA's Airborne Topographic Mapper (ATM). The objective was to compare elevations in each year and determine the amount of thinning that occurred in the intervening five-year period. In general, most of the individual ice caps or groups of ice caps in a specific region exhibit an inverse relationship between elevation and thinning rate. The areas of lowest elevation showed the most thinning, while the higher portions of the ice caps appear to either be thinning less, or in some cases thickening. The same appears to be true for latitude, with the more southern ice caps showing greater thinning rates than the colder ones further north. Barnes Ice Cap on Baffin Island exhibited the most substantial thinning, at about 1 m/yr in its lower regions. Nearby Penny Ice Cap also thinned by about 0.5 m/yr at its lower elevations. In the more northern regions, while some thinning was observed, it was not quite as large in magnitude as that of Barnes and Penny ice caps. On nearly all of the ice caps there was slight thickening (less than 10 cm/yr) at the highest elevations. In general, the magnitude of the observed changes is consistent with what might be expected from recent temperature and precipitation anomalies in the region.

Climate Change, Degradation of Permafrost, and Hazards to Infrastructure in the Circumpolar Arctic

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Warming, thawing, and disappearance of permafrost have accelerated in recent decades, damaging engineered structures and raising public concerns. By the middle of the 21st century, anthropogenic climate change may cause 2^{o} to 3^{o} C warming of the frozen ground, 10- to 16-percent reduction of the total permafrost area, 30- to 50-percent deepening of the active-layer thickness, and shifts between the permafrost zones due to cumulative effect of changing surface temperature, soil moisture, and vegetation. Such changes will have important implications for northern engineering and infrastructure built upon permafrost. The foundations supporting engineered structures are designed for constant climatic conditions with a construction-specific safety factor, which in the practice of cold-region engineering varies typically from 5 to 60 pecent with respect to the bearing capacity. In the zone of discontinuous permafrost. a 2.0^{o} C rise in air temperature may decrease the bearing capacity of frozen ground under buildings by more than half. This may have important consequences for the infrastructure, and particularly for residential buildings constructed in the permafrost zone between 1950 and 1990 in the northern Russian cities of Vorkuta, Yakytsk, Norylsk, and Magadan. Many of them are already weakened or damaged, which may in part be attributed to the effect of climate change. Susceptibility of permafrost to environmental hazards associated with thermokarst, ground settlement, and other destructive

cryogenic processes may be crudely evaluated using the geocryological hazard index, which is the combination of the predicted for the future climate relative change in the active-layer thickness and the ground ice content. Predictive maps constructed for scenarios of climate change indicated that several population centers (Barrow, Inuvik), river terminals on the arctic coast of Russia (Salekhard, Igarka, Dudinka, Tiksi), and gas production complexes with associated infrastructure in northwest Siberia fall in the high-risk category with respect to potential environmental hazards associated with degradation of permafrost.

On the Relationship Between Atmospheric Circulation and the Cosmonaut Sea Polynya

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The Cosmonaut Sea of Antarctica contains an annually recurring polynya characterized by a succession of open and closed phases generally occurring between July and October (i.e., the austral winter months). In its open phase, reduced sea ice concentration of 30- to 40-percent ice cover is evident relative to the 80- to 90-percent cover in the surrounding pack ice. The Cosmonaut Sea has been theorized to be a "sensible heat polynya" in which oceanic upwelling is responsible for formation and maintenance. However, recent modeling work by Bailey (2000) shows that, once a threshold oceanic heat flux is prescribed, the opening and closing of the polynya (i.e., ice divergence) is correlated with low-level atmospheric divergence. In this study, we explore this hypothesis using satellite-derived observations of sea ice cover and ice motion (derived from SSM/I), surface temperature (from AVHRR), and ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis fields (sea level pressure, geopotential, and wind motion). These data are analyzed to identify relationships between atmospheric and ice/ocean surface characteristics in the Cosmonaut Sea region. In particular, a survey of the frequency and strength of the passage of low pressure systems over the region and their relation to the polynya's existence is also investigated.

On the Relationship Between Enhanced Flow in an Ice Sheet and Basal Topography

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Modeling studies suggest that it is possible to explain the existence of areas of enhanced flow through an increase in ice thickness, which induces enhanced internal deformation, without the need for invoking basal sliding in the model. Improvements in the accuracy and coverage of ice thickness and surface elevation data for the Greenland and Antarctic ice sheets have recently been published allowing this hypothesis to be examined using observational data. These new data sets have been used to investigate the relationship between basal topography and the onset of enhanced and/or streaming flow. Balance velocities for Greenland and Antarctica have been calculated using the latest accumulation and ice thickness data and are used as a proxy for the dynamic regime of the ice mass. Onset areas were identified using a threshold for the acceleration of flow. These areas were mapped in relation to basal topography and, in particular, the location of bedrock depressions. Preliminary results indicate that a complex relationship exists and that bedrock depressions are not a necessary condition for the existence of areas of enhanced flow, although they appear to be associated with the majority of distinct onset areas. A thermal mechanism for a change in flow regime appears to be unlikely for those onset areas not associated with deeper, thicker ice. In Greenland, the northeast ice stream, which constitutes the only spatially extensive feature exhibiting enhanced flow, is clearly linked to a narrow, deep bedrock depression that extends as far as the upstream limit of the feature, close to the ice divide. The ice stream can be reproduced, within a model, based on a mechanism of enhanced internal deformation (due to the deeper ice within the bedrock depression) without the need for invoking basal sliding along its entire length.

Initiation of Snow Melt on the North Slope of Alaska as Observed with Spaceborne Passive Microwave Data

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The initiation of snow cover melt is a significant event of the Arctic annual cycle marking the return of air temperatures from sub-freezing to near and above 0^oC. Snowmelt initiation occurs at the very beginning of the melt season shortly after maximum daily air temperatures begin to rise above 0^oC and the first free water appears in the snowpack. Spatial and temporal patterns of snow melt initiation provide useful information regarding local and regional climate characteristics. We have developed a snow melt initiation (SMI) algorithm based on the diurnal difference of brightness temperatures (TBDD) observed in the SSM/I 19-GHz, horizontally-polarized channel. The NOAA/NASA Pathfinder Program Special Sensor Microwave/Imager (SSM/I) Level 3 Equal Area Scalable Earth-Grid (EASE-Grid) Brightness Temperatures (Northern Hemisphere projection) dataset, which is produced by the National Snow and Ice Data Center, was used in the analysis. The SMI algorithm uses a dynamic threshold technique applied to the EASE-Grid brightness temperatures and was applied to the North Slope area of Alaska to evaluate spatial and temporal patterns of snow melt initiation. By using a dynamic threshold approach, geographic effects on snowpack characteristics that influence brightness temperatures can be minimized (eg. grain size and internal layers); thus allowing for comparison of melt initiation days over large areas. The spatial patterns evident in the melt initiation days calculated by this method show excellent correspondence with National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) meteorological reanalysis data. Observed variations in TBDD values between climatologic zones are consistent with diurnal differences in mesoscale seasonal air temperature patterns.

Mass Balance and Area Changes of Four High Arctic Plateau Ice Caps, 1959 - 2001

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Small, stagnant ice caps without appreciable iceflow are particularly sensitive to climatic fluctuations, especially with regard to variations in ablation-season temperature. In a general sense, the areal extent of a stagnant ice cap is strongly related to its annual mass balance. Here we report the initial results of recent mass balance and area measurements of four small, thin plateau ice caps located on the Hazen Plateau, Ellesmere Island, Canada, and compare these measurements with topographic maps and aerial photography from 1959. Most of the plateau is currently unglacierized and the ice caps persist today at approximately the same elevation as adjacent ice-free areas, indicating that the plateau surface is close to the local equilibrium line altitude. Small changes in climate may therefore lead to profound changes in the extent of snow and ice cover on the Hazen Plateau.

Murray Ice Cap has experienced negative mass balance for at least the past three years (1999-2001), with net balance (b_n) ranging from -0.19 to -0.7 m (1999), -0.12 to -0.87 m (2000), and -0.22 to -0.96 m water equivalent (2001). The mass balance of nearby Simmons Ice Cap was also negative in 2000 (b_n = -0.15 to -0.72 m w.e.) and 2001 (b_n = -0.37 to -0.7 m w.e.). The St.Patrick Bay ice caps have experienced overall negative mass

balance since 1972. All four ice caps showed considerable marginal recession and resulting area reduction between 30 and 47 percent since 1959.

Overall, the Hazen Plateau ice caps experienced considerable mass loss since 1959, except for a period of net accumulation and lateral growth in the mid-1960s to mid-1970s. The available long-term records show that glaciers in the Canadian Arctic have experienced an overall negative mass balance over the last approximately 30 years, with a turn towards more negative values during the 1990's. We hypothesize that the sensitivity of the Hazen Plateau ice caps to changes in climate is enhanced by (1) the low amounts of winter snow accumulation, (2) the absence of iceflow, and (3) the small vertical relief. The regional ELA appears to have risen, on average, above the summits of the ice caps, indicating that they are remnants of former climatic conditions and out of equilibrium with modern climate. If current climatic conditions persist, the ice caps are likely to disappear within the next 30-50 years. Further investigations into the relationship between snow and ice extent on the Hazen Plateau and climatic variability are currently underway. See Braun Figure 1, page 125.

The Advanced Microwave Scanning Radiometer-Earth Observing System Data Products from the Aqua Mission

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The Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) is scheduled to launch on NASA's Aqua Satellite in early 2002. The Aqua mission is an important part of the NASA Earth Science Enterprise (ESE). The Aqua mission provides a multi-disciplinary study of the Earth's atmospheric, oceanic, cryospheric, and land processes and their relationship to global change. With six instruments aboard, the Aqua satellite will travel in a polar, sun-synchronous orbit. The AMSR-E will measure passive microwave radiation, allowing for derivation of many geophysical parameters, including cloud properties, radiative energy flux, precipitation, land surface wetness, sea surface temperatures, sea ice, snow cover, and sea surface wind fields. The AMSR-E has much greater spatial resolution than previous passive microwave radiometers; approximately double the spatial resolution of the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I). Further, the AMSR-E combines in one sensor all the channels that SMMR and SSM/I had individually. The AMSR-E has the following frequencies (in GHz): 6.9, 10.7, 18.7, 23.8, 36.5, and 89. The level 1A data product will contain chronological antenna temperature count data. The level 2A data product will contain spatially-resampled brightness temperatures (in global swath format) at resolutions of 56, 38, 21, 12 and 5.4 km. Level 2B data will include ocean, soil moisture, and rain products. Level 3 data will include gridded ocean, soil moisture, and rain products; gridded snow water equivalent products; gridded brightness temperatures; and gridded sea ice concentration and snow depth products. The National Space Agency of Japan (NASDA) will process level 0 data to level 1A data. The AMSR-E Science Investigator-led Processing System (SIPS) will process the level 1A data product to level 2 and 3 data products. The National Snow and Ice Data Center (NSIDC) will archive and distribute all AMSR-E products, including Levels 0, 1A, 2, and 3 data. This presentation describes the AMSR-E data products and compares the AMSR-E sensor specifications with those of SMMR and SSM/I.

Recent Climate Variability in the Canadian Arctic: Implications for Ice Caps

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The climate of the Canadian Arctic determines response in ice cap and glacier mass balance. Our ability to predict changes in mass balance depends on understanding the relationship between climate variability and ice caps. This paper investigates climate variability in the Canadian Arctic, established by analyzing temperature records from a 1977-1999 World Meteorological Organization (WMO) coastal weather station dataset, the NCEP-NCAR Reanalysis temperature dataset, and 1948-2000 precipitation records from the Meteorological Service of Canada. Temperature analyses are extrapolated from coastal weather stations to ice cap elevations by comparing the WMO temperature dataset to the NCEP-NCAR Reanalysis at 1000 hPa and then calculating environmental lapse rates based on NCEP-NCAR Reanalysis temperature values at 850, 700, and 500 hPa. Temperature and precipitation anomalies from 1995-1999 are discussed in detail to provide explanations for ice cap elevation changes measured by the Arctic Ice Mapping (AIM) laser altimetry/GPS measurements of 1995 and 2000.

A Practical Method for Long-Range Forecasting of Sea Ice Conditions in the Beaufort Sea

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An alarming feature noted in many climate models is the rapid and pronounced loss of Arctic sea ice due to poleward amplification of warming. Within the Beaufort Sea, changes in summer ice conditions are a particular concern because they affect the subsistence lifestyle of Alaskan North Slope residents (by altering wildlife habitats) and the fossil fuel industry (through altering the duration of the summer shipping season). An objective prediction of summer ice conditions months in advance therefore could assist residents and industries along the Alaskan North Slope react to potential changes in ice conditions. Utilizing monthly averaged low-frequency atmospheric teleconnection indices and multiyear sea ice concentrations, a statistical forecasting system is developed to predict ice severity monthly in the Beaufort Sea, from October of the preceding year through to June of the prediction year. Variations in the October predictors explain 68 percent of the variability in ice severity of the next year, and the proportion of variance explained increases to 93 percent using June predictors. Generally, light (heavy) ice years are related to reduced (increased) total ice extent and multiyear ice concentrations, and low frequency teleconnection patterns that increase (decrease) offshore wind flow. Temperature variations exert little influence over ice conditions.

Spatial and Temporal Variability of Arctic Summer Sea-Ice Albedo and its Dependence on Meltwater Hydraulics

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Next to ice extent and thickness, the area-averaged albedo of the summer sea-ice cover is a key parameter in determining the large-scale heat exchange over the Arctic Ocean. Various remote sensing applications have yielded a substantial database for the former two parameters, not least due to the efforts of the National Snow

and Ice Data Center (NSIDC) over the past 25 years. In contrast, the spatial and temporal variability of Arctic summer sea-ice albedo is much less well described. Despite its importance (including for ice-albedo feedback processes), few if any large-scale sea-ice and global circulation models actually predict summer ice based on the underlying physical processes. Most models employ simple parameterization schemes instead. Remote sensing of surface ice albedo also faces substantial challenges, some of which still need to be addressed in more detail.

Here, we report on albedo measurements completed over first- and multi-year sea ice in the summers of 1998, 2000, and 2001 in North America at the SHEBA (Surface Heat Budget of the Arctic Ocean) drifting ice camp and in fast ice near Barrow, Alaska. As has been established in a number of studies, spatial and temporal variability in summer sea-ice albedo is mostly determined by the areal extent of meltwater ponding at the ice surface. Given the importance of this process, a comprehensive ice hydrological program (meltwater distribution, surface topography, meltwater flow and discharge, ice permeability) has been carried out in conjunction with the optical measurements (Eicken Figure 1, page 126). Measurements demonstrate that Arctic summer sea-ice albedo is critically dependent on the hydrology of surface melt ponds, as controlled by meltwater production rate, ice permeability, and topography. Both remarkable short-term variability (a reduction of albedo by 43 percent within two days) as well as the seasonal evolution of the pond fraction, and hence area-averaged albedo, are forced by changes in pond water level on the order of a few centimeters (Eicken Figure 1, page 126). While some of these forcing functions may be difficult or impossible to represent in large-scale models, simulations with a simple hydrological model capture the essential features and variability in pond fractions and depth, identifying a promising alternative path towards predicting rather than prescribing ice albedo in numerical simulations. This work also underscores the importance of interannual variability in ice albedo for the large-scale energy exchange over the Arctic Ocean.

Autonomous Measurements of Ice Mass Balance

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The Arctic sea ice cover is an integrator of the surface heat budget and of the ocean heat flux. Because of this, the mass balance of the ice cover is an important component of climate change studies. Autonomous mass balance stations are a means of routinely monitoring the ice mass balance over a wide area for durations as long as a few years. A combination of a datalogger, an Argos transmitter, and a vertical string of thermistors provides a time series of profiles of air, snow, ice, and ocean temperatures. Information on ice growth and decay, snow accumulation and ablation, and ocean heat flux can be determined from the temperature data. Acoustic rangefinders monitoring the position of the ice surface and bottom can be added to the system for more precise spatial and temporal resolution of ice growth and melt. Mass balance results from deployments in the Arctic and Antarctic are presented. A comparison of results from an autonomous station to observations from an extensive mass balance study indicates that point measurements from an autonomous station can be extrapolated to generate regional estimates of mass balance.

STAR-Light: Enabling a New Vision for Land Surface Hydrology in the Arctic

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STAR-Light, a 1.4-GHz radiometer for use on light aircraft, is an enabling instrument for monitoring thickness and water content of the active layer throughout the pan-Arctic. Our underlying vision is that the active layer can be modeled with a Soil-Vegetation-Atmosphere Transfer (SVAT) model that is forced by available data on weather and downwelling radiance. Through near-daily assimilation of satellite observations of microwave brightness at a frequency that is sensitive to liquid water in the upper few centimeters of soil, these SVAT models will maintain reliable spatial fields of the thickness and water content of the active layer.

Key elements for this vision are accurate SVAT models for Arctic terrains, an airborne radiometer for the extensive field observations necessary to calibrate these models, and a satellite radiometer to provide near-daily observations. SVAT/Radiobrightness models for Arctic tundra are in the early stages of development. The hydrology community has converged upon 1.4 GHz brightness as the most effective observation for sensing soil moisture, and the European Space Agency is in Phase B of developing a 1.4-GHz Soil Moisture Ocean

Salinity (SMOS) satellite sensor for launch later this decade. STAR-Light is an NSF-funded, airborne instrument for SVAT model calibration in the Arctic beginning in 2004. See England Figure 1, page 127.

Glacier Dynamics of Antarctic Ice Streams From Radarsat Interferometry

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Two mapping campaigns of the Antarctic Ice Sheet have been completed using the Radarsat-1 Synthetic Aperture Radar (SAR). The first Radarsat Antarctic Mapping Project (RAMP) acquired data over a 30-day period in the fall of 1997, providing a static “snapshot” of the entire ice sheet. Since Radarsat-1 has a 24-day orbit cycle, repeat-pass interferometric SAR (InSAR) data were also acquired for large portions of the ice sheet. The second mission, the Modified Antarctic Mapping Mission (MAMM) flew from September to November 2000, acquiring ascending and descending passes over three 24-day cycles producing six images for most areas north of about 80 degrees. This allows the measurement of two components of the surface velocity vector and the removal of topographical effects. The extensive InSAR data sets can be used to measure ice surface velocity, providing a view of ice sheet kinematics. We use the traditional InSAR “phase” technique as well as “speckle matching” to generate velocity maps and interpret glacier dynamics. These data sets are also used in comparison with crevasse locations, to estimate strain rates and the fracture toughness of ice.

Tides on Filchner-Ronne Ice Shelf from ERS Radar Altimetry

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We use harmonic analysis of eight years of ERS satellite radar altimeter (RA) data at orbital crossovers to retrieve complex amplitude (amplitude and phase) coefficients for several major tidal harmonics over the Filchner-Ronne Ice Shelf (FRIS), Antarctica. We describe a method for estimating the accuracy of this method, which ranges from approximately 2 to 8 cm per harmonic. A comparison between M_2 complex amplitude from a recent ocean model and from our ERS RA analyses identifies two regions of the FRIS where the RA data are inconsistent with the model. In both regions, the differences can be attributed to incorrect specification of the grounding line location in the model. Our study demonstrates the value of ERS RA data in Antarctic ice shelf tide modeling, and the potential for future altimeter satellites with high polar orbits to contribute to the definition of global tide height variations. See Fricker Figure 1, page 127.

Note: Fricker, Helen, "Tides on Filchner-Ronne Ice Shelf from ERS Radar Altimetry," Geophysical Research Letters, In Press, 2002.

Snow Cover in Canada: Data and Information for Understanding the Role of the Cryosphere in the Climate System

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Snow cover exhibits the largest spatial extent of any component of the cryosphere in Canada, and exerts a significant influence on climate and hydrology through modification of energy and moisture transfers and the storage of water. In addition, snow cover information (extent, depth, and water equivalent) is used in many applications such as numerical weather forecast modelling, water resource management, agriculture, construction, calculation of forest fire severit,y and validation of satellite algorithms and snow process models. Improved knowledge of the interactions and feedbacks of terrestrial snow and ice in the current climate system, in land surface processes, and in the hydrological cycle are required to address potential future changes in the cryosphere. A reliable database of snow cover information over a range of temporal and spatial scales is essential to achieve improved understanding of the changing nature of the cryosphere in Canada. Canada's snow cover observing system has undergone substantial changes over the last 30 years, making it a challenge to develop consistent spatial and temporal information. In-situ measurements of snow water equivalent (SWE) and snow depth have declined markedly with network rationalization and automation of observing systems. Changes in methods of observation, such as for winter precipitation, have produced new systematic errors and the need to develop new adjustment and analytical techniques. On the other hand, Canadian advances in satellite-based monitoring of snow cover, especially using passive microwave data, provide the capability to derive snow cover properties in varying landscapes, and to provide new insights into snow cover-atmosphere interactions. Merging of in-situ and satellite information has yielded new information on variability and change in continental snow cover since the early 1900s. A renewed interest in the cryosphere system in Canada has provided the impetus to rescue snow data and make it easily available to the community. Cryosphere networks have received new funding and there is a strategic enhancement to contribute to Global Climate Observing System (GCOS) requirements. Data and information will be more accessible to the scientific community and the public through the Cryosphere System in Canada (CRYSYS) and State of the Canadian Cryosphere Websites, and the Canadian Cryosphere Information Network. This paper provides an overview of the changes in the data available for monitoring and modelling snow cover in Canada. Topics addressed include the status of existing networks, an evaluation of remotely sensed products and their use, information on snow cover variability and change, access to snow cover information, and identification of outstanding issues and challenges in producing reliable snow cover information.

CRYSYS: Monitoring and Modelling the Cryospheric System in Canada

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CRYSYS (Cryosphere System in Canada) is a national collaborative research effort to improve the ability to observe, monitor, and model the cryosphere, and its processes and feedbacks in the climate system. The project is a Canadian contribution to NASA's Earth Observing System and will contribute to the World Climate Research Programme's (WCRP) new initiative on Climate and Cryosphere (CliC). Better observation, monitoring, and modelling is essential to understand cryosphere/climate interactions and cold climate processes. This paper provides examples of key developments from the CRYSYS investigation over the past five years that contribute to these objectives. These include: the merging of in-situ and satellite information on snow cover to document 20th-century snow cover variability over North America; the development of new approaches for mapping snow water equivalent (SWE) from passive and active microwave data for various landcover regions of Canada, including the boreal forest, and the use of the derived information in studying climate/cryosphere interactions and in application to flood forecasting and drought monitoring; the application of Radarsat SAR and passive microwave data for studying change in sea ice (e.g., motion, regional extent) and lake ice (e.g., freeze-up/break-up); the investigation of atmospheric circulation anomaly patterns associated with glacier mass balance conditions in the Canadian Arctic and Cordillera regions; development and validation of an improved 1-D thermodynamic sea ice and lake ice model; and, the integration of cryospheric information through the CRYSYS "State of the Canadian Cryosphere" Web site to allow the scientific community and the public to have access to current information on the cryosphere in Canada. CRYSYS is one of the first national efforts to study the cryosphere as an entity within the climate system and to assess whether it is an effective indicator of climate change.

Observations of the Energy and Mass Balance of Coastal Ice Covers in Northern Alaska - an Overview

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An ongoing program is being carried out at Barrow, Alaska, to obtain surface-based observations on the relative energy budgets and mass balance processes for the major surface types in the Arctic coastal zone. The major objectives of our program are to clarify the land-ice interactions in the Arctic coastal regions and compare the results with corresponding conditions in the central Arctic as documented during the SHEBA experiment. Measurements were initiated in November 1999 shortly after freezup of the sea ice and are ongoing at five locations: shorefast sea ice sites on the Chukchi and Beaufort Sea coasts, a coastal seawater

lagoon site, a freshwater lake site, and a tundra site. Observations at each site consist of spatial surveys at selected intervals adjusted throughout the year of total and spectral albedo, ice thickness, surface characteristics and physical properties, and snow properties and thickness distribution. Detailed vertical temperature profiles have been obtained in the ice and in the tundra using data buoys. An intensive period of observation has been carried out each year beginning in late May, just before the onset of melt, until shortly before breakup of the sea ice in early July, when changes in the physical and optical properties of the snow and ice vary most rapidly in response to surface melting, melt pond formation, and lead development. The ice-based sites were reestablished in the fall shortly after stabilization of the newly frozen sea ice cover. To determine the temporal variations in the size and spatial distribution of melt ponds and other surface types on a spatial scale on the order of 10 x 10 km, photographic images of the ice were made from a small aircraft, along with thermal infrared photometric scans to determine skin temperatures of the surface. Selected results of our major efforts to date are shown in the accompanying figures, Grenfell Figures 1, 2, and 3, page 128.

Full set of measurements have been made from November 1999 through June 2001 at five sites including two shorefast sea ice locations, a sea water lagoon, a fresh water lake, and an undulating tundra site. These sites were selected to encompass the wide range of conditions found in the Barrow area. The locations of the sites are indicated on the map (Grenfell Figure 1, page 128).

The Effect of Rheology on Simulated Sea Ice Drift and Deformation

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Observations of ice motion and deformation archived at the Snow and Ice Data center provide a unique data set to examine the effects of nonlinear sea ice models on sea ice drift and deformation. This investigation focuses on the effects of different nonlinear rheologies on simulated ice drift and, to a lesser degree, on ice deformation. For this purpose, a hierarchy of simulations with four different nonlinear rheologies are performed over the time period 1979-85 and compared to daily observed buoy drift. The four yield curves used are elliptical, sine lens, cavitating fluid, and a mohr coulomb rheology. In the first three rheologies a normal flow rule is used, whereas in the Mohr Coulomb case a non-normal flow rule is used with the shear stress dependent on compressive stress. Overall, the results indicate that the amount of allowable shear stress within a given rheology exerts significant control on simulated ice drift, with realistic ice drift requiring a moderate amount of shear stress. In the case of an elliptical rheology, it is found that a fixed pressure term results in excessive ice stoppage. This feature is substantially ameliorated by making the pressure term deformation dependent; a feature which also causes the rheology to be fully energy dissipative for all strain rates. In all rheologies with moderate shear stress, the simulated ice drift correlates extremely well with geostrophic wind, a fact that appears to arise from the high negative correlation of the large ice interaction force with the wind. For daily unsmoothed buoy and wind data, the observed ice drift is found to correlate better with simulated values than with the geostrophic wind. In the case of deformation, all the models with some type of nonlinear rheology show a predominantly diverging strain field in the central Arctic, in general agreement with observations, whereas free drift estimates show a dominantly converging flow. Differences between simulated drift and observations from moderate shear strength models were statistically small, except in the Fram Strait region where the mohr coulomb rheology with pressure-dependent shear stress was found to yield higher ice speeds and less ice stoppage in somewhat better agreement with observations.

Greenland Near Surface Temperature Model

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The climate of the Greenland ice sheet has become the focus of considerable attention in recent years due to suspected sensitivity to global climate change. The Greenland Climate Network (GC-Net) is a network of eighteen climate-monitoring stations distributed across Greenland to provide a long-term record for the assessment of Greenland's evolving climate. The objective of this analysis is to present a GIS-based model of near-surface monthly mean temperatures for the Greenland ice cap based on the temperature record produced by the GC-Net from January 1995 through July 2000. The confidence interval for the modeled temperature surface is of central importance to this analysis in order to compare the results with previous observations to assess climate change and variability. The two primary drivers for near-surface temperature variability in Greenland, measured at the monthly scale, are annual variability in the radiation budget due primarily to changing solar geometry, and location, primarily latitude and elevation. A simple linear model is proposed to predict monthly mean temperature of the form: Mean monthly temperature at month t = b0 + b1*Latitude + b2*Elevation + b3*X(t), where X(t) is a function of the month of the observation and is specified as X(t) = 30 sin (Pi(t-3)/8), when $2 < t < 11$ (March through October) and X(t) is 1, 2, 3, 4 if t is November, December, January, or February, respectively. The model described above was estimated from the GC-Net data set using standard Ordinary Least Squares (OLS) regression and a high-resolution DEM for Greenland. The model explains 89 percent of the wintertime variance in the monthly mean temperatures and 95 percent of the summertime variance. The 95-percent confidence interval for the model is 4.6^{o}C for March through October, and 4.9^{o}C otherwise. The results are discussed in detail for different seasons.

Investigating the SAR Ice Deformation Product in Validation of Sea Ice Rheology Models

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The use of highly non-linear ice rheologies is becoming popular for sea ice models in climate simulations and ice forecasting systems. Inter-comparison projects have shown the viscous-plastic rheology with elliptical yield curve [Hibler 1979] reproduces buoy drift velocities well in comparison with rheologies that neglect shear viscosity or viscosity non-linearity [Kreyscher et al. 2000]. Analysis of Synthetic Aperture Radar (SAR) derived ice motion shows ice deformation is characterized by thin failure zones, with localized increase in maximum shear strain [Personal Communication: Kwok]. We believe failure occurs along characteristic directions, which depend upon the local confinement ratio between principle stress components, boundary conditions, the shape of yield curve and flow rule relating stress to strain rate [Hibler and Schulson 2000]. Hence, it is expected SAR data will be useful in verifying how realistically different yield criteria reproduce ice deformation. This will lead to models with improved characterization of lead opening, ice growth, and ridge building.

We show it is possible to simulate fractures (failure zones) with an isotropic rheology and ice strength field that is not smoothly varying, if care is taken to ensure spurious fractures are not introduced through numerical error (such as non-convergence to the plastic solution or non-smooth wind fields). Direct comparisons are made between ice deformation from three rheological models, with elliptical, sine lens, and modified-coulombic [Hibler and Schulson 1997] yield curves. Fine resolution (5 km) simulations of the Beaufort Sea are compared to time coincident SAR data. Fracture length and orientation vary for different yield criterion; the modified-coulombic rheology giving more dense fracture patterns than the elliptical and sine-lens rheologies. It is investigated whether the SAR ice deformation product [Kwok et al. 1990] provides sufficient information to differentiate between these yield criteria. We find neither the sine-lens nor the ellipse give the dense fracture patterns apparent in the SAR data. The modified-coulombic rheology performs better, though fracture orientation is wider than found in the SAR data. Further model development is required before SAR data may be used effectively in rheology validation.

Controls on Surging in East Greenland Derived From a new Glacier Inventory

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This study provides new insights into controls on glacier surging. Glacier surging is often classified as a distinct type of bimodal flow behaviour. Yet, studies of surging show a spectrum in surge behaviour, where initiation and termination, as well velocity development and periodicity, can vary greatly from glacier to glacier. It is clearly possible that different classes of surge behaviour involve different controls on glacier flow. Environmental and glacial characteristics that distinguish surge-type from normal glaciers can serve as benchmark data to test surge theories and to identify boundary conditions for surging. Different regional glacier population analyses have revealed that surge potential is controlled by a combination of glacier geometry, local climate, thermal and substrate conditions. In this study we use the results of multivariate logit modelling of a surge cluster in central East Greenland and compare the controls on surging in this region to those found for other regions.

Central East Greenland is characterised by a variety of glacier types, such as small icecaps and valley glaciers, and large dissection glaciers draining local ice plateaux. Many of these are tidewater terminating, and former surges have caused extreme calving events. For the purpose of this research we constructed a glacier inventory for this region (Jiskoot Figure 1, page 63). For 259 local glaciers, of which 71 are of surge type, 24 glacial and environmental factors were analysed. These data were collected from remotely sensed images (SAR ERS 1/2 and Landsat 7), aerial photographs, and maps and assembled in a geographic information system (GIS). This provides a baseline digital glacier inventory for the local glaciers in East Greenland, which covers a total glaciated area of approximately 55000 km^2. Variables of interest are geologic controls (e.g., homogeneity and type of substrate), geometric controls (e.g., glacier type, shape, channel curvature, and complexity) and mass-balance-related properties. Three different models suggest that glaciers with a large complexity, low slope, and oriented in a broad arc from NE to S are most likely to be of surge type. Further, geologies younger than Precambrian, and relatively high equilibrium line altitudes (ELAs), appear conducive to surging. On the basis of these results and the surge dynamics in this region, we suggest a hydrologically controlled surge mechanism in central East Greenland.

Spatial and Temporal Hydrologic Data Sets for the Arctic

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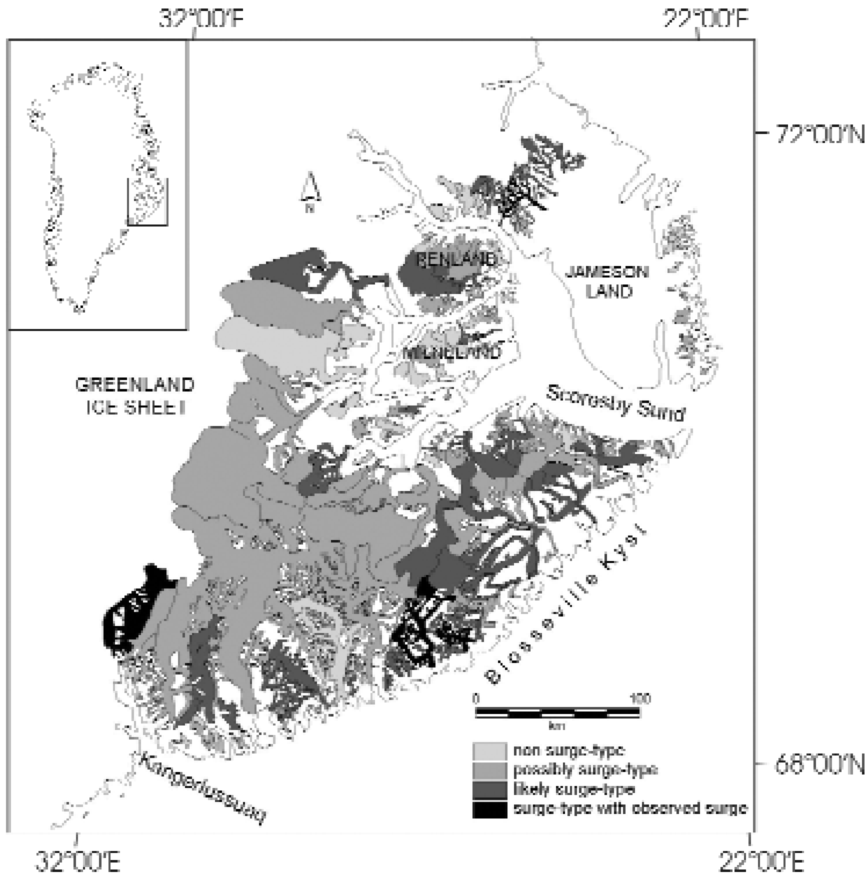
Little progress in our understanding of earth's surface processes will be made without continuous, high-quality spatial data. For improving our understanding of arctic hydrology, we need good quality meteorological, topographic, vegetation, soil, hydraulic, and thermal data – all spatially distributed. Most of these data sets are either non-existent or at coarse resolution on the order of 1 km. Almost all existing digital elevation data is of



Jiskoot Figure 1. Glacier inventory map of central East Greenland with general information and surge classification.

poor quality; this makes it very difficult to hydrologically model areas with low topographic gradients that exist extensively along northern coastal areas of North America, Europ, and Asia. Good temporal data are needed to quantify variability and trends; good quality spatial data are needed for interfacing hydrologic processes with other processes such as thermal, biologic, chemical, and geomorphic. Except for Russia, most of our arctic data is of short duration. Point data collected at hydrologic and meteorological stations were initially collected for addressing problems of water supply, hydropower, flooding, etc. Today we need even better quality data to assess man's impact on our climate and how these climate impacts cascade down through all of the other processes at the surface where we live. We understand the need to collect high-quality hydrological and meteorological data in the Arctic; unfortunately, there are very few sites where this is happening. Remote sensing is one tool that can help alleviate some of these problems; further sensor development is needed for better quality data acquisition and a broader range of capabilities. Also, more hydrologic observatories of a permanent nature need to be established and supported in the circumpolar Arctic.

An Evaluation of MODIS Snow Cover and Sea Ice Extent Products at the NSIDC DAAC

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With the launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA's Earth Observing System (EOS) Terra satellite, a new era of cryospheric monitoring from space began. For the first time, daily global maps of snow cover and sea ice extent are being produced in a fully automated fashion from space-borne measurements in optical wavelengths. The capabilities and limitations of the MODIS instrument for measuring snow cover and sea ice extent will be highlighted in several case studies in which the MODIS products are compared with other available operational analyses based on both optical and passive microwave measurements. The 1-km-resolution MODIS sea ice product, as determined from both solar reflective and terrestrial emissive bands, will be compared to sea ice concentration based on passive microwave measurements. The 500-m MODIS snow cover product will be compared both to analyses based exclusively on passive microwave as well as to NOAA operational analyses based on multiple satellite sensors.

The new 3D Austrian Glacier Inventory: Volume, Area, Altitude

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Of the 925 Austrian glaciers inventoried in 1969, many have disappeared since. A new, three-dimensional inventory is being elaborated based on aerial photographs of 1996 to 99 and on continuing radio-echo soundings of ice thickness. The 1969 inventory is being reprocessed with up-to-date techniques aiming at an accuracy of surface elevation of 0.7 m. Ortho-photo maps at a scale of 1:10,000, and digital elevation models with a 30-m grid, are being produced of all glaciers in the new inventory and of the majority of glaciers in the old inventory. Maps of surface-elevation changes capture the remnants of the positive balances that prevailed up to 1982 on the tongues of some glaciers, while most of them display sinking of the surfaces of the firn basins. Ice thickness was determined by surface-based radio-echo sounding for a limited number of glaciers comprising representative specimens of plateau, valley, and cirque glaciers. Total volume will be determined from area-volume scaling; preliminary results giving a relatively high power of 1.45. Maximum depth was 275 m on a glacier of 18 km^2 surface area. Test glaciers show good agreement of 30-year volume changes with simultaneous direct mass balance determinations, approaching 1-m water equivalent losses throughout the past decade. Models of energy fluxes, mass balance and ice dynamics are applied in order to understand the climatic forcing of the 1969 to 99 changes of the glacier surfaces.

Comparison of Sea Ice Concentration Derived from Small-Scale Ice Motion and Interpretation of Spaceborne Passive Microwave Radiometry

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Openings in the Arctic Ocean sea ice cover can be derived from the fine-scale sea ice motion fields derived

from time-sequential synthetic aperture radar (SAR) imagery. These fine-scale ice motion fields are available as routine products from the RADARSAT Geophysical Processor System (RGPS). Ice concentration over an enclosed area can be directly calculated as the ratio of the difference between that area and the integrated openings within, and the total enclosed area. We compare the ice concentration obtained in this manner with that derived from spaceborne passive microwave observations. Preliminary results indicate that, due to the footprint of the Special Sensor Microwave/Imager (SSM/I), current retrieval algorithms are relatively insensitive to small areas of open water. In the winter central sea-ice pack, where most of the openings are localized along long, linear lead patterns, lead areas are substantially smaller than the sensor footprint, thus resulting in over-estimates of the ice concentration. In certain areas, however, anomalous and persistent areas of lower ice concentrations can be found in the SSM/I retrievals that would tend to have an opposite effect on the concentration estimate. These seem to be due to weather or surface effects but the causes are not well understood. Here, we highlight the results from our preliminary comparison and emphasize the availability and importance of the RGPS dataset for validation of the retrieval algorithms for lower-resolution sensors.

Post-Processing of Bi-directional Reflectance Distribution Function Measurements of Summer Sea ice in the Southern Ocean

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Surface spectral bi-directional reflectance distribution function (BRDF) is a fundamental surface property in radiation interaction with the atmosphere-earth surface system. However, spectral BRDF values directly measured in the field, even under clear skies, are often not BRDF in the true sense. They are actually directional spectral reflectance measurements under given surface and sky conditions. Several factors can cause substantial departure of the direct measurements from the true BRDF values. Measurements made through scanning through the surface at various viewing zenith and azimuth angles on a tripod are impacted by errors caused by spatial variation of surface reflectance because the sensor does not view the same portion of the surface during the scanning. The measurement can be also biased if the actual spectral reflectance (or albedo) values of a reference Lambertian panel differ from their nominal values due to tarnish of the panel. Finally, strong diffuse sky radiation in the UV, violet, and blue wavelengths makes the beam assumption in the BRDF measurement a poor approximation. To reduce the errors caused by those factors, post-processing is conducted for the summer sea ice BRDF measured during our Southern Ocean cruises in 2000 and 2001. The post-processing includes three steps: smoothing raw data, calibrating spectral albedo of the reference panel, and removing the impact of diffuse radiation. Smoothing directional spectral reflectance by averaging measurements made at adjacent viewing zenith and azimuth angles can help reduce the error caused by surface heterogeneity. Based on the relationship between directional spectral reflectance and spectral albedo, the smoothed directional spectral reflectance values are integrated over the hemisphere and the results are compared with surface spectral albedo measurements. Because the spectral albedo values were derived in dependently from upward and downward spectral irradiance directly measured from a same flux sensor, they are not influenced by the possible errors of the spectral albedo values of the reference panel. As a matter of fact, the actual spectral albedo values of the reference panel are calibrated by comparison of the hemispherical integrals of the directional spectral reflectance values of the surface with the flux-derived spectral albedo values. The resulting spectral albedo values of the reference panel are used for further calibration of the directional spectral reflectance of the sea ice surface. Finally, the clear sky downward spectral irradiance measurements made without and with shading to the flux sensor are used to separate direct and diffuse spectral irradiance from the total spectral irradiance. The resulting proportions of diffuse radiation are combined with directional spectral reflectance measurements made under overcast conditions to remove the impact of diffuse radiation on BRDF. The resulting BRDF patterns are compared with direct measurements.

Numerical Simulation of Thermal Regime of Permafrost and Talik Formation Under Shallow Thaw Lakes in the Arctic and Subarctic

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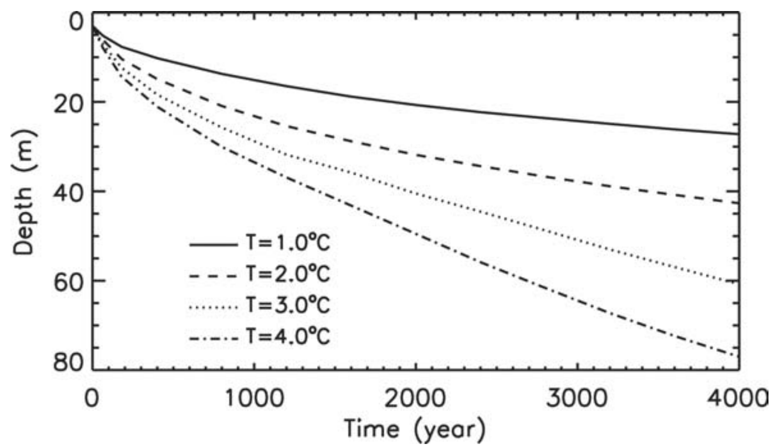
The extent of the role of thaw lakees in arctic climatic and hydrologic systems has not fully been investigated. This study assessed the long-term impacts of shallow thaw lakes in the Arctic and Sub-Arctic on the temperature field of permafrost and talik formation. A two-dimensional, physically based finite element model of heat transfer with phase change under a cylindrical coordinate system was developed to simulate the potential influence of shallow thaw lakes on the thermal regime of permafrost. The initial simulation assumes that permafrost thickness is 600 m, with a mean annual temperature at the permafrost surface of -9.0°C. A thaw lake was developed with a diameter of 800 m and lake water depths of 1.3 m, 2.0 m, 2.5 m, and 3.0 m. The long-term mean annual temperature at the lake bottom varied from -2.0°C to 4.0°C with an increment of 1.0°C, depending on lake water depth and lake ice thickness. Preliminary simulated results indicate that 4000 years after initiation of a shallow thaw lake over permafrost, talik thickness ranges from 27 m, 43 m, 60 m, to 77 m, with mean lake bottom temperatures of 1.0°C, 2.0°C, 3.0°C and 4.0°C, respectively. Talik cannot form under thaw lakes with a mean lake bottom temperature at or below 0.0°C, but permafrost temperature increases significantly. The rates of talik formation and permafrost temperature increase with time. Variation of mean lake bottom temperature, which is a product of changes in air temperature, snow thickness and properties, lake ice thickness, and lake water depth, has a significant influence on talik formation and permafrost thermal regime under thaw lakes.



Ling Figure 1. Variations of talik thickness over time under a thaw lake with depth of 3.0 m in the Alaskan Arctic (where T=1.0°C, 2.0°C, 3.0°C, and 4.0°C are the long-term mean annual lake bottom temperatures).

An End-to-End Description of the Data Flow of AMSR-E and GLAS Data Products: Product Generation Through Product Delivery to Users

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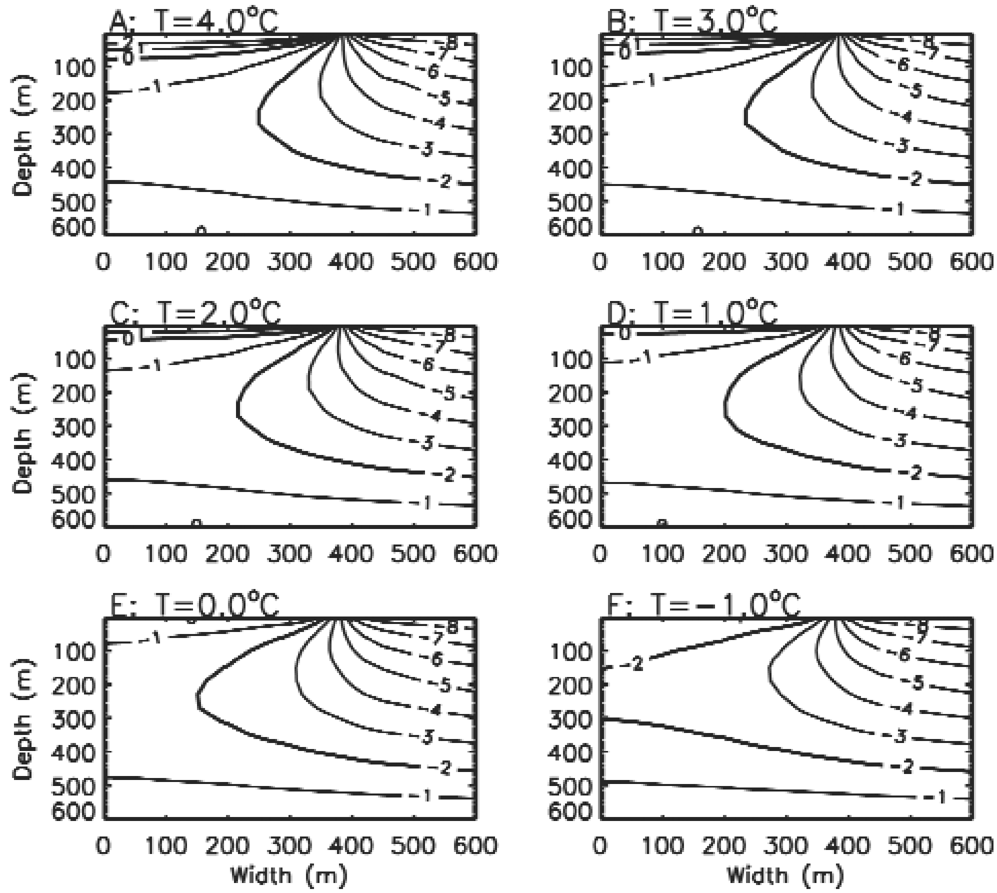
The Aqua and ICESat missions are components of the Earth Observing System (EOS). The Advanced Microwave Scanning Radiometer (AMSR-E) instrument will fly on the Aqua satellite planned for launch in Spring 2002. AMSR-E is a passive microwave instrument, modified from the AMSR instrument, which will be deployed on the Japanese Advanced Earth Observing Satellite-II (ADEOS-II). AMSR-E will observe the



Ling Figure 2. Simulated thermal regimes of permafrost after the presence of a thaw lake with depth of 3.0 m over permafrost for 4000 years in the Alaskan Arctic (where T=4.0^{o}C, 3.0^{o}C, 2.0^{o}C, 1.0^{o}C, 0.0^{o}C, and -1.0^{o}C are the lake bottom temperatures).

atmosphere, land, oceans, and cryosphere, yielding measurements of precipitation, cloud water, water vapor, surface wetness, sea surface temperatures, oceanic wind speed, sea ice concentrations, snow depth, and snow water content. The Geoscience Laser Altimeter System (GLAS) instrument will fly aboard the ICESat satellite scheduled for launch in Winter 2002. This instrument will measure ice-sheet topography and temporal changes in topography; cloud heights, planetary boundary heights and aerosol vertical structure; and land and water topography. The GLAS and AMSR-E teams have both chosen to utilize Science Investigator-led Processing Systems (SIPS) to process their respective EOS data products. The SIPS facilities are funded by the Earth Science Data and Information System (ESDIS) Project at NASA's Goddard Space Flight Center and operated under the direction of a science team leader. The SIPS capitalize upon the scientific expertise of the science teams and the distributed processing capabilities of their institutions. The SIPS are charged with routine production of their respective EOS data products for archival at a Distributed Active Archive Center (DAAC). The National Snow and Ice Data Center (NSIDC) DAAC in Boulder, Colorado, will archive all AMSR-E and GLAS data products. The NSIDC DAAC will distribute these data products to users throughout the world. The SIPS processing flows of both teams are rather complex. The AMSR-E SIPS is composed of three separate processing facilities (Japan, California, and Alabama). The ICESat SIPS is composed of one main processing center (Maryland) and an important secondary data set processing center (Texas) that generates required auxiliary data products. The EOSDIS Core System (ECS) has developed extensive protocols and procedures to ensure timeliness and completeness of delivery of the data from the SIPS to the DAACs. The NSIDC DAAC, in addition to being the repository of AMSR-E and GLAS data products, provides enhanced services, documentation, and guides for these data. NSIDC is a liaison between the science teams and the user community. This poster displays flow diagrams showing: a) the AMSR-E and the ICESat SIPS, and the process of how their Level 1, 2, and 3 data products are generated; b) the staging and delivery of these sets of data to the NSIDC DAAC for archival, and the ECS protocols required to ensure delivery; and c) the services and "value-added" products that the NSIDC DAAC provides to the user community in support of the Aqua (AMSR-E) and ICESat missions.

Glacier Land Ice Measurements from Space (GLIMS) and the GLIMS Information Management System at NSIDC

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GLIMS (Global Land Ice Measurements from Space) is an international project to survey a majority of the world's glaciers with the accuracy and precision needed to assess recent changes and determine trends in glacial environments. This will be accomplished by: comprehensive periodic satellite measurements, coordinated distribution of screened image data, analysis of images at worldwide Regional Centers, validation of analyses, and a publicly accessible database. The primary data source will be from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument aboard the EOS Terra spacecraft, and Landsat ETM+ (Enhanced Thematic Mapper Plus), currently in operation. Approximately 700 ASTER images have been acquired with GLIMS gain settings as of mid-2001. GLIMS is a collaborative effort with the United States Geological Survey (USGS), NASA, other U.S. Federal Agencies, and a group of internationally distributed glaciologists at Regional Centers of expertise. The National Snow and Ice Data Center (NSIDC) is developing the information management system for GLIMS. We will ingest and maintain GLIMS-analyzed glacier data from Regional Centers and provide access to the data via the World Wide Web. The GLIMS database will include measurements (over time) of glacier length, area, boundaries, topography, surface velocity vectors, and snowline elevation, derived primarily from remote sensing data. The GLIMS information management system at NSIDC will provide an easy-to-use and widely accessible service for the glaciological community and other users needing information about the world's glaciers. The structure of the international GLIMS consortium, status of database development, sample imagery and derived analyses, and user search and order interfaces will be demonstrated. More information on GLIMS is available at http://www.glims.org/.

Revisiting the Fast-ice Regimes of the Chukchi and Beaufort Seas 25 Years On

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Interest in the fast-ice regime of the Alaskan coast was prompted by the needs of coastal oil development, coincident with an increasing interest in the ice cover of the polar regions as a component of the climate system. While the latter led to the foundation of the NSIDC, Barry et al. (1979) focused on the former in a key study of fast-ice climatology and implications for offshore development. Twenty-five years on, offshore development has forged ahead with an increased economic commitment, while concerns are rising both locally and globally about the response of the coastal ice to recent climate trends.

The land-fast ice environment of arctic Alaska extends from the shoreline to the inshore boundary of the shear zone where it interacts with the drifting pack ice. Acting as an extension of the land, it is used as a habitat by some marine mammals and birds and for subsistence hunting activities by native peoples. It also serves to distance the coast from erosive forces of ocean and ice.

As a component of the ocean, however, it acts as a hindrance to navigation and as a mechanism to transmit stress over large distances, making it an essential consideration for shipping and offshore hydrocarbon exploration in the Arctic. Changes in the length of the fast-ice year would then seem to offer a variety of advantages and disadvantages for all concerned. Here we combine an analysis of Advanced Very High Resolution Radiometer (AVHRR) and ground-truth data for the years 1998-2001 in the vicinity of Barrow, Alaska. Although common anecdotal evidence suggests the ice-year is shortening, this study suggests that this not the case. Rather, the timing of events within the ice-year have changed.

Generally, the behavior of the fast-ice in these three ice-seasons agree with the broad descriptions given by Barry et al. in terms of freezing and break-up times and mean ice-thickness and extent. However, it is the less general, episodic events which may be more telling of regime changes, and are certainly of greater impact at a local scale for economic and subsistence activities in the Arctic.

The ice-season of 2000-2001 was characterized by mid-winter ice break-outs opening a lead at the beach near Barrow. In June 2001, the ice was pushed onshore over a length of at least 20 km during an ivu event. Based on aerial photography, ground observations, and side-looking radar we examine the extent and variability of the shove as well as large scaling forcing. This study highlights the importance of small-scale processes impacting local communities but forced by regional or hemispheric atmosphere-ice-ocean dynamics. See Mahoney Figure 1, page 129. Visit http://www.gi.alaska.edu/%7Emahoney/Poster.jpg for a JPEG version of this poster.

Geoscience Laser Altimeter System (GLAS) Data Products from NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) Mission

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The Geoscience Laser Altimeter System (GLAS) is the sole instrument being developed to fly on the Ice, Cloud, and Land Elevation Satellite (ICESat). The main objective of the GLAS mission is to provide accurate, high-resolution data that will contribute to our understanding of ice-sheet mass balance in the polar regions. The ICESat mission is an integral part of the NASA Earth Science Enterprise (ESE). The projected launch date for the GLAS instrument on the ICESat satellite is late 2002.

The ICESat mission has two sets of objectives. The primary objectives utilize altimetry to study the cryosphere. These goals are to provide accurate, high-resolution elevation measurements of the Greenland and Antarctic ice sheets. Time-series of elevation changes will enable determination of the present-day mass balance of the ice sheets and estimation of present and future contributions of the ice sheets to global sea level rise. These data will also increase our understanding of the way that changes in the ice sheets affect changes in polar climate, such as precipitation, temperature, and cloudiness.

The secondary objectives utilize Light Detection and Ranging [LIDAR] to study the atmosphere, and altimetry to study land and oceans. These goals are to measure cloud heights and the vertical structure of clouds and aerosols in the atmosphere; land topography and vegetation canopy heights; sea ice roughness and thickness; ocean surface elevations; and surface reflectivity.

The ICESat Science Investigator-led Processing System (I-SIPS), at Goddard Space Flight Center, will produce Level 1A, 1B, 2 and 3 products.

The National Snow and Ice Data Center (NSIDC) will archive and distribute all standard GLAS products.

The North Pole Environmental Observatory

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The Arctic environment is changing. The North Pole Environmental Observatory (NPEO) was established as a type of program of long-term observations required to understand Arctic change. The North Pole region was chosen because it is central to observed changes, there is a reasonable past history of measurements, and there is often a large gap there in the coverage of surface measurements. NPEO has three main components: (1) an automated drifting station composed of several buoys to measure atmospheric, upper ocean, and ice variables, (2) a sub-surface mooring at the Pole measuring ocean properties and ice draft, and (3) an airborne hydrographic survey that provides a snapshot spatial description of upper ocean properties. The first observatory was established at the Pole in April 2000 by aircraft flying out of Alert. The drifting station portion consisted of ocean ice and meteorological buoys. Over one year, the drifting station passed south through Fram Strait and stopped operating in the Greenland Sea. The airborne hydrographic survey made six stations between Alert, the Pole, and beyond. The sub-surface mooring was not deployed. In 2001, the drifting station was similar, but the operation was expanded to deploy a 4000-m mooring at the Pole. The mooring includes current meters, C-T sensors, Acoustic Doppler Current Profiler (ADCP), and an ice draft-profiling sonar. It will be recovered in 2002. The hydrographic survey covered a new line from the Pole to 85N, 170W. The 2000 hydrographic survey showed that the changes characterizing the Pole region in the 1990s persist, but with some deepening and some slight retreat toward climatology. The section from Alert shows that upper ocean conditions near the coast have become much like the Western Arctic, with low mixed-layer salinity and a secondary shallow temperature maximum. The observations indicate a general counterclockwise shift in water mass locations. Among other things, the NPEO 2000 drifting station data indicate the cold halocline is still thinner than climatology in the Eastern Arctic, and provide a detailed record of ice conditions over the course of the drift out of the basin. The NPEO 2001 hydrographic survey shows departures from climatology consistent with the 1990s, but with some differences. Conditions near the Pole appear to be more variable than previously thought. The 2001 drifting station has suffered heavy ice damage, but has successfully produced a unique record of solar radiation during the spring transition.

Ice Dynamics During Svalbard Surges Using Satellite Radar Interferometry

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Svalbard surges are known to be of long duration and relatively low speed compared to surges in other regions. We present results from dual azimuth satellite radar interferometry that reveal ice dynamics during the 1990s surges of two Svalbard glaciers: Monacobreen and Fridtjovbreen. Surge initiation and termination were progressive, with approximately linear acceleration and deceleration. Surge initiation was more rapid than termination, which occurred over 4+ years. At both glaciers, the velocity and strain rate increased by more than an order of magnitude during the surge and there was no indication at either of a surge front travelling downglacier. The spatial pattern of both velocity and strain rate was remarkably constant, and was probably controlled by bedrock features. From these results, and those published in the literature, we attempt to reconstruct a typical Svalbard surge cycle and compare this to published surge dynamics from other cluster regions, especially that of Variegated Glacier in Alaska. Surge dynamics at Svalbard glaciers are in marked contrast to the observed surge of Variegated Glacier, which started rapidly and terminated over a period of only a few days. At Variegated Glacier, the rapid velocity transitions are thought to result from switches in the basal hydrological system from a distributed high-pressure linked cavity system to a lower volume and pressure system of tunnels. We argue that the strong contrast in dynamics between Svalbard and Alaskan surges suggest that there are at least two markedly different types of glacier surges. We further suggest that it is very unlikely that the same surge mechanisms are involved. This result has implications for studies of populations of surge-type glaciers that attempt to disentangle surge controls, especially if both mechanisms operate in some surge clusters.

High-Resolution Airborne InSAR DEM of Bagley Ice Valley, South-central Alaska: Geodetic Validation with Airborne Laser Altimeter Data

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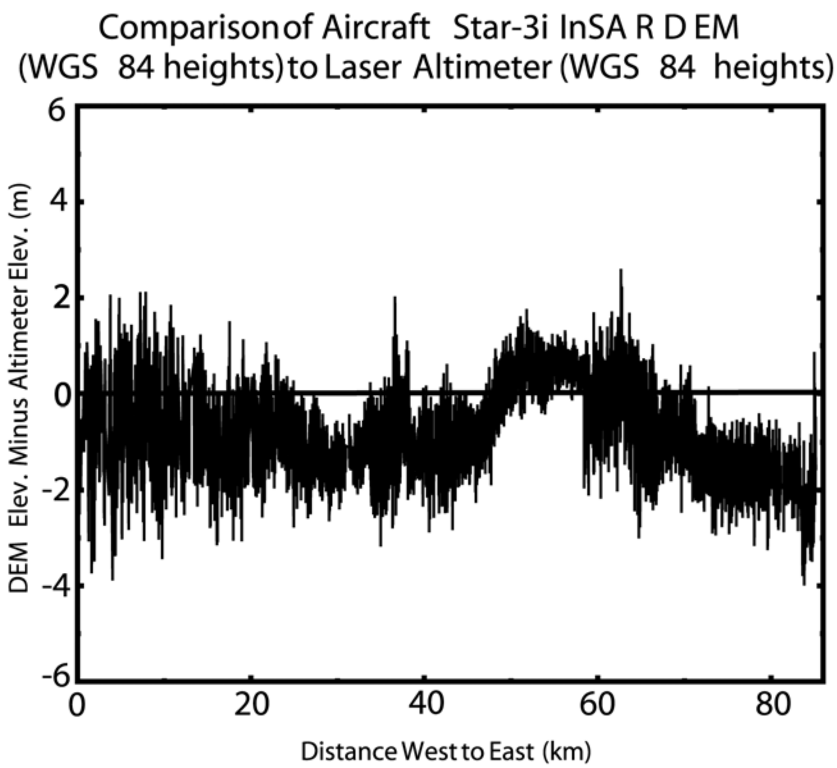
Bagley Ice Valley, in the St. Elias and Chugach Mountains of south-central Alaska, is an integral part of the largest connected glacierized terrain on the North American continent. From the flow divide between Mt. Logan and Mt. St. Elias, Bagley Ice Valley flows west-northwest for some 90 km down a slope of less than 1^{o}, at widths up to 15 km, to a saddle-gap where it turns south-west to become Bering Glacier. During 4-13 September 2000, an airborne survey of Bagley Ice Valley was performed by Intermap Technologies, Inc., using their Star-3i X-band SAR interferometer. The resulting digital elevation model (DEM) covers an area of 3243 km^2. The DEM elevations are orthometric heights, in meters above the EGM96 geoid. The horizontal locations of the 10-m postings are with respect to the WGS84 ellipsoid. On 26 August 2000, 9 to 18 days prior to the Intermap Star-3i survey, a small-aircraft laser altimeter profile was acquired along the central flow line for validation. The laser altimeter data consists of elevations above the WGS84 ellipsoid and orthometric heights above GEOID99-Alaska. Assessment of the accuracy of the Intermap Star-3i DEM was made by comparison of both the DEM orthometric heights and elevations above the WGS84 ellipsoid with the laser altimeter data. Comparison of the orthometric heights showed an average difference of 5.4 to 1.0 m (DEM surface higher). Comparison of elevations above the WGS84 ellipsoid showed an average difference of -0.77 to 0.93 m (DEM surface lower). This indicates that the X-band Star-3i interferometer was penetrating the glacier surface by an expected small amount. The WGS84 comparison is well within the 3-m RMS accuracy quoted for GT-3 DEM products. Snow accumulation may have occurred, however, on Bagley Ice Valley between 26 August and 4-13 September 2000. This will be estimated using a mass balance model and used to correct the altimeter-derived surface heights. The new DEM of Bagley Ice Valley will provide a reference surface of high accuracy for glaciological and geodetic research using ICEsat and small-aircraft laser altimeter profiling of this glaciologically important region of south-central Alaska. See Muskett Figure 1.



Muskett Figure 1. The datum(0) represents the altimeter elevations. The Star-3i DEM heights are lower, on average by -0.77 0.93 (standard deviation). This can probably be taken as an approximation of the X-band SAR penetration depth.

Mapping Snow Grain Size and Albedo on the Greenland Ice Sheet Using an Imaging Spectrometer

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The Hyperion sensor, onboard NASA's Earth Observing-1 (EO-1) satellite, is a hyperspectral imaging spectroradimeter with 220 spectral bands over the spectral range from 0.4-2.5 microns. Over the course of summer 2001, the instrument acquired numerous images over the Greenland ice sheet. Our main motivation is to develop a more accurate and robust approach for measuring the broadband albedo of snow from satellites. Satellite-derived estimates of broadband albedo have typically been plagued with three problems: errors resulting from inaccurate atmospheric correction, particularly in the visible wavelengths; errors from the conversion of reflectance to albedo (accounting for snow Bidirectional Reflectance Distribution Function [BRDF]); and errors resulting from regression-based approaches used to convert narrowband albedo to broadband albedo.

A hyperspectral method has been developed that substantially reduces these three main sources of error and produces highly accurate estimates of snow albedo. This technique uses hyperspectral data from 0.98-1.06 microns, spanning a spectral absorption feature centered at 1.03 microns. A key aspect of this work is that this spectral range is within an atmospheric transmission window, and reflectances are largely unaffected by atmospheric aerosols, water vapor, or ozone. It has been shown in previous work that the scaled area of that absorption feature is directly related to the optically-equivalent grain size. A discrete-ordinates radiative transfer model (DISORT) is used to create a lookup table that relates grain size to the scaled area. Scaled area is then computed for pixels in the Hyperion image and the lookup table is used to convert scaled area to grain size. This grain size estimate is then input into the radiative transfer model and used to compute spectral albedo at 3-nm resolution over the broadband spectrum. Thus, we obtain an estimate of albedo that is essentially free of errors due to atmospheric correction. We then weight the spectral albedo by the incoming solar irradiance at the surface and use direct integration to compute broadband albedo. In this way we avoid the three main pitfalls of estimating broadband albedo. Comparisons with concurrently collected in situ measurements at sites on the Greenland ice sheet indicate that the Hyperion-derived broadband albedo measurements are accurate to within less than one percent, a dramatic improvement from the usual five- to ten-percent accuracies that are reported for traditional albedo retrievals.

Regional-Scale Modeling of Soil Seasonal Freeze/Thaw Over the Arctic Drainage Basin

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Understanding the dynamics of seasonal freezing and thawing processes; seasonal and interannual variations in timing, duration, area extent, and thickness; and responses to climatic change are important aspects of predicting future changes in climate and the global environment.

Changes in active layer depth over permafrost during summer have direct impacts on soil water storage and river discharge through partitioning surface runoff. Since only the uppermost part of the soil is available for investigation by remote sensing techniques, and direct measurements are sparse, modeling is the only possibility to observe the thermal status of soil on a large scale.

A finite difference model for one-dimensional heat conduction with phase change is applied to investigate soil freezing and thawing processes over the Arctic drainage basin. Calculations are performed on the 25-km resolution EASE-Grid. Soil bulk density and the percentages of silt/clay and sand/gravel are from the SoilData System of the International Geosphere-Biosphere Programme. Soil moisture is kept constant for each layer over the domain. The model domain is divided into three layers with distinct thermal properties of frozen and thawed soil, respectively. Calculations are performed on 54 model nodes ranging from a thickness of 10 cm near the surface to 1 m at 15 m depth. Initial temperatures are chosen according to the pixel's permafrost classification in the Circumpolar Active-Layer Permafrost System (CAPS) on EASE-Grid. NCEP re-analyzed sigma-0.995 surface temperature with a topography correction, and SSM/I-derived weekly snow height, are used as forcing parameters. Using an annual cycle of snow density for different snow classes is important for the thermal conductivity of snow.

Active layer depths, simulated for the period September 1998 through December 2000, compare well to maximal thaw depths measured at Circumpolar Active Layer Monitoring project (CALM) field sites, although the horizontal scale of the model pixels is 4 to 5 magnitudes larger. This study shows for the first time the regionally highly variable active layer depth for the whole pan-Arctic land mass, ranging up to 200 cm in mid-latitude regions of isolated permafrost, and frozen ground depth of up to 250 cm in unfrozen northern areas of discontinuous permafrost. Soil freezing and thawing periods reveal large regional differences (see Oelke Figure 1 on page 129 for permafrost areas in 2000; seasonally-frozen ground is masked in black), as well as for the day when the maximum is reached. Sensitivity studies for changes in seasonally frozen and thawed depths with air temperature, physical and thermal properties, and soil moisture are also conducted over the entire Arctic drainage basin.

Permafrost Warming, Thawing and Impacts

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Global circulation models predict a warming of 2 to 5^{o}C for the next century in response to increases in greenhouse gas concentrations in the atmosphere. Permafrost in Northern Alaska warmed 2 to 4^{o}C over the last century and there was a concurrent warming of discontinuous permafrost at this time. Modeling indicates that continuous permafrost at Barrow generally cooled from 1950 until the latter 1970s and has generally warmed since then. Observations of permafrost temperatures north of the Brooks Range since 1983 indicate that the active layer and permafrost warmed about 2 to 3^{o}C at West Dock and Deadhorse from the mid-1980s to the present. There is widespread warming and thawing of discontinuous permafrost, and extensive areas of thermokarst terrain are now being created as a result of climatic change. Estimates of the magnitude of the warming at the discontinuous permafrost surface are 0.5 to 1.5^{o}C. Warming rates near the permafrost surface were 0.05 to 0.2^{o}C per year. In warm discontinuous permafrost, thermal offset allows mean annual temperatures at the permafrost surface to remain below 0^{o}C while ground surface temperatures are positive, up to 2.5^{o}C. Thawing permafrost and thermokarst have been observed at several sites in interior Alaska. Thawing rates at the permafrost table at two sites were about 0.1 m per year. Modeling at a site in discontinuous permafrost shows that the observed warming is part of a warming trend that began in the late 1960s and is correlated to changes in snow cover. Thermokarst drastically modifies and remolds the ground surface. This process can severely change or disrupt ecosystems, human activities, infrastructure, and the fluxes of energy, moisture and gases across the ground surface-air interface.

The Seasonal Evolution of Albedo in a Snow-Ice-Land-Ocean Environment

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As part of a program studying arctic coastal processes, we investigated the ice-albedo feedback in a land-ice-ocean regime near Barrow Alaska. For the past two years, from April through June, spectral and wavelength-integrated albedos were measured along 200-m survey lines. These lines were installed at four sites and included sea ice, lagoon ice, fresh ice, and tundra. Initially all sites were completely snow-covered and the albedo was high (0.8-0.9) and spatially uniform. As the melt season progressed, albedos decreased at all sites. The decrease was greatest and most rapid at the tundra site, where the albedo dropped from 0.8 to 0.15 in only two weeks. The spectral signature also changed as the wavelength of maximum albedo at the tundra site shifted from 500 nm for snow to 1100 nm for tundra. As the snow cover melted on undeformed first-year ice, there was rapid and extensive ponding resulting in a decrease of the spatially averaged, wavelength-integrated albedo from 0.6 to 0.2 in only five days. Extensive pond drainage and below-freezing temperatures caused the albedo to rebound briefly to 0.55 before resuming a steady decrease. Comparision of these results to data collected in the Central Arctic indicated that albedos of fast ice in the coastal regime decreased more rapidly than pack ice albedos.

Sea Ice Stress and Deformation During the SHEBA Field Experiment

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The Surface Heat Budget of the Arctic Ocean (SHEBA) project focuses on thermodynamic processes that govern the heat exchange between the atmosphere, sea ice cover, and ocean. A key element in this complex interaction is the thickness distribution of the ice cover, which can very widely in both space and time. Thermodynamic processes are an important component in determining the thickness distribution, since they control the growth and ablation of the ice cover. Equally important, however, is the role played by sea ice dynamics. Sea ice dynamics result in the formation of leads and ridges, which thin and thicken the ice cover, respectively. Because of its recognized importance in defining the thickness distribution of the sea ice cover, and, hence, the atmosphere-ice-ocean heat exchange system, measurements associated with sea ice dynamics were made during the SHEBA field experiment. These measurements included the internal ice stress and ice deformation. The internal ice stress was determined from instrumentation frozen directly into the ice cover. The ice deformation was determined by the Radarsat Geophysical Processor System, which tracks points on the ice in radar backscatter images. The objective of this presentation is to quantitatively consider the relationship between the measurements of ice deformation and internal ice stress. Specifically, we will consider the temporal correlations and the impact of the spatial resolution of the deformation parameters on this relationship. Ultimately, we intend to use the results of this work in the development and evaluation of high-resolution sea ice dynamics models.

On the Present-Day Mass Balance of the Antarctic Ice Sheet

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Using interferometric observations combined with other data, we estimate the grounding-line fluxes of 18 of the largest glaciers draining West and East Antarctica with a precision better than ever before. The results are compared to accumulation in the interior of the basins to determine the state of mass balance of the glaciers. The major results are as follows. 1) Areas identified in prior studies as exhibiting a large positive mass balance – due to an erroneous knowledge of the grounding line – are in fact close to mass balance, if not loosing mass. 2) Glaciers not draining East Antarctica into the Ross or Filchner/Ronne ice shelves are remarkably close to a state of mass balance. 3) West Antarctica glaciers are close to a state of mass balance except for the Pine Island/Thwaites/Dotson glaciers sector, which is significantly out of balance and thinning. 4) As the glaciers reach the ocean waters and become afloat, a large fraction of the ice is removed from the bottom, not from iceberg calving. This latter result emphasizes the fundamental importance of ice-ocean interactions in the overall mass balance of Antarctic ice and on the potential evolution of ice shelves and grounded ice in a warmer climate.

Acceleration of Pine Island Glacier Ice Shelf

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The Pine Island Glacier is one of the fastest ice streams in West Antarctica. It empties into a small ice shelf, bordering the Amundsen Sea, that is commonly considered part of this glacier system. Previous investigations of this glacier, based on Landsat images of the early to mid-1970s, estimated a velocity of 2.1-2.4 km/yr at the ice front. Recent studies have determined velocities on the order of 2.6-2.8 km/yr at the front. The discrepancy may be due to errors in positional control of the early Landsat images, or it may reflect a true acceleration. To determine whether the apparent velocity increase is real, we coregistered several sets of earlier images to a Landsat 7 Enhanced Thematic Mapper (ETM+) image of 2000. The sets include Landsat multispectral scanner (MSS) images of 1973 and 1975, European Remote Sensing (ERS) synthetic aperture radar (SAR) images of 1994 and 1996, and Landsat thematic mapper (TM) images of 1997 and 2000. Velocities were obtained by feature tracking and were restricted to the floating, ice-shelf part of the glacier. Velocities for the interval 1973 to 1975 ranged from 2.21-2.37 km/yr. For the same area, velocities for 1994 to 1996 ranged from 2.46-2.81 km/yr, and for 1997 to 2000 from 2.54-2.84 km/yr. The spread in velocities for each image set is mostly due to slower moving ice near the margin. According to the above data, in the central fast part, the ice shelf accelerated by more than 400 m/yr between about 1974 and 1995. The acceleration between about 1995 and 1999 is only around 50 m/yr. The total acceleration between about 1974 and 1999 is nearly 500 m/yr. These data indicate the majority of the acceleration took place before the mid-1990s, and it has decreased somewhat since then. However, whether the increase in velocity occurred mostly in the 1970s or was more evenly distributed over the mid-1970 to mid-1990 period can only be determined with intervening data. Rignot and others (in press) noted an acceleration of the Pine Island Glacier between 1992 and 2000 using ERS images; they suggest an increase in basal lubrication as a probable cause. A large calving event in the early 1970s may have contributed to the acceleration within the ice-shelf part, especially if the pre-calving ice shelf was pinned. Overall, our data support a general increase in velocity.

Antarctic Photoclinometry using AVHRR and MODIS

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We use a combination of satellite image data and existing Digital Elevation Models (DEMs) to provide greater detail in elevation mapping of the Antarctic ice sheet. The technique relies on calibration of low-pass filtered, visible channel image data to low-resolution (5- to 50-km) slope information from an input DEM. We then apply the calibration function to unfiltered image data to derive a 2-km (AVHRR) or 500-m (MODIS) slope image of the ice sheet. We invert this slope data to elevation, but control the effect of image noise by constraining the resulting map to have a zero net difference to the input DEM at a scale of 50 km.

Two study areas are shown: the region around the Institute Ice Stream (81°S, 75°W) and the onset area of the Ross Embayment Ice Streams (82°S 130°W). The input DEMs for these two areas are derived from different sources; the first from satellite radar altimetry, and the second from airborne laser altimetry acquired under the Corridor Aerogeophysics Survey of the Eastern Ross Transition Zone (CASERTZ) program.

The figure is a subscene from the area we enhanced near the onset regions for the Ross ice streams. We present the enhanced DEM as a simulated three-dimensional perspective view. The region illustrated is a portion of the boundary between Whillans Ice Stream and Ice Stream C. This region has undergone dramatic recent changes in surface elevation as Whillans Ice Stream rapidly draws down its catchment, lowering the ice surface relative to Ice Stream C. The 'C0' feature, formerly a tributary to Ice Stream C, has now reversed slope and is flowing back towards Whillans Ice Stream. The improved DEM resolves the major features better, and provides quantitative elevation information at the stream boundaries and flowlines. See Scambos Figure 1, page 130.

Scientific Applications of Two U.S. Antarctic Program Projects at NSIDC

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The National Snow and Ice Data Center maintains two Antarctic science data management programs supporting both the efforts of Principal Investigators (PIs), and the science that is funded by the NSF Office of Polar Programs (OPP). These programs directly relate to the OPP "Guidelines and Award Conditions for Scientific Data," which identify the conditions for awards and the responsibilities of PIs regarding the archival of data, and submission of metadata, resulting from their NSF OPP grants. The U.S. Antarctic Data Coordination Center (USADCC) is funded by the NSF to assist PIs as they meet these requirements, and to provide a U.S. focal point for the Antarctic Master Directory, a Web-based searchable directory of Antarctic scientific data. The USADCC offers access to free, easy-to-use online tools that PIs can use to create the data descriptions that the NSF policy requires. We provide advice to PIs on how to meet the data policy requirements, and can answer specific questions on related issues. Scientists can access data set descriptions submitted to the Antarctic Master Directory, by thousands of scientists around the world, from the USADCC Web pages. The USADCC Web site is at http://nsidc.org/usadcc/. The Antarctic Glaciological Data Center (AGDC) is funded by the NSF to archive and distribute data collected by the NSF Antarctic Glaciology Program and related cryospheric investigations. The AGDC contains data sets collected by individual investigators on specific grants, and compiled products assembled from many different PI data sets, published literature, and other sources. Data sets are available electronically and include access to the data, plus useful documentation, citation information about the PI(s), locator maps, derived images, and references. The AGDC Web site is at http://nsidc.org/agdc/. The utility of both of these projects for scientists is illustrated by a typical user-driven case study to research, obtain, and use Antarctic data for a science application.

Rapid Glacier Thinning Along the Amundsen Coast, West Antarctica

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Together with the Pine Island glacier (PIG), the Thwaites (TG) and Smith (SG) glaciers are the principal drainage systems of the Amundsen Sea (AS) sector of the West Antarctic ice-sheet. We use satellite radar altimetry to show that a rapid thinning of ice has occurred along the AS coastline, and satellite radar interferometry (SRI) to show that the pattern of thinning was restricted to the fastest flowing sections of the outlet glaciers. Between 1991 and 2001, the TG and SG thinned by more than 25 and 45 m at their grounding lines, and a total of 157 cubic kilometres of ice was lost from the AS sector into the ocean. Using BEDMAP elevation data, we show that the thickness changes may have caused the PIG, TG, and SG to retreat inland by over 8, 4, and 7 km, respectively. This is in line with our, and other independent, estimates of grounding line retreat rates derived from SRI. If the glaciers continue to thin at the present rates they will become afloat within 150-1500 years.

Ice Sheet Temperature Records - Satellite and In Situ Data from Antarctica and Greenland

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Recently completed decadal-length surface temperature records from Antarctica and Greenland are aiding the study of climate change. Models have predicted that any climate warming may be amplified at high latitudes; documented thinning of the Greenland ice sheet margins and the breakup of Antarctic Peninsula ice shelves suggest this process may have begun. Confirmation of climate trends at interior ice sheet locations requires development of temperature baselines that subsequent data can be compared against.

Satellite data provide an excellent means of documenting climate parameters across both temporal and spatial domains. Infrared sensors can provide excellent temperature information, but cloud cover and calibration remain as problems. Passive-microwave sensors can obtain temperature estimates through clouds but also have calibration issues and a much lower spatial resolution. In situ observations from automatic weather stations (AWS) provide accurate surface data with high temporal resolution but are spatially restricted and may have long gaps due to equipment failure in the harsh environment. Combining information from all of these sources is now possible, and allows temperature baselines to be established with known reliability. All three sources are now available for most of the last two decades. Composite records can be used to test climate model output, to calibrate proxy temperature records from firn and ice core stable isotope (δD and $\delta^{18}O$) profiles, as well as constraining borehole thermometry. This presentation discusses these issues and elaborates on the development and limitations of composite temperature records from selected sites in Antarctica and Greenland.

The figure (Shuman Figure 1, page 130) illustrates the challenge of accurately determining the temperature history for an ice sheet location. Byrd Station, approximately 80^{o}S 120^{o}W in West Antarctica, has been the site of an AWS since February 1980, and it continues through the present day. The AWS temperature record (TA, in red) is interrupted by equipment problems in June 1992. The infrared record (TIR, in blue) is nearly continuous (1-4 day gaps exist but aren't shown) and clearly diverges from the in situ record from mid- May to early June. And finally, the passive microwave record (TC, in black) is continuous but doesn't record the high-frequency temperature variations obtained by the other types of data. Consequently, all three types of temperature information are beneficial to the development of a continuous record.

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The Radiation Paradox at Summit Camp, Greenland?

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Clouds play an enhanced role in governing surface radiation balances in the dry polar atmosphere, yet their frequency, thermodynamic properties, and radiative properties are poorly understood over Greenland. In the dry snow regions of Greenland, a net warming effect is expected from cloud cover – the effect known as the radiation paradox. This research investigates the occurrence of the radiation paradox at Summit Camp, Greenland, using data from two instruments that were installed during the summer 2001 field season. A whole sky imager captures a digital sky image, quantifying the cloud cover each minute. A ceilometer sounds the atmosphere with a laser pulse, monitoring cloud base height every 15 seconds. These high-frequency measurements, together with a sophisticated surface radiation data set, constitute a new means for evaluating the net effect of clouds on the surface radiation budget over snow and ice. The ceilometer serves as a useful guide for partitioning the effects of clouds at different heights above the surface. Results will be presented focusing on the diurnal variability of the radiation paradox and its relationship with cloud height.

Mapping and Monitoring Changes in the Antarctic Ice Sheet from Combined RADARSAT SAR and GEOSAT to ERS Radar Altimeter Data Analysis

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Although it is generally understood that the Antarctic Ice Sheet plays a critical role in the changing global system, there is to date still a lack of generally available information on the subject. Much of our knowledge depends on models, but realistic modeling requires observations. Satellite data are an important source of information. One of the challenges today is to develop geophysically meaningful processing software as fast as we can develop new hardware. We present maps based on two data types: Synthetic Aperture Radar (SAR) data from the Antarctic Phase of the Canadian RADARSAT, and radar altimeter (RA) data from GEOSAT and ERS-1. Radar altimeter data provide absolute elevation and continent-wide coverage to 81.5 degrees S, but have low spatial resolution. In SAR data, elevation is not measured, but the spatial resolution is much better. A solution lies in a combination of both data types. Co-referencing and geolocating of SAR and radar altimeter data is a nontrivial task, because of nonlinear distortion in the SAR data and a general lack of fix points in most areas of Antarctica. Rather than map the entire Antarctic continent in one sheet, data are processed in atlas style. For interpolation of RA data, specific geostatistical methods are applied. Improved kriging methods are developed that utilize local morphologic characteristics, which is particularly important for mapping regions along the Antarctic margin, as these are both topographically complex and play a key role in the study of ice-ocean fluxes and changes in the ice sheet. Applications are in monitoring changes in Antarctic glaciers, ice streams, and ice shelves, and in detailed regional studies of outlet glaciers of the inland ice that are particularly exciting. At this time, the Antarctic atlas contains a total of 136 maps, some of which will be presented, including a new RADARSAT/ERS map of the Lambert Glacier/Amery Ice Shelf System and part of its drainage area, and detailed maps of numerous glaciers. See Stosius Figure 1, page 81.

Comparison of Snow Albedo from MISR, MODIS and AVHRR with Ground-based Observations on the Greenland Ice Sheet

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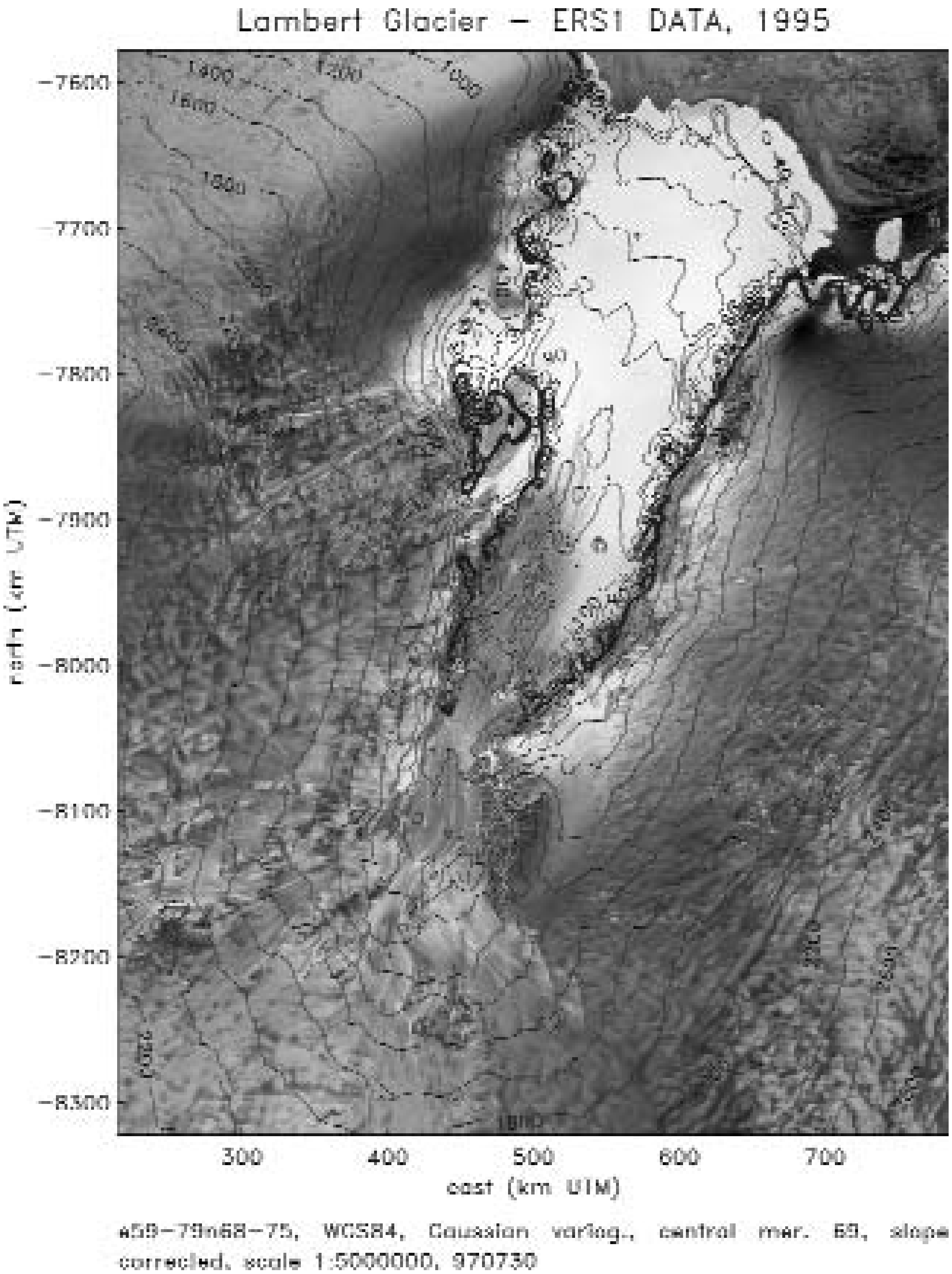
Surface albedo is an important climate parameter, as it controls the amount of solar radiation absorbed by the surface. For snow-covered surfaces, the albedo may be greater than 0.80, thereby allowing very little solar energy to be absorbed by the snowpack. As the snow ages and/or begins to melt, the albedo is reduced considerably, leading to enhanced absorption of solar radiation. Consequently, snow melt comprises an unstable, positive feedback component of the climate system, which amplifies small pertubations to that system. Satellite remote sensing offers a means for measuring and monitoring the surface albedo of snow-covered areas. This study evaluates snow surface albedo retrievals from MISR, MODIS, and AVHRR through comparisons with surface albedo measurements obtained in Greenland. Data from automatic weather stations, in addition to other in situ data collected during 2000, provide the ground-based measurements with which to compare coincident clear-sky satellite albedo retrievals. In general, agreements are good with the satellite data. However, satellite calibration and difficulties accurately representing the angular signature of the snow surface make it difficult to reach an albedo accuracy within 0.05.



Stosius Figure 1. ERS1 image of the Lambert Glacier.

Where has the ice Gone? Rapid Thinning of Arctic Sea Ice in the Western Arctic Ocean

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Examination of springtime ice drafts obtained from submarine profiles in a narrow band of the western Arctic Ocean from offshore Alaska to 89∞N indicates that the mean ice draft decreased 1.5 m between the mid-1980s and early 1990s. No similar trend was evident in ice drafts located near the North Pole. The 1980s drafts were composed largely of ice exceeding 3.5 m, while the early 1990s drafts contained more ice in thinner categories. The differences in drafts between the two periods appear to be related largely to ice dynamics effects associated with the presence and strength of the Beaufort Gyre, which weakened considerably in the early 1990s. The strength of the Arctic anticyclone, which dominates the Beaufort Gyre ice circulation and influences the ice thickness, is reflected in the indices of the Arctic Oscillation and North Atlantic Oscillation.

NSIDC at the Millenium

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Over the past 25 years the National Snow and Ice Data Center (NSIDC) has played a proactive role in cryospheric data management. Three themes illustrate the advances that have been made. (1) Delivery of integrated data products. NSIDC has developed stand-alone, packaged integrative products, frequently published on CD-ROMs or on the Internet. Examples include the first global assembly of data and information on frozen ground and permafrost; passive microwave gridded time series products from the ESMR, SMMR, SSMI sensors; and collaborative development and distribution of the Environmental Atlases for arctic meteorology, oceanography, and sea ice. The Arctic System Science Data Coordination Center (ADCC) at NSIDC archives and distributes data via our Web site. These data sets are based on research under programs such as Land Atmosphere Ice Interactions (LAII), Ocean Atmosphere Ice Interactions (OAII), including the Surface Heat Budget of the Arctic (SHEBA), and Paleoenvironmental Arctic Science (PARCS), and related reconnaissance satellite imagery. R-ArcticNet: a Regional Hydrographic Data Network for the Pan-Arctic Region is available on CD-ROM. Future data sets include the Rapid Integrated Monitoring System (RIMS), a collection of hydrometeorological data for river systems that discharge into the Arctic Ocean. (2) Leadership in data set archival and dissemination through active collaboration with scientific societies and organizations. Currently active affiliations include the International Permafrost Association (IPA), the World Glacier Monitoring Service (WGMS) for glacier inventory data, CONMAP SCAR for the US National Antarctic Data Center for Antarctic metadata, the Joint WMO-IOC Commission for Oceanography and Maritime Meteorology (JCOMM) for the Global Sea Ice Data Bank, and the International Antarctic Buoy Program (IABP), as well as the National Science Foundation (NSF) in the form of the Arctic System Science Data Coordination Center and the Antarctic Glaciological Data Center, and NOAA and NASA. (3) Delivery of large volume satellite data. In particular, the NSIDC DAAC has begun delivery of snow and ice products derived from MODIS data on the Terra satellite, and will deliver passive microwave data from the AMSR instrument on the upcoming Aqua satellite, and laser topography data from the ICESat. We expect an increasing emphasis on multi-sensor products and multi-disciplinary data sets.

Monitoring long-term regional changes in the Arctic and Antarctic with AVHRR 5 km Polar Pathfinder Data

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This project illustrates applications of Advanced Very High Resolution Radiometer (AVHRR) 5-km Polar Pathfinder data in large-scale climate studies for the Arctic and Antarctica. The National Snow and Ice Data Center (NSIDC) archives and distributes AVHRR Polar Pathfinder data at 1.25-km and 5-km resolution. The 5-km data include five AVHRR channels, clear sky surface broadband albedo and skin temperature, solar zenith angle, satellite elevation angle, sun-satellite relative azimuth angle, surface type mask, cloud mask, and Universal Coordinated Time (UTC) of acquisition. Data are composited onto two grids per day, based on common local solar times and scan angle. Temporal coverage is from July 1981 to August 1998.

AVHRR 5-km data provide a time series of consistent observations. The temporal coverage is designed to provide information on diurnal variations and seasonal-to-interannual evolution in climate and surface conditions. The 5-km products are useful for studies of regional changes and monitoring over longer time periods.

Applications of 5-km products include: (1) monitoring a time series of coastline changes along West Antarctica and the Ronne Ice Shelf from 1984 to 1998 and (2) analyzing albedo and temperature data for three locations in Greenland during the melt season, 1991-1992.

Lena River Ice Regime And Recent Change

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River ice is one of the important components of hydrological processes in cold regions. To quantify the hydrological cycle in cold regions, it is necessary to observe and study river ice. In Siberian regions, river ice thickness, dates of river freeze-up and break-up, stream water temperature, and discharge have been measured since the late 1940’s. Based on the preliminary and on-going analysis of river ice and streamflow records of the past 40-50 years, this presentation describes the seasonal regime of river ice condition (thickness) and its change for the Lena river basin. This study did not find significant change in annual total discharge, summer discharge, or daily peak flow. However, noticeable changes in hydrological conditions in winter season were identified; these include an increase of winter discharge at the outlet of the watersheds, and thinning of the river ice-cover in the Lena river basin. These changes may indicate a seasonal regime shift of hydrological cycle due to recent climate warming over the eastern Siberian regions. Further efforts are needed to identify the changes in hydrological regimes in different sub-basins of the watershed, and to examine the inter-annual variation of monthly discharge/river ice and their responses to climate factors, such as air temperature, precipitation and snow cover.

Quasi-Biennial and Quasi-Decadal Variations in Snow Accumulation over Northern Eurasia and Their Connections to the Atlantic and Pacific Oceans

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The study of 60 years of winter snow depth records reveals quasi-biennial variations of about 2.5 years and quasi-decadal variations of about 11.8 years and about 8 and 14 years. The quasi-biennial snow depth variation over the region east of the Caspian Sea and west of China is associated with sea surface temperatures over the northern North Pacific and tropical western Atlantic extending into the Gulf of Mexico. The associated atmospheric circulation pattern of Eurasia-I and the Pacific/North American pattern determines the surface air temperature conditions and thus snow depth at the biennial time scale. The quasi-decadal snow variation over central European Russia and western central Siberia is associated with a well-known SST anomaly pattern over the Atlantic, having opposite SST variations in alternating latitudinal belts, and SSTs over the tropical Pacific Ocean. The associated atmospheric North Atlantic Oscillation and the circulation anomaly over central Siberia affect both surface air temperature and precipitation and thus snow depth anomaly at a quasi-decadal time scale.

Distribution of Frozen Ground in the Northern Hemisphere

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Freeze/thaw cycles influence the thermal and hydraulic characteristics of the soil, which have a significant impact on the surface energy and moisture balance; hence, on the climate system. Frozen soils increase the soil heat flux significantly due to the increase in thermal conductivity. Freezing of soil moisture reduces the hydraulic conductivity of the soil, leading to either more runoff due to decreased infiltration, or higher soil moisture content due to restricted drainage. Existence of a thin frozen layer essentially decouples the moisture exchange between the atmosphere and the deeper unfrozen soils. Hence, information on seasonal freeze/thaw cycles (timing, duration, and the number of days), areal extent, and depth of seasonal freezing and thawing is crucial for investigating land surface processes in cold seasons/cold regions. Here, we investigate the seasonal freeze/thaw cycles of the soils in the Northern Hemisphere using ground-based measurements, remote sensing, and numerical modeling. Ground-based measurements indicate that soils at 5-cm depth experience freezing for at least two to three weeks when the mean monthly air temperature was at or near 0^{o}C. The extent of seasonally frozen ground with freeze/thaw cycles greater than two weeks is determined using the 0^{o}C isotherm of the mean monthly air temperature. Using passive-microwave satellite remote sensing data, the daily freeze/thaw boundary in the Northern Hemisphere is detected and is generally in good agreement with the 5^{o}C isotherm of air temperature. The onset of surface soil freezing starts in September or October at high latitude/altitude regions, and in December or even January over middle latitude lowlands. The last day of surface soil freezing ranges from February or March in middle latitude regions to May or June at high latitude/altitude regions. These results show that the duration of surface soil freezing varies from a few weeks to several months. The number of days that surface soil actually experiences freeze/thaw cycles varies from a few days to more than five months. Generally, surface soil experiences freezing before snow covers the surface. However, modeling results indicate that the frozen soil may be thawed quickly after a consistent snow cover is established over the freezing surface, especially in the mid-latitudes. For 1988-1999, more than 50 percent of the land surface in the Northern Hemisphere is either snow covered or experiences freeze/thaw cycles, as detected from the passive microwave remote sensing data, and 55 percent as detected from the mean monthly air temperature. The long-term trends of snow cover and frozen ground extent and their relationship with climatic conditions are also discussed.

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1990 to Present
Organized by year

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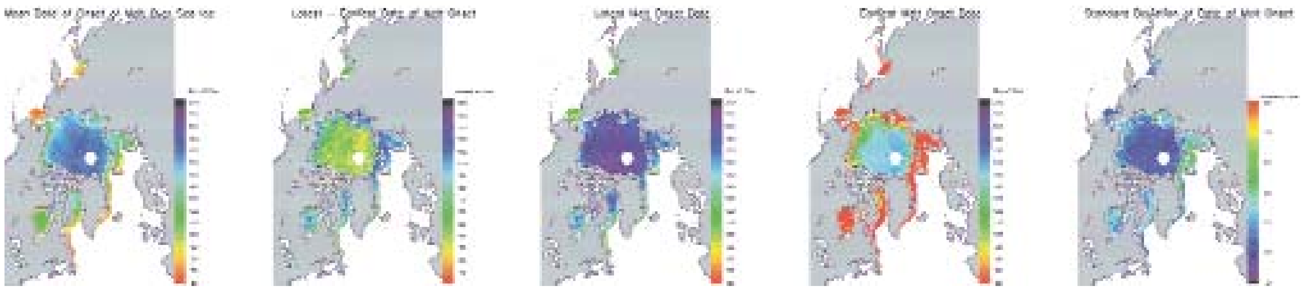
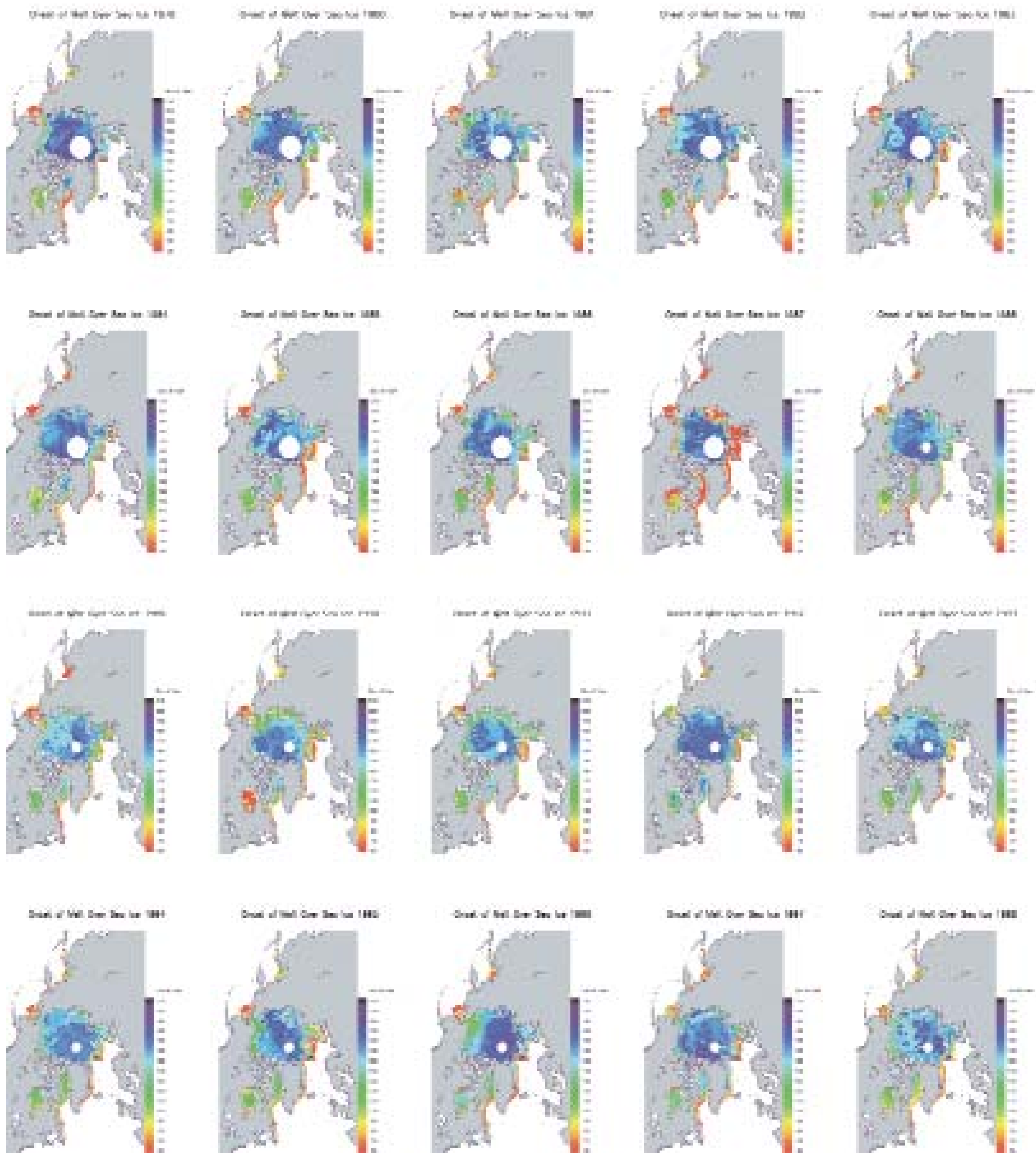
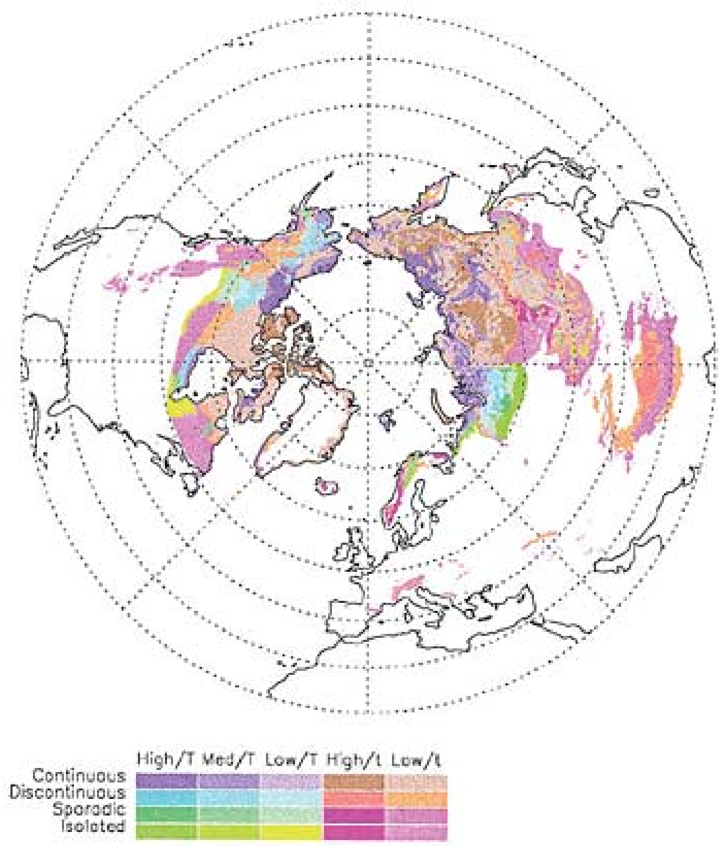
Color Figures accompanying Invited Papers



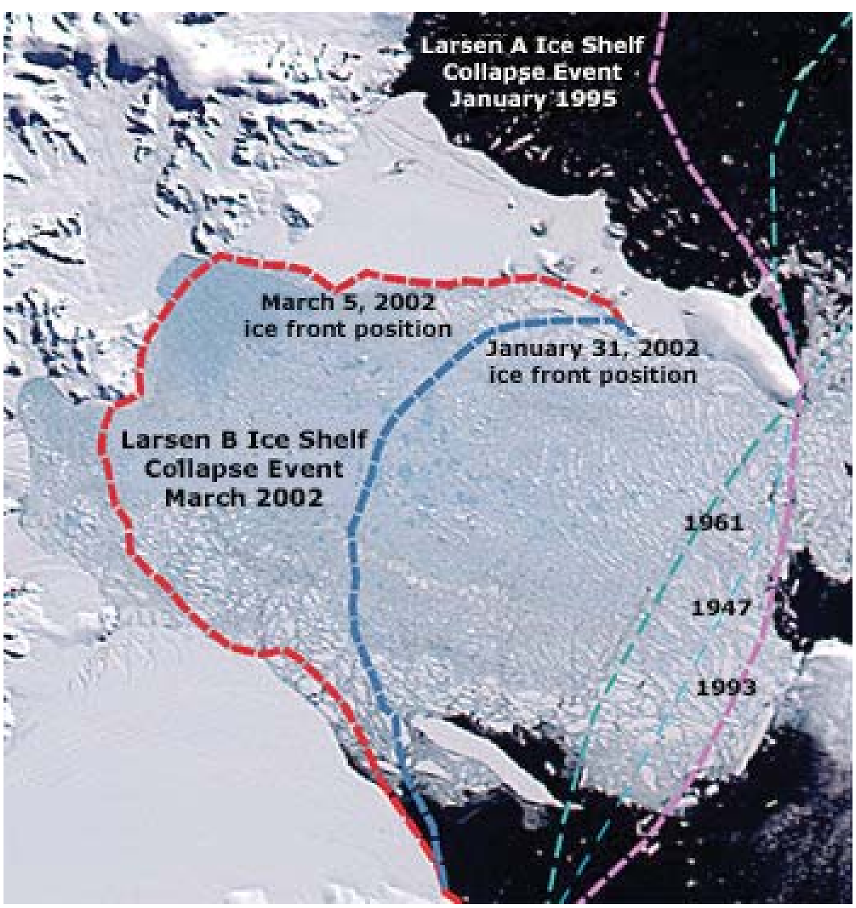
Anderson Figure 1. Mean, range, maximum, minimum, and one-standard deviation maps (from left to right) derived from the 20-year melt onset dates.



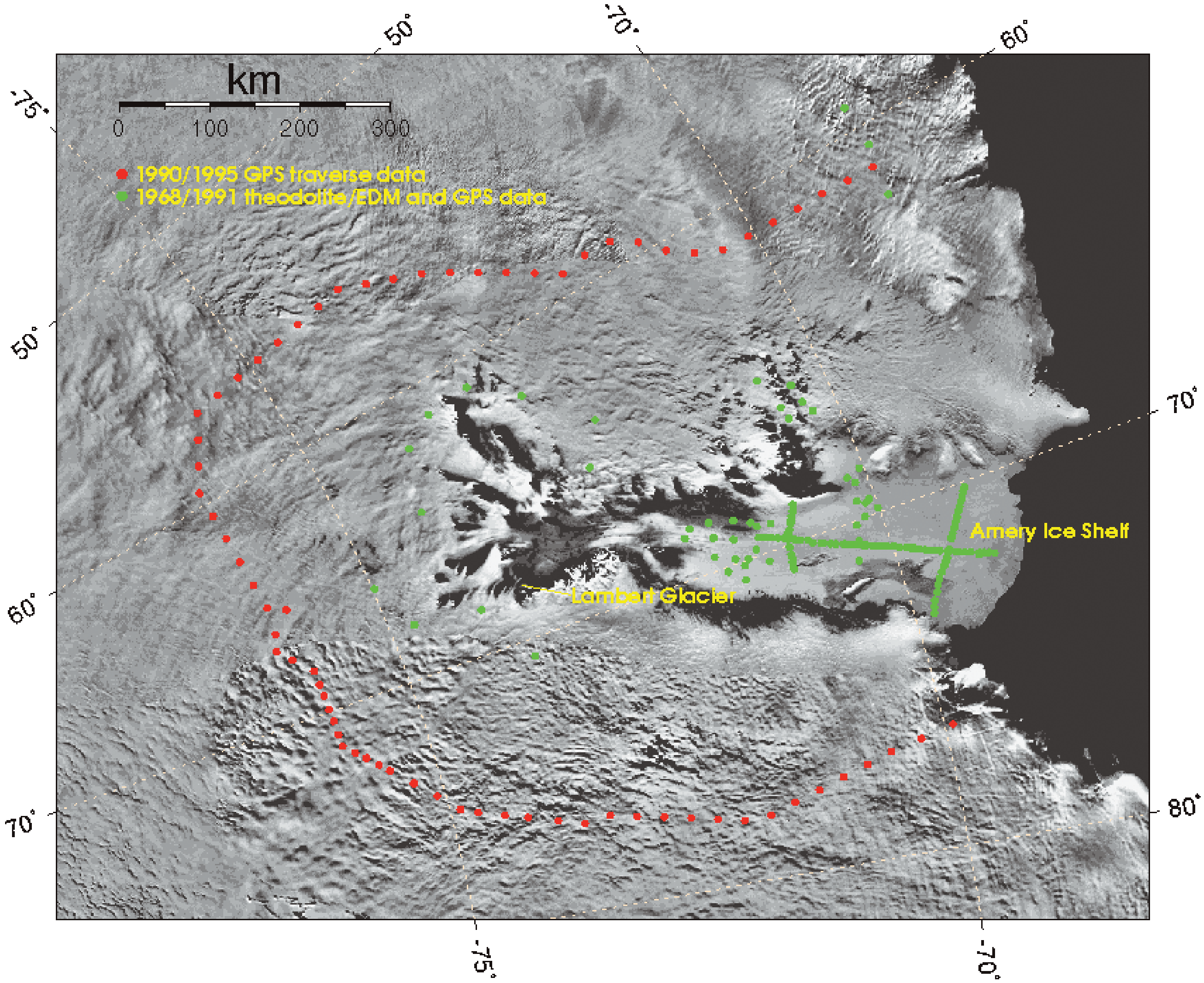
Anderson Figure 2. Individual years of melt onset derived from AHRA.



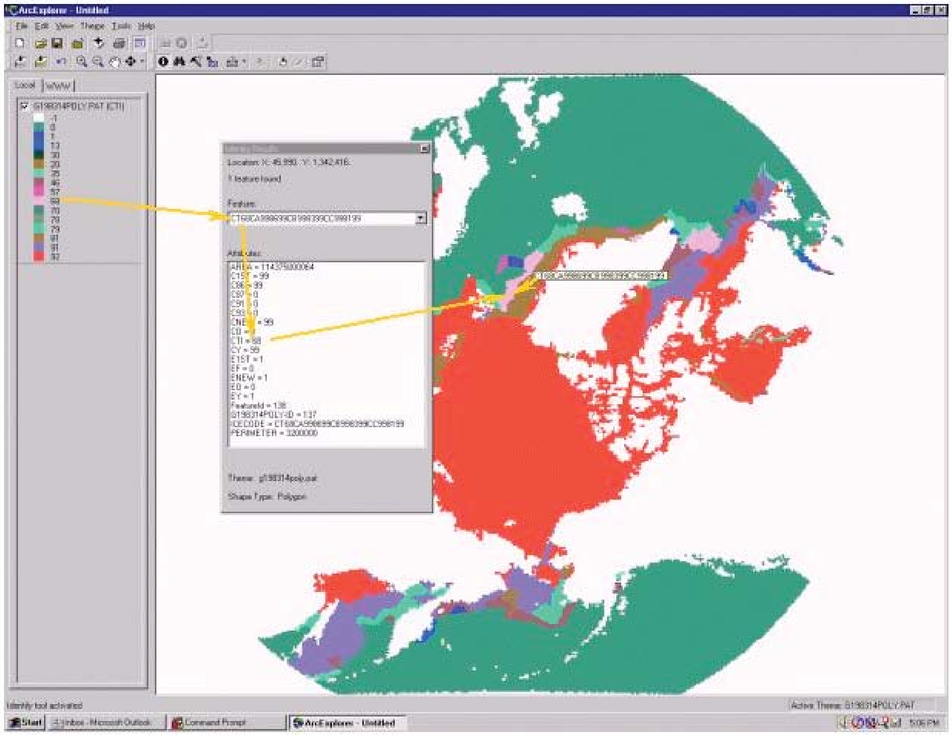
Armstrong Figure 3. Distribution of permafrost and ground ice in the Northern Hemisphere, based on the EASE-Grid version of the International Permafrost Association map. "High," "Med," and "Low" refer to ice content and "T" and "t" refer to thick and thin overburden, respectively. Image courtesy of the International Permafrost Association, supplied by Tingjun Zhang, National Snow and Ice Data Center, University of Colorado, Boulder.



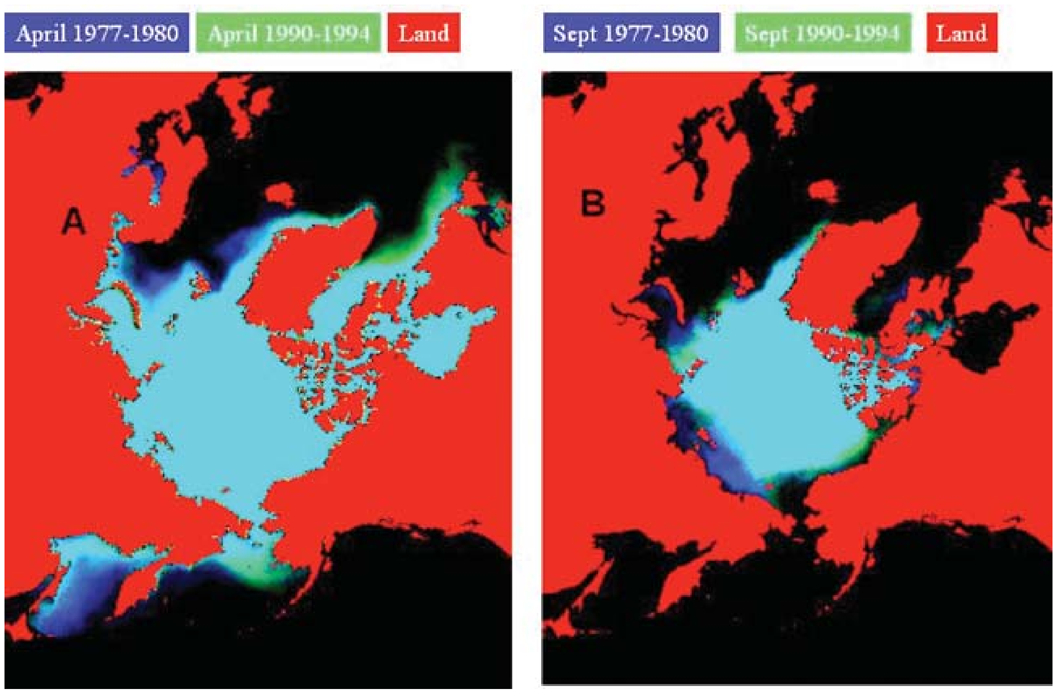
Armstrong Figure 5. Extent of Larsen Ice Shelf retreat. MODIS image courtesy of Ted Scambos, National Snow and Ice Data Center, University of Colorado, Boulder.



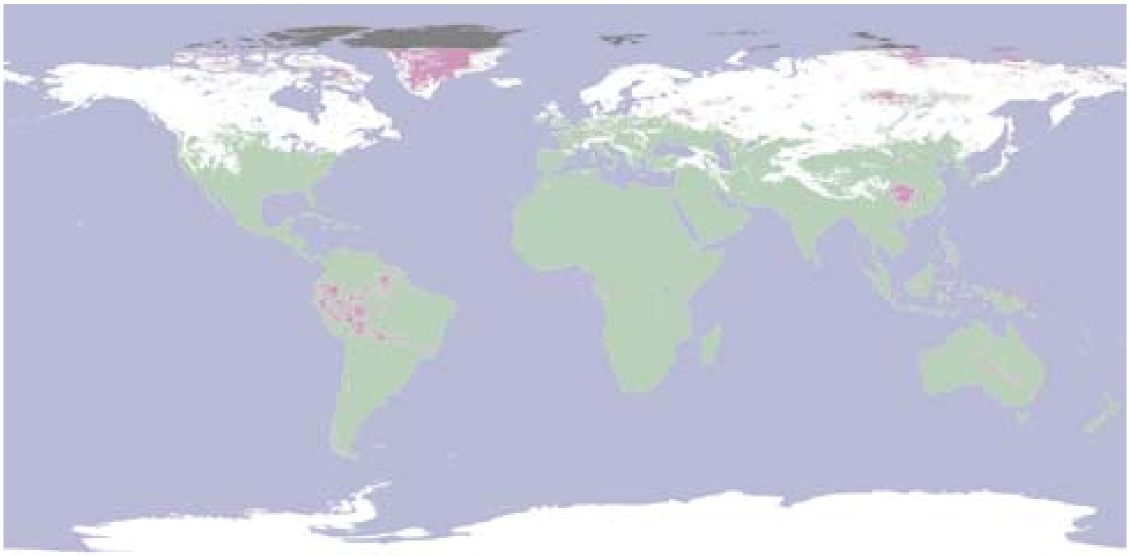
Bauer Figure 1. Antarctic Ice Velocity Data (VELMAP).



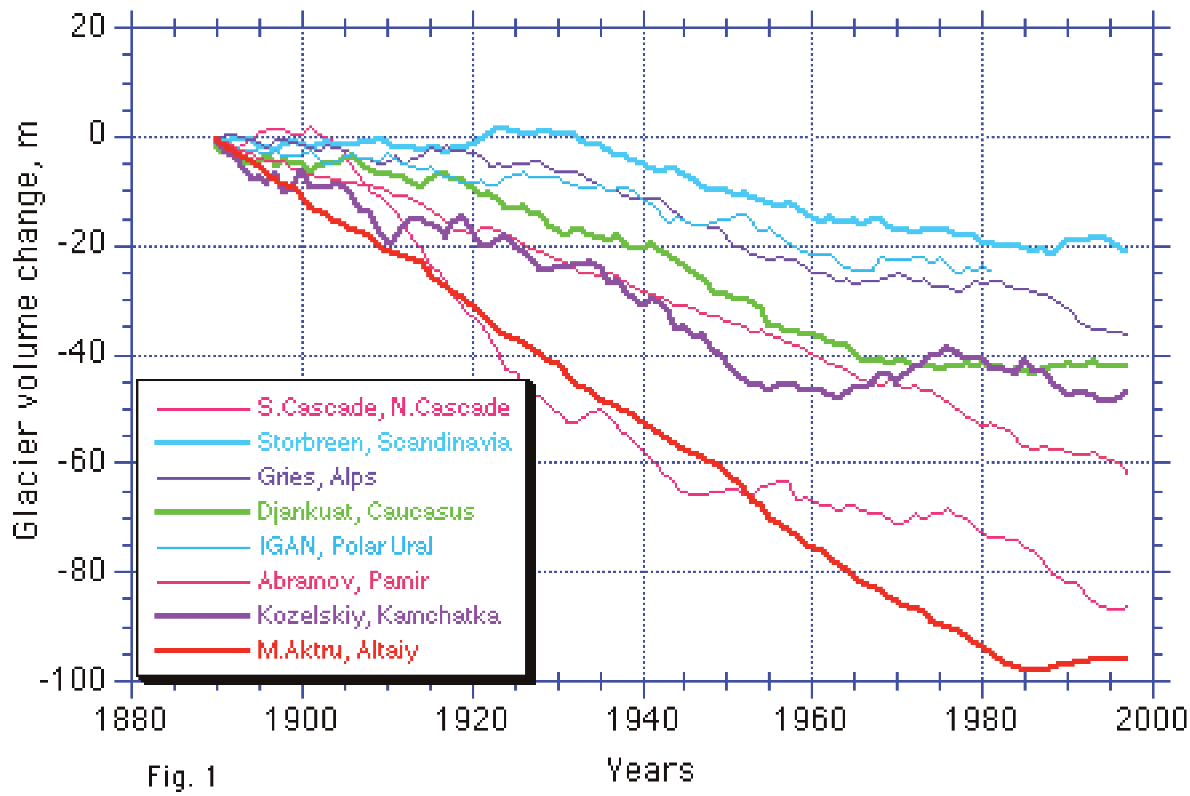
Dedrick Figure 1b. An example of a completed Arctic sea ice chart in ArcExplorer GIS Data Viewer (ESRI, Inc., Redlands, CA). Note the association between polygon features in the chart and attribute data containing the WMO SIGRID ice codes



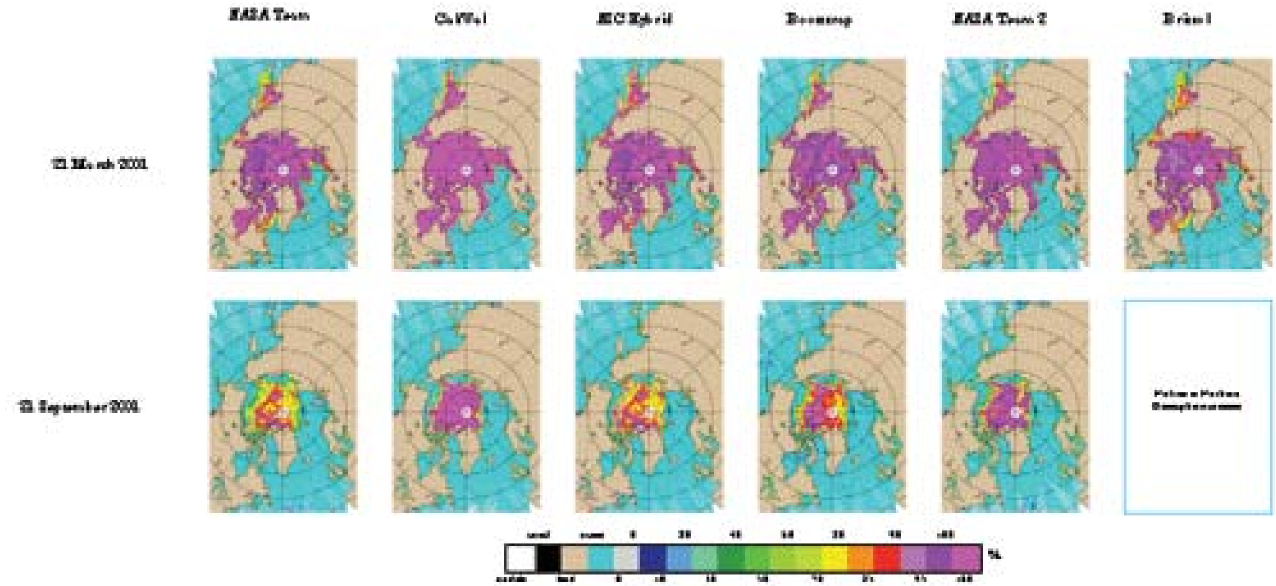
Dedrick Figure 2. Color Composite of Mean Ice Concentration Data for two periods, including Negative NAO Index Years (blue) and Positive NAO Index Years (green). Equal contributions of blue and green create the cyan areas across much of the Arctic, indicating no change in ice concentration between the two periods.



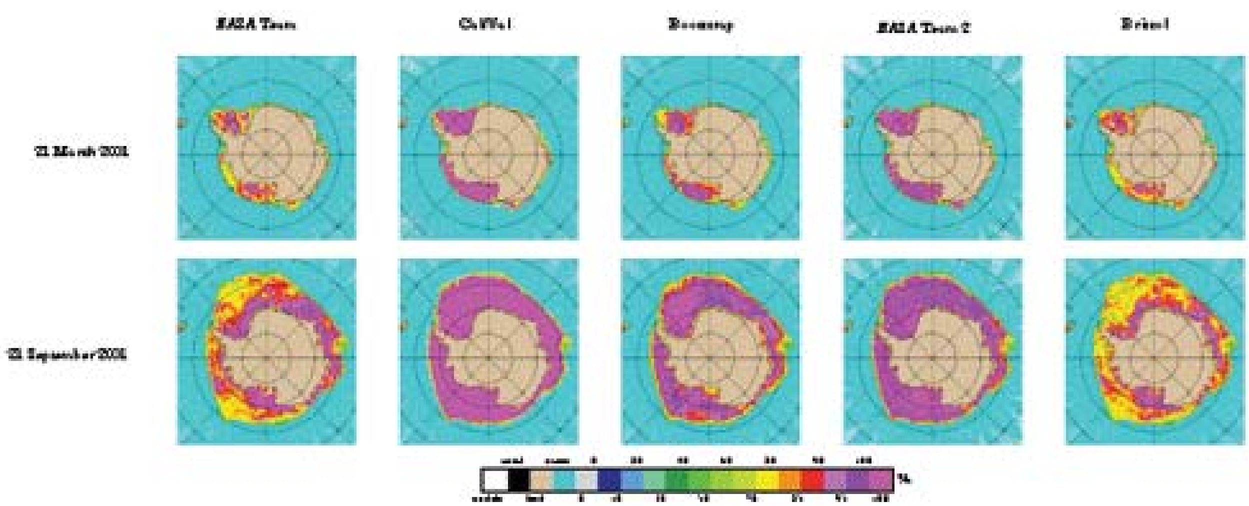
Hall Figure 1. Climate-modeling grid (CMG) eight-day composite (February 18-25, 2002) MODIS snow map produced at 0.05^{O} resolution (see http://modis-snow- ice.gsfc.nasa.gov/MOD10C2.html). Snow is shown in white, persistent clouds are shown in pink, non-snow-covered land is green, and darkness is shown in grey.



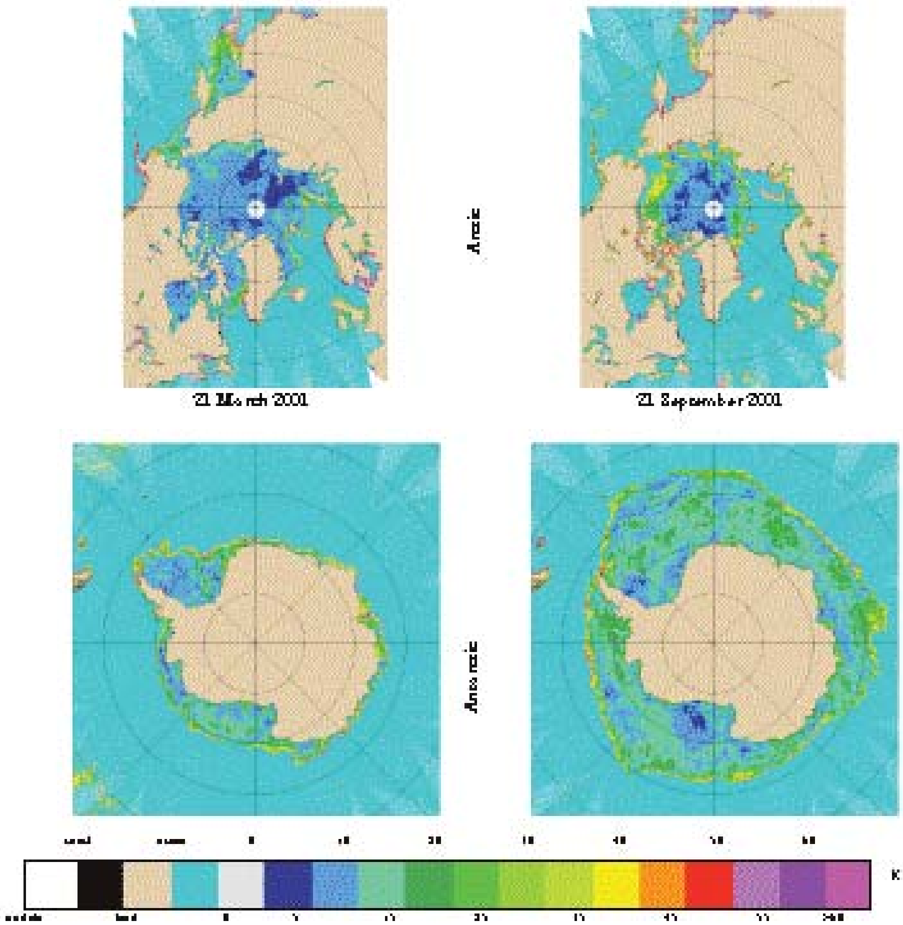
M. Meier Figure 1. Selected long-term series of cumulative volume changes for glaciers in different regions. South Cascade (North Cascades, Washington, U.S.), Gries (Alps, Switzerland), Storbreen (Jotunheimen, Norway), Abramov (Pamir, Kirgizstan), Kozelskiy (Kamchatka, Russia), Djankuat (Caucasus, Georgia), Maliy Aktru (Altaiy, Siberia, Russia), IGAN (Polar Ural, Russia). All values are relative to 1890. Adapted from Dyurgerov and Meier (2000).



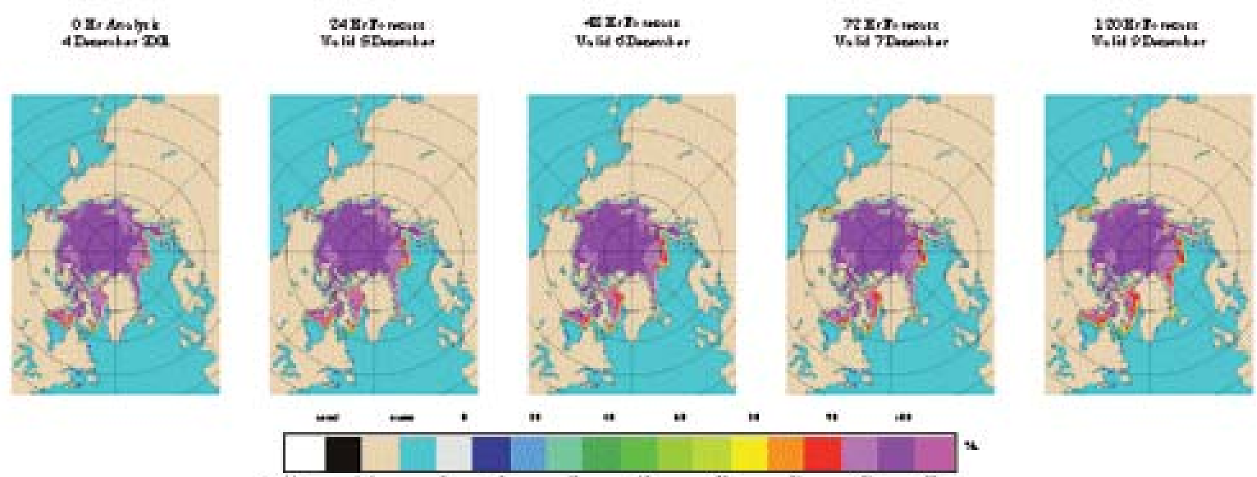
W. Meier Figure 1. Northern Hemisphere winter (21 March 2001) and summer (21 September 2001) SSM/I sea ice concentration products. The Bristol algorithm is not running during summer.



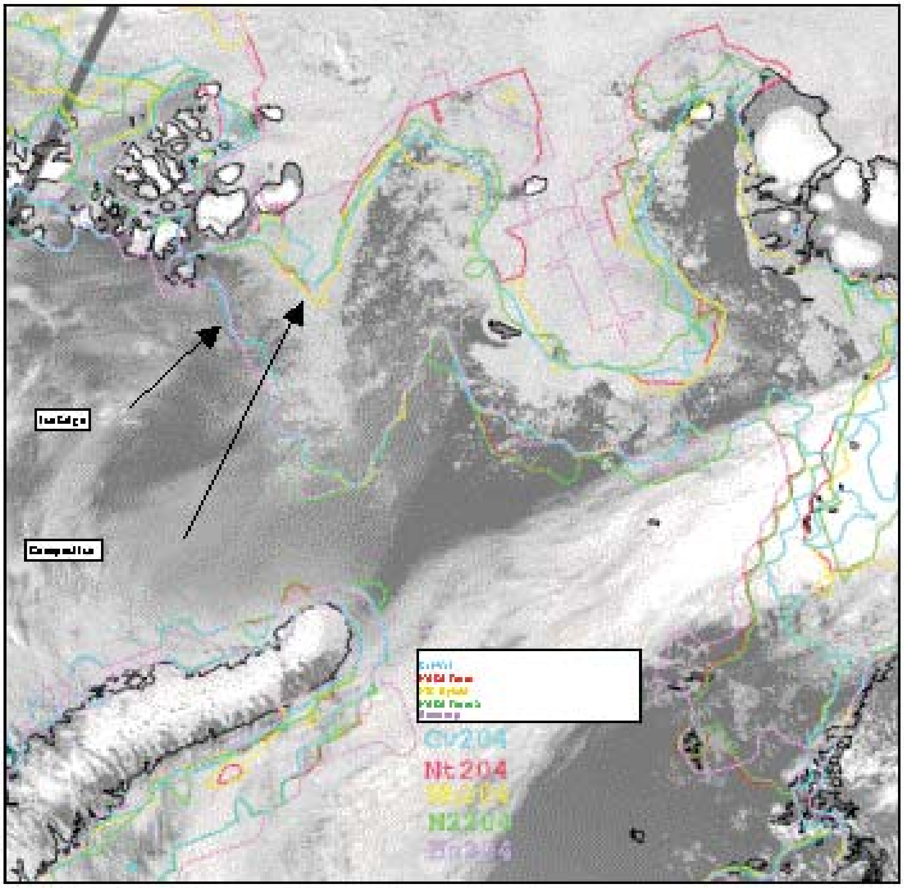
W. Meier Figure 2. Southern Hemisphere summer (21 March 2001) and winter (21 September 2001) SSM/I sea ice concentration products.



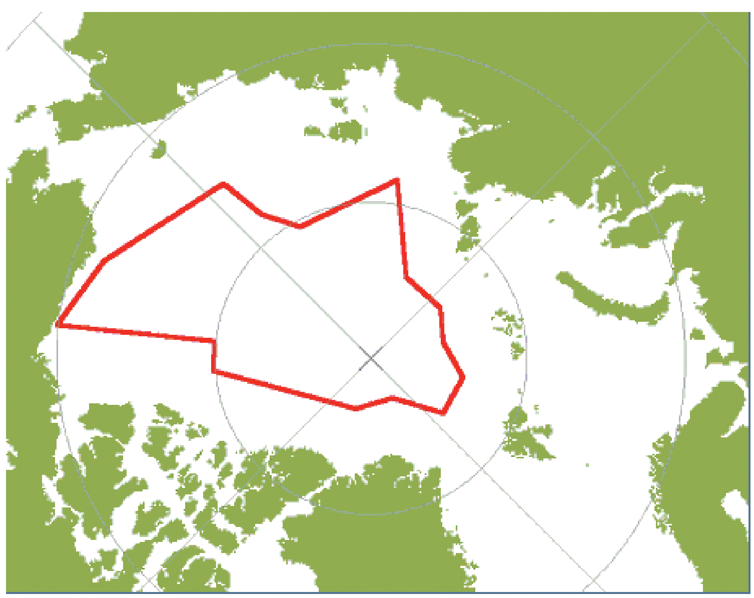
W. Meier Figure 3. Brightness temperature difference between horizontally and vertically polarized channels of 85 GHz (H-V, in Kelvins). Left image is 21 March 2001, right image is 21 September. The Arctic is on top, with Antarctic below.



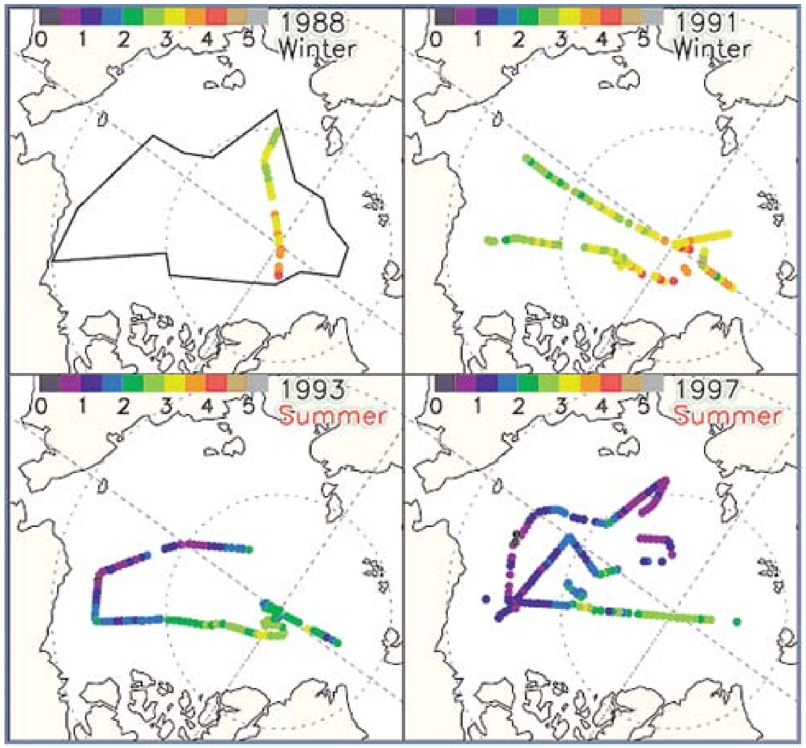
W. Meier Figure 5. PIPS sea ice concentration analyses for 4 December 2001 and forecasts for 24, 48, 72, and 120 hours



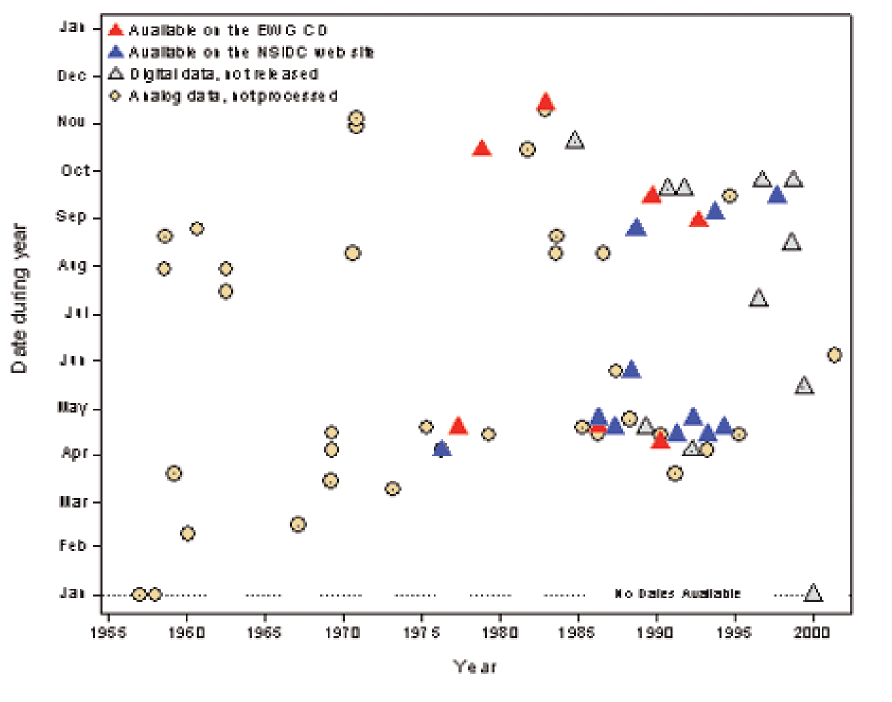
W. Meier Figure 6. Contours of SSM/I ice edge and compact ice boundary overlain on OLS infrared imagery on 23 July 2001



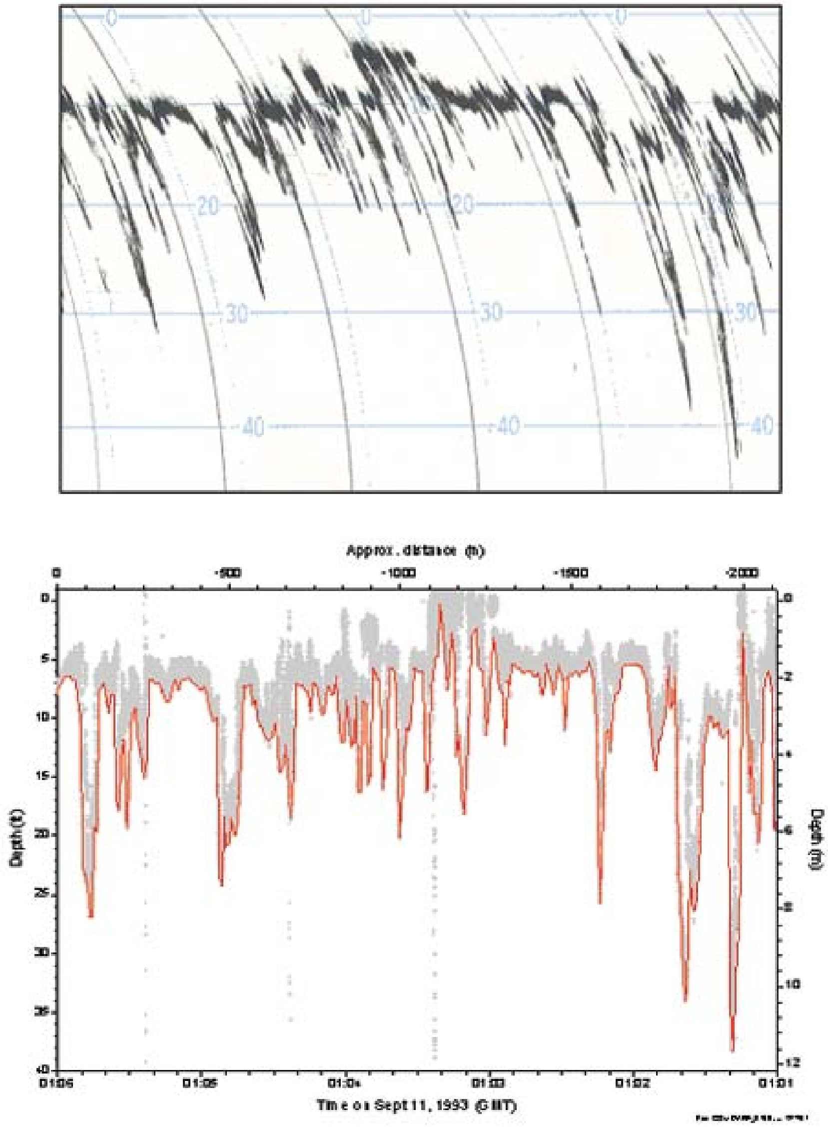
Wensnahan Figure 1. Data release area. The red polygon is the SCICEX Box in which data can be released. This region lies outside the exclusive economic zones of foreign nations.



Wensnahan Figure 2. The tracks of four typical cruises. The color bar indicates the mean draft in meters. Winter 1991 includes both U.S. and U.K. data.

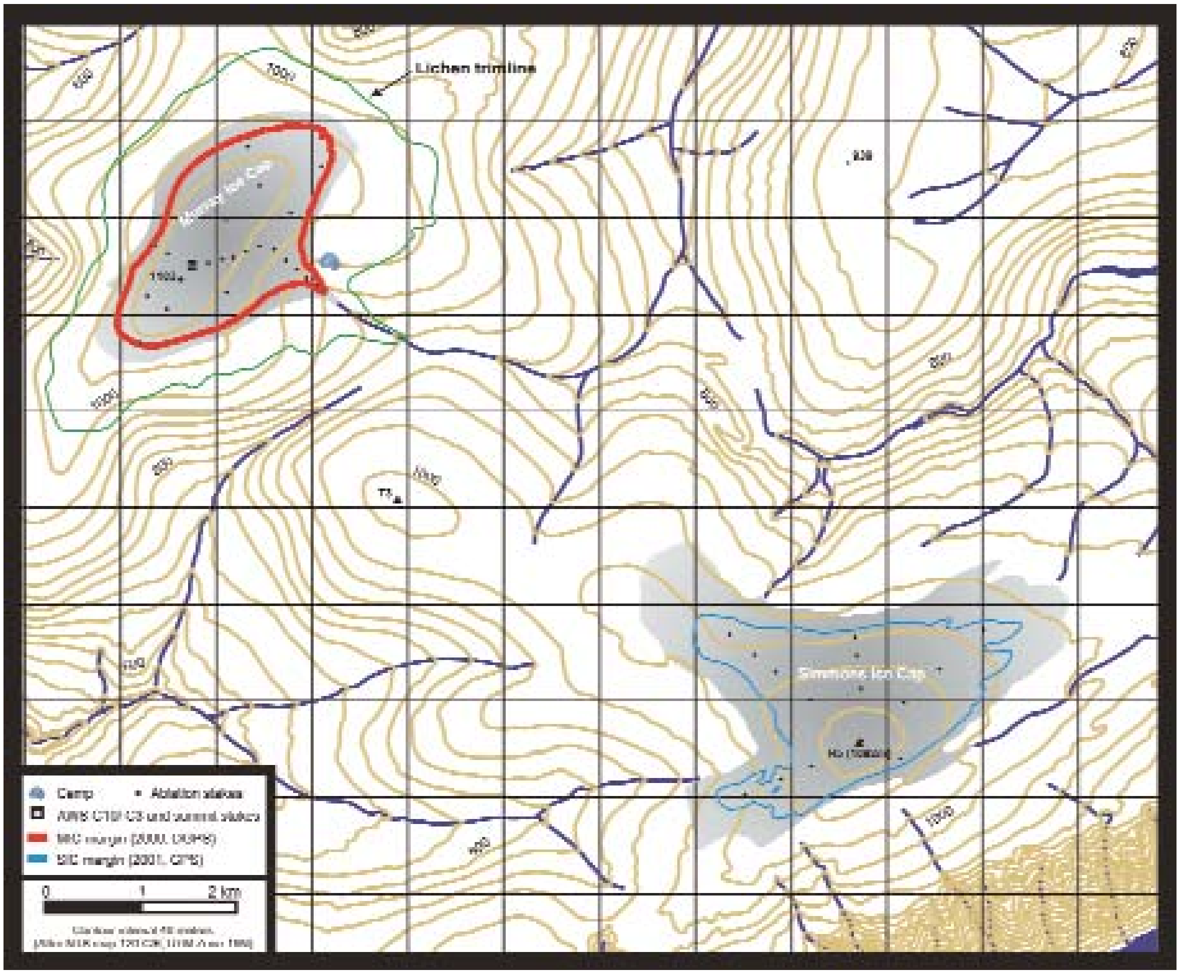


Wensnahan Figure 3: Summary of ice thickness data available from U.S. submarines

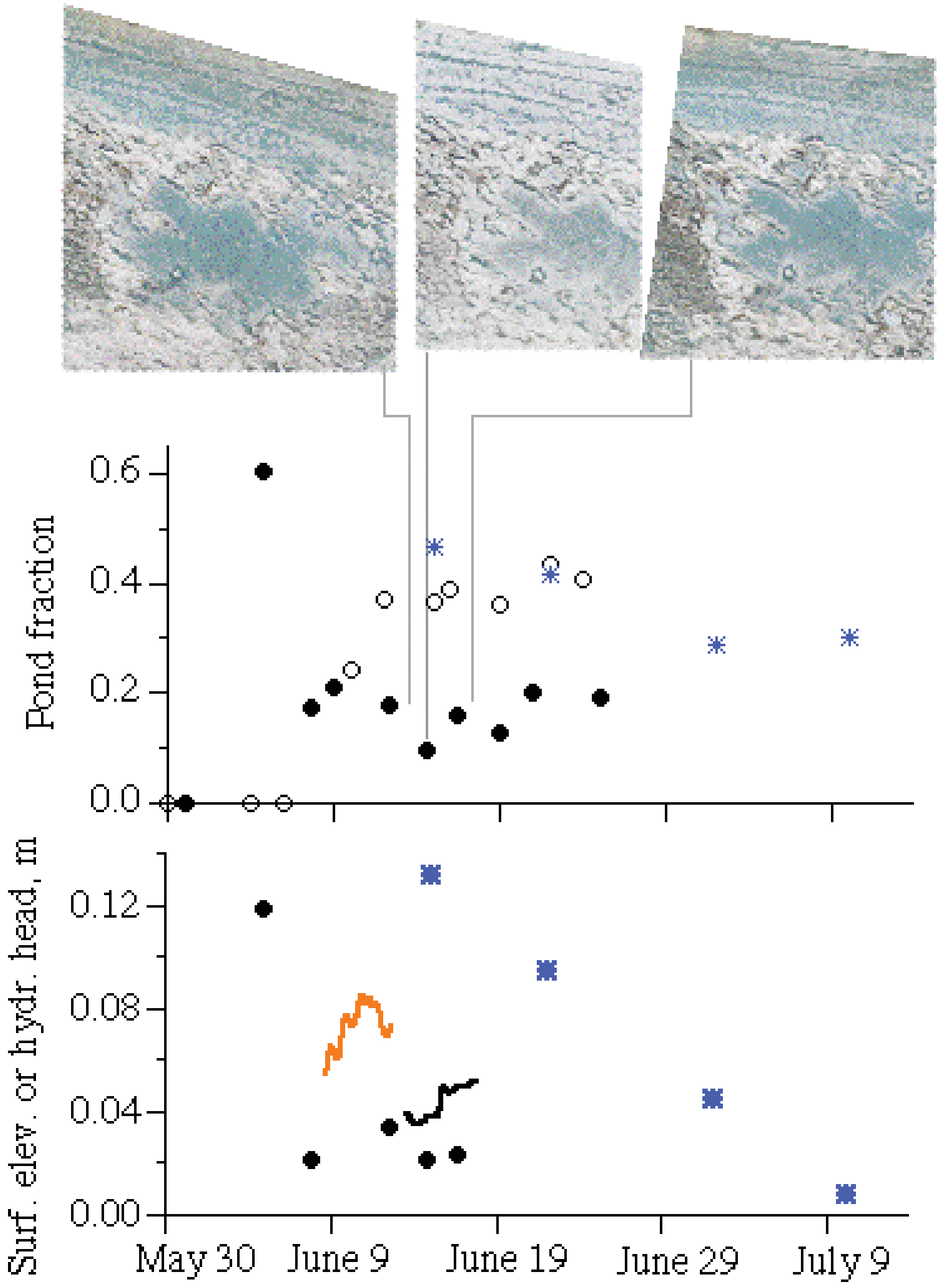


Wensnahan Figure 4. A curvilinear chart and its digital conversion to rectilinear data scaled to time and depth (grey dots) and then to a digitized trace (red).

Color Figures accompanying Abstracts

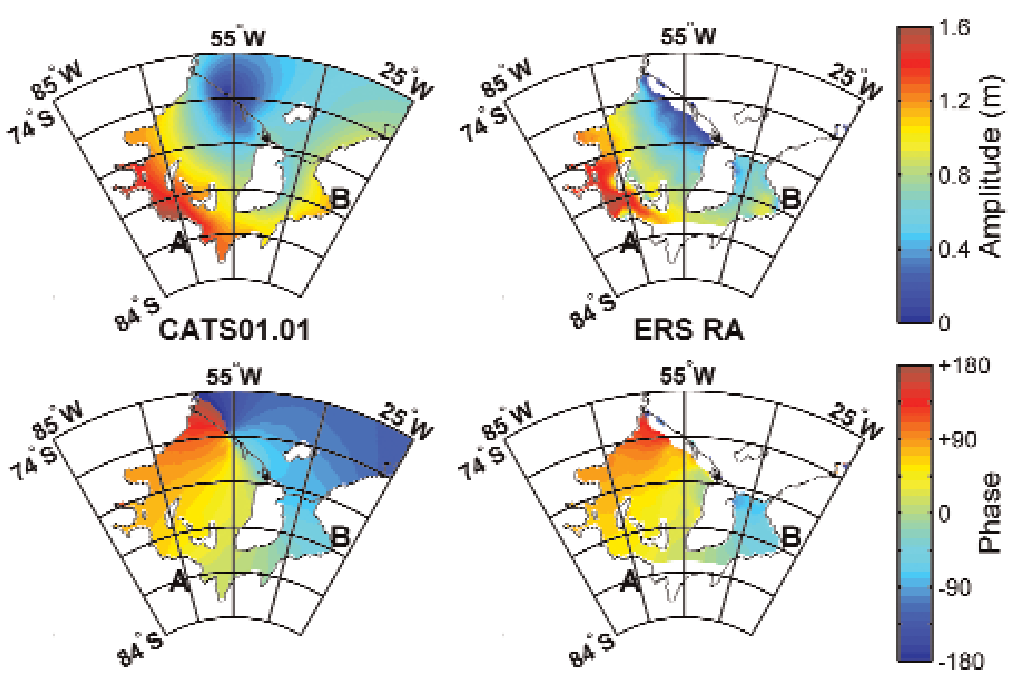


Braun Figure 1. Contour map of Simmons and Murry Ice Caps, Hazen Plateau, Ellesmere Island.

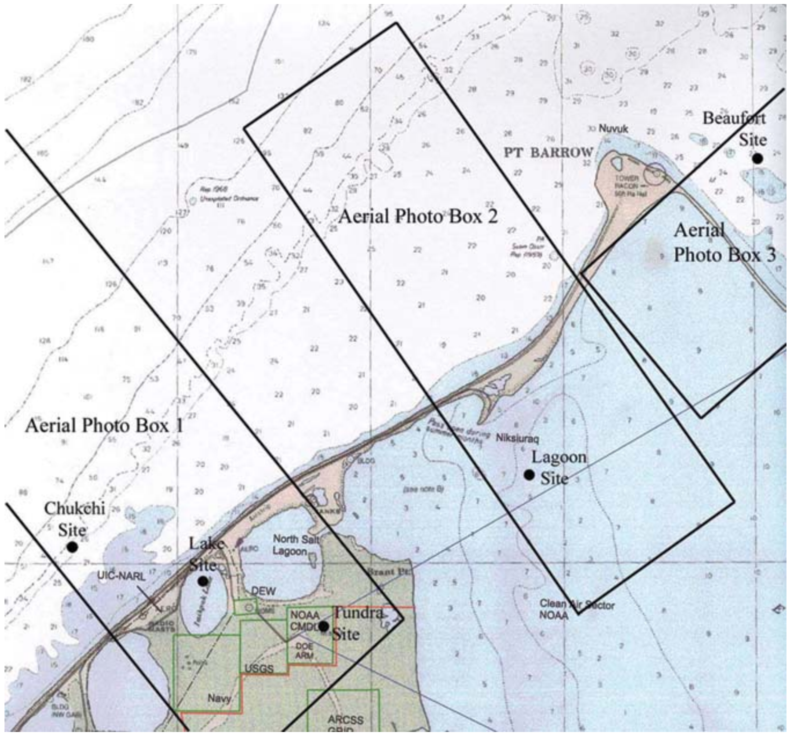


Eicken Figure 1. Pond coverage and water level. Areal fraction and hydraulic head of melt ponds in multiyear ice (asterisks) and first-year ice near Barrow (open circles: 2000, dots: 2001). Solid lines show water level in a single pond (pressure-gauge measurement; red: 2000, black: 2001). Aerial photographs (upper panel, central image ca. 600 m wide) show a sequence of drainage and flooding events for June 13 to 15 in first-year ice near Barrow. Areally averaged albedo α and pond fraction f_p varied correspondingly on June 12 (α = 0.37, f_p = 0.18), 14 (α = 0.49, f_p = 0.10) and 16 (α = 0.28, f_p = 0.16). Decreasing pond hydraulic head towards the later season greatly reduces lateral meltwater transport, reducing shrinkage or expansion of ponds in combination with steepening of ponds walls.

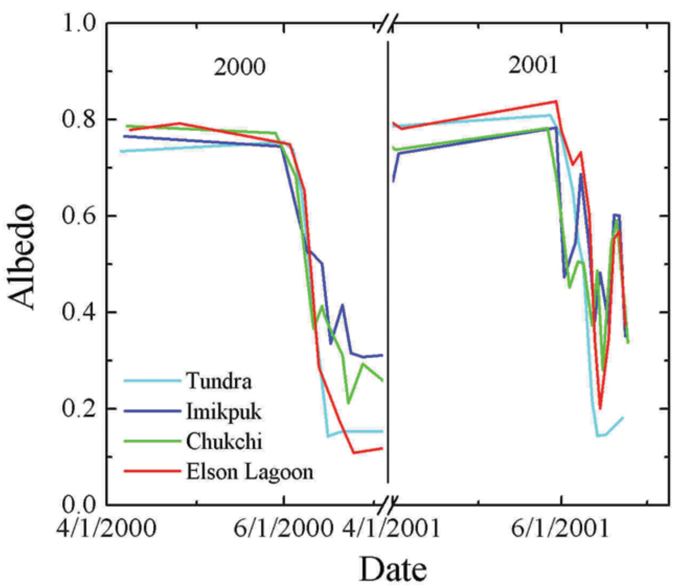
England Figure 1. Overview of STAR-Light Objective and Strategy.



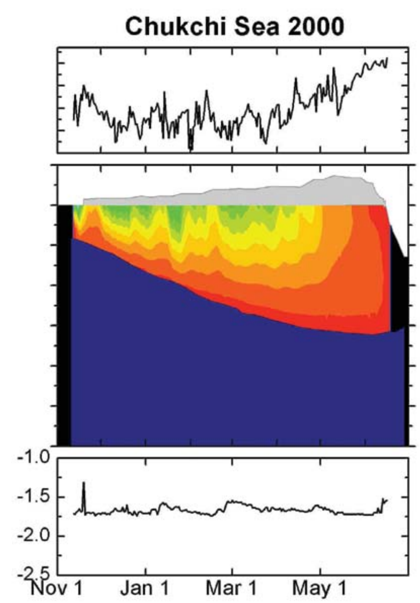
Fricker Figure 1. Tidal harmonics over the Filchner-Ronne Ice Shelf, Antarctica.



Grenfell Figure 1. Energy and mass balance measurements at five locations: shorefast sea ice sites on the Chukchi and Beaufort Sea coasts, a coastal seawater lagoon site, a freshwater lake site, and a tundra site. These sites, indicated on the map, were selected to encompass the wide range of conditions found in the Barrow, Alaska area.

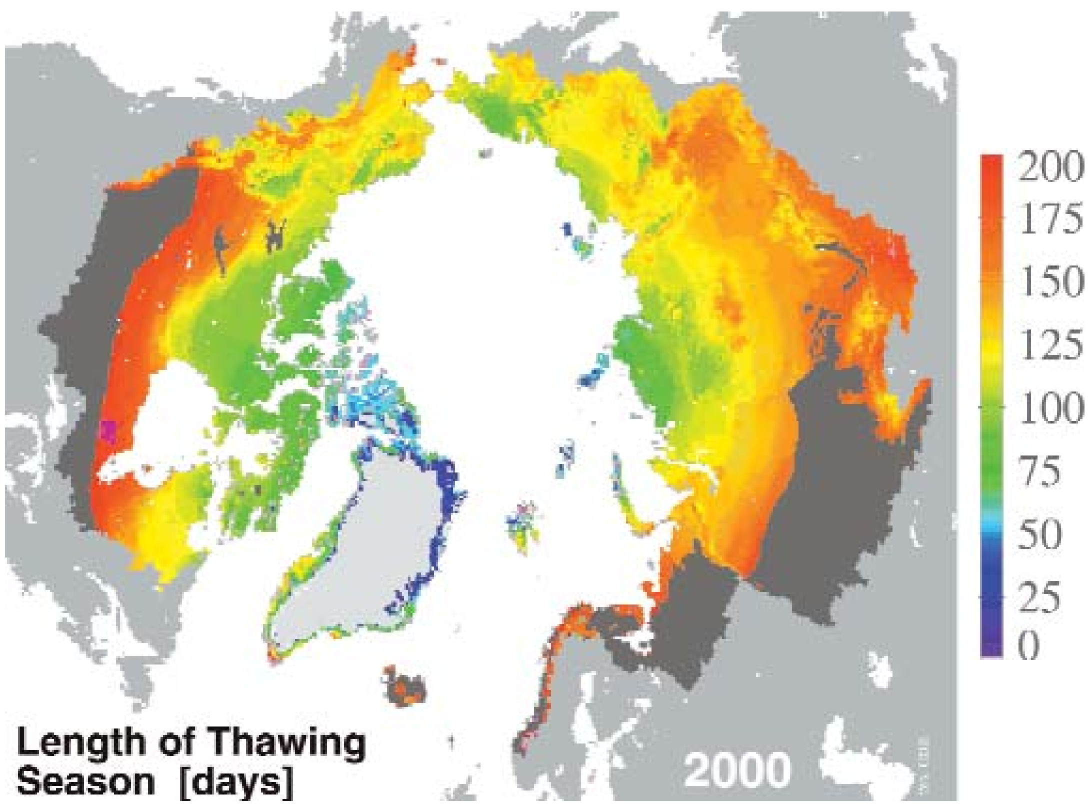


Grenfell Figure 2. Albedo measurements over four locations in the Barrow, Alaska area.

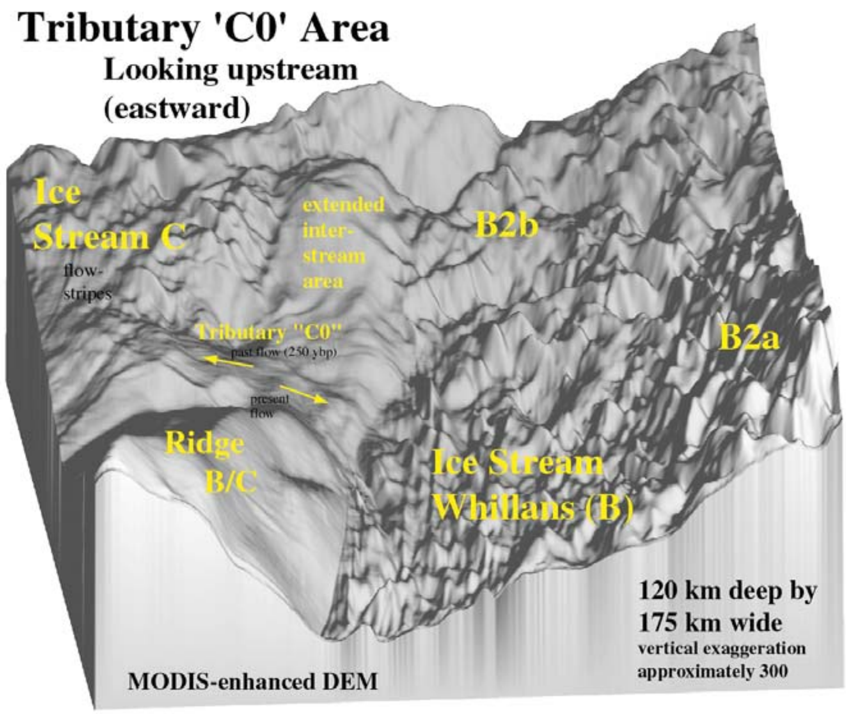


Grenfell Figure 3.

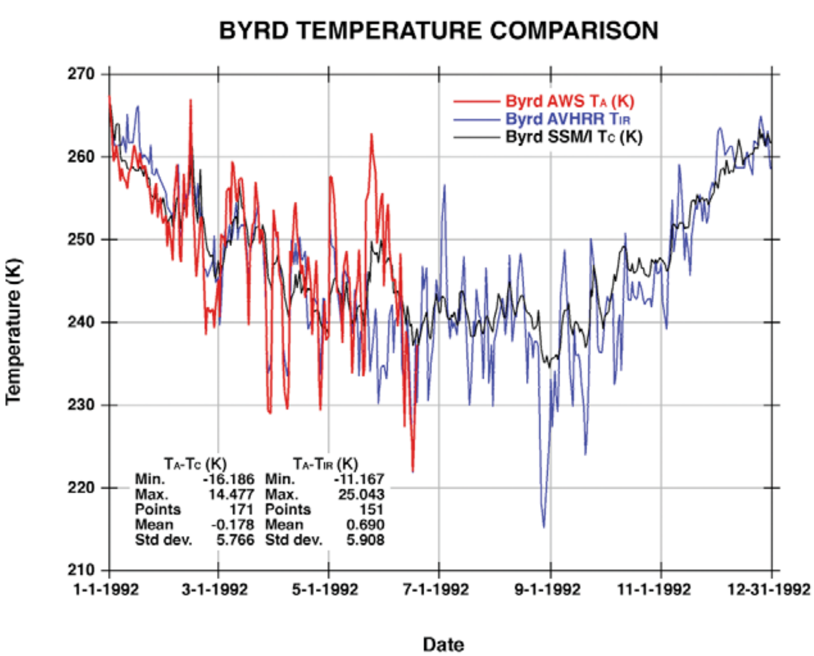
Mahoney Figure 1. The seasonal evolution of the landfast sea ice cover is highly variable both spatially and temporally from year to year. Episodic events such as the ice shove illustrated here can profoundly affect the subsequent behaviour of the nearshore ice.



Oelke Figure 1. Length of thawing season (days) in permafrost areas in 2000; seasonally-frozen ground is masked in black.



Scambos Figure 1. Subscene from the enhanced area near the onset regions for the Ross ice streams. The region illustrated is a portion of the boundary between Whillans Ice Stream and Ice Stream C. This region has undergone dramatic recent changes in surface elevation as Whillans Ice Stream rapidly draws down its catchment, lowering the ice surface relative to Ice Stream C. The 'C0' feature, formerly a tributary to Ice Stream C, has now reversed slope and is flowing back towards Whillans Ice Stream. The improved DEM resolves the major features better, and provides quantitative elevation information at the stream boundaries and flowlines.



Shuman Figure 1. The figure illustrates the challenge of accurately determining the temperature history for an ice sheet location. Byrd Station, approximately 80^{o}S 120^{o}W in West Antarctica, has been the site of an AWS since February 1980, and it continues through the present day. The AWS temperature record (T_A, in red) is interrupted by equipment problems in June 1992. The infrared record (T_{IR}, in blue) is nearly continuous (1-4 day gaps exist but aren't shown) and clearly diverges from the in situ record from mid-May to early June. And finally, the passive microwave record (T_C, in black) is continuous but doesn't record the high-frequency temperature variations obtained by the other types of data. Consequently, all three types of temperature information are beneficial to the development of a continuous record.

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