Cryosphere Theme Report

IGOS

Integrated Global Observing Strategy

For the Monitoring of our Environment from Space and from Earth

2007

An international partnership for cooperation in Earth observations

A CRYOSPHERE THEME REPORT FOR THE IGOS PARTNERSHIP

August 2007
WMO/TD-No. 1405

WCRP·SCAR CliC
WCRP World Climate Research Programme
WMO
UNESCO
IOC
ICSU International Council for Science
SCAR

Preface

The Integrated Global Observing Strategy (IGOS) is a strategic planning process initiated by a partnership of international organizations that are concerned with the observational component of global environmental change issues. It links research, long-term monitoring and operational programmes, bringing together the producers of global observations and the users that require them to identify products needed, gaps in observations, and mechanisms to respond to the needs of the science and policy communities. Its principal objectives are to address how well user requirements are being satisfied by the existing observations systems, and how they could be met more effectively in the future through better integration and optimisation of satellite, airborne, and in-situ observation systems.

The IGOS partners are comprised of the Global Observing Systems (GOS), the International Organizations that sponsor the Global Observing Systems, the Committee on Earth Observation Satellites (CEOS), and International Global Change Science and Research programmes.

The IGOS Partners recognise that a comprehensive global earth observing system is best achieved through a step-wise process focused on practical results. The IGOS Themes allow for the definition and development of a global strategy for the observation of selected environmental issues that are of common interest to the IGOS Partners and to user groups. IGOS currently has the following themes: the Oceans, the Carbon Cycle, Geohazards, the Water Cycle, Atmospheric Chemistry, the Coastal Zone and a Coral Reef Sub-theme.

The IGOS Cryosphere Theme was initiated in 2004 by the World Climate Research Programme (WCRP) Climate and Cryosphere (CliC) project and by the International Council for Science (ICSU) through the Scientific Committee for Antarctic Research (SCAR). The proposal to develop the theme was approved by the IGOS Partners at their 11th Plenary in Rome, Italy, in May 2004 and a Theme Team was formed. With the support of a worldwide cryospheric science community, a draft report was submitted to the IGOS Plenary in Paris, France, in May 2007.

Further information on IGOS can be obtained from: http://www.igospartners.org
The Cryosphere Theme report is available from: http://igos-cryosphere.org
Inquiries to the IGOS Cryosphere theme can be sent to: info@igos-cryosphere.org

Barbara J. Ryan

Keith Alverson
IOC
IGOS-P co-chair

Barbara Ryan
USGS
IGOS-P co-chair

Foreword

The climate science community, national and international policy makers, the media, and the general public are giving considerable attention to the cryosphere for the following reasons:

- Many glaciers, the Greenland ice sheet, permafrost and frozen ground, snow cover, Arctic sea ice, are exhibiting dramatic changes. Melting permafrost and sea ice in the Arctic affect ecosystems and the sustainability of human activities. Melting glaciers and ice sheets is a key contributor to rising sea levels. The stability of the cryosphere is therefore a matter of significant concern for science and international policy, particularly in light of the global warming identified by the 2007 reports of the Intergovernmental Panel on Climate Change (IPCC).
- Adequate knowledge of the cryosphere is important for weather and climate prediction, assessment and prediction of sea level rise, availability of fresh water resources, navigation, shipping, fishing, mineral resource exploration and exploitation, and in many other practical applications.
- The cryosphere provides indicators of climate change, yet it may be the most under-sampled domain in the climate system.

The Integrated Global Observing Strategy (IGOS) Cryosphere Theme is required to create a framework for, and facilitate improved coordination of, cryospheric observations, and to generate the data and information needed for both operational services and research. In the polar regions, the cost of in situ observations is very high, and satellite monitoring is challenging. Therefore, there is a particularly strong need for a close coordination of observations. There is also a need to strengthen national and international institutional structures responsible for cryospheric observations, and to increase resources for ensuring the transition of research-based projects to sustained observations. The likelihood of achieving such goals will be significantly enhanced through the development of a comprehensive, coordinated, and integrated approach of the kind represented by an IGOS Theme.

This report aims to initiate a process that will ultimately result in a more comprehensive, coordinated, and integrated cryospheric observing system. The report starts with an Executive Summary that includes major recommendations. Chapters 1 and 2 define the cryosphere and the major applications of cryospheric data. Chapters 3-10 describe our current capabilities and requirements for observing essential climate variables (ECVs) in the major domains of the cryosphere. Each of these chapters contains domain-specific recommendations. Chapter 11 reviews the cryospheric observing system by observation types; i.e., in situ, satellite, and airborne. Data management objectives are detailed. Chapter 12 presents the Theme implementation considerations and their timeline. Throughout the report we will refer to the Cryosphere Theme as **CryOS**, the Cryosphere Observing System.

Many people and agencies have supported this effort. We thank the Canadian Space Agency (CSA), the Japan Aerospace Exploration Agency (JAXA), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the European Space Agency (ESA), the U.S. National Oceanic and Atmospheric Administration (NOAA), the U.S National Aeronautics and Space Administration (NASA), the Scientific Committee for Antarctic Research (SCAR), and the World Climate Research Programme (WCRP) for supporting three workshops. We would like to thank the authors and all contributors listed here and on our web site. Approximately 80 scientists from 17 countries have contributed to this report. Their efforts and commitment were essential to its completion and will be critical to the success of the Theme.

Jeffrey R. Key

Jeffrey Key
National Oceanic and Atmospheric
Administration USA
IGOS Cryosphere Theme Chair

Mark Drinkwater
European Space Agency
The Netherlands
IGOS Cryosphere Theme Vice-chair

Jinro Ukita

Jinro Ukita
Chiba University
Japan
IGOS Cryosphere Theme Vice-chair

Executive Summary

The cryosphere collectively describes elements of the earth system containing water in its frozen state and includes sea ice, lake and river ice, snow cover, solid precipitation, glaciers, ice caps, ice sheets, permafrost, and seasonally frozen ground. The presence of frozen water in the atmosphere, on land, and on the ocean surface affects energy, moisture, gas and particle fluxes, clouds, precipitation, hydrological conditions, and atmospheric and oceanic circulation. Elements of the cryosphere also contain important records of past climate providing benchmarks for interpreting modern climate change. The cryosphere exists at all latitudes and in about one hundred countries.

Observations of the cryosphere and associated data products can contribute to all societal benefit areas of the Global Earth Observation System of Systems (GEOSS). Snowmelt and glacier run-off are major sources of hydropower and in many areas the only sources of water for sustaining life and agriculture. Several natural hazards are directly related to the cryosphere including avalanches, icebergs, and catastrophic flooding from glacial lakes. The cryosphere affects all modes of transportation even at the local level where seasonal melt and refreezing can damage roads.

The cryosphere is associated with cold climates, though snow and ice are also found in the high mountains of tropical and subtropical regions. Environmental conditions in areas where the cryosphere exists are, as a rule, harsh, and observations there are costly. Some cryospheric observing networks are declining due to lack of investment, e.g., there are substantial reductions in networks monitoring glaciers and lake and river ice. Satellite monitoring overcomes some of the logistical obstacles but satellites are also costly and do not fully address the range of geophysical variables needed to understand the cryosphere. For these reasons, there is a practical economic incentive for conducting and sharing cryospheric observations and data products for the benefit of various user communities and nations. To address the decline in cryospheric networks and to strengthen the cooperation between the multiple programs and entities working with cryospheric observations and data, the IGOS partnership asked the Cryosphere Theme Team to identify ways to:

- improve coordination of cryospheric observations conducted by research, long-term scientific monitoring and operational programmes,
- facilitate the generation and exchange of data and information for operational services and research,
- strengthen national and international institutional structures responsible for cryospheric observations,
- increase resources for ensuring the transition of research-based cryosphere observing projects to sustained observations.

An IGOS Theme for the entire cryosphere provides economies of scale and ensures that the cryosphere is adequately addressed by the observing systems that support climate, weather and environmental research and operations.

This report summarizes the work of the IGOS Cryosphere Theme Team to devise CryOS – the Cryosphere Observing System. It provides a concise presentation of the requirements in cryospheric observations, data and products, and recommendations on their development and maintenance. The report does not propose to establish a new, dedicated and stand-alone observing system for the cryosphere. Instead, it proposes measures to develop and coordinate cryospheric components of the World Meteorological Organization's (WMO) Integrated Global Observing System, the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), the Global Terrestrial Observing System (GTOS), and other systems, so that the set of cryospheric products to be developed meets most identified user requirements, within approximately 10-15 years. In addition, it proposes arrangements to ensure that existing cryospheric data and products are known, available and openly accessible to the users in a timely and interoperable way. It highlights the need for the identification and coordination of resources to continuously improve observations as requirements and technology evolve, and reiterates the required commitment of observing system operators to sustain and augment existing cryospheric components of the observing systems.

CryOS includes more than simply measurements of snow and ice properties. It must include the following five components:

- Satellite remote sensing instruments,
- Networks of ground-based instrumentation,
- Aircraft-based measurements,
- Modelling, assimilation, and reanalysis systems, and
- Data management system.

Satellite instruments are essential for delivering sustained, consistent observations of the global cryosphere. No one all-encompassing sensor exists; rather, the combination and synthesis of data from different yet complementary sensors is essential, and underlines the critical importance of maintaining key synergetic elements of the system. Equally important are surface and airborne observations, in that they provide key data that cannot currently be measured from space, more detailed information in critical areas, and observations with which to calibrate and validate satellite retrievals. Satellites in turn are a key to extending local in situ measurements. CryOS needs to foster the evaluation of the cryosphere in models, to disentangle the role of the cryosphere in climate and its predictability as simulated by climate models, and to stimulate improvements in the parameterization of cryospheric processes. The data and information management component must facilitate the flow of data and information in cryospheric research, long-term scientific monitoring, and operational monitoring. However, it must go beyond the traditional metadata service or web portal by encouraging the development of tools to combine all types of data, including model fields, from diverse and distributed data centers.

Specific recommendations for each cryospheric element (e.g., terrestrial snow, ice sheets, permafrost) are given in the individual chapters of this report. General recommendations are given below for the near-, mid-, and long-term. The near term coincides with the period of the International Polar Year 2007-2008 (IPY). These recommendations include (order does not imply priority):

Near Term (2007-2009):

- Ensure coordinated interagency planning of the IPY Polar Snapshot (particularly Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR); high-resolution visible and InfraRed (Vis/IR); and optimization of coverage in respect to ICESat laser cycles). Coordinate near-surface, high-resolution remote sensing activities from aircraft, Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs) with satellite and in situ experiments during the IPY.
- Achieve better continuity in high-level polar data products from existing satellites for an IPY legacy dataset.
- Supplement sparse and sporadic basic in situ observation networks for precipitation, snow water equivalent (SWE), permafrost borehole temperatures, ice sheet core properties, met/ocean/ice mass balance tracked buoys, and mountain glaciers, and plan selection and augmentation of at least 15 reference “Supersites” with suites of relevant cryospheric measurements (e.g., by augmentation of existing Coordinated Enhanced Observing Period (CEOP) sites and/or Global Terrestrial Network (GTN) sites).
- Begin implementing a CEOP-oriented integrated approach for production of integrated cryosphere-related data products. Develop tools for integrating diverse and geographically distributed data including in situ measurements and satellite retrievals.
- Develop satellite concepts for measurements of snow water equivalent and solid precipitation and initiate a comprehensive validation program for in situ and satellite observations of these elements.
- Promote research and development of operational methods to determine sea ice thickness; in particular, by enhancing the Antarctic ice thickness-monitoring project. Develop appropriate best practices via establishment of ‘observer’ protocols and standard suites of instrumentation for in situ sampling and coordinate amongst respective communities (e.g. ASPeCt standard for sea-ice observation; CEOP standards). Ensure that moorings in oceans with ice cover contain Upward Looking Sonars to measure ice draft.
- Continue to develop and improve methods for estimating the spectral properties of snow and ice from optical satellite sensors.
- Propose and forge relationships for developing a virtual multi-frequency, multi-polarisation SAR constellation for meeting cryospheric requirements for: routine and frequent mapping, InSAR for topographic change and ice dynamics; and snow mapping.
- Prepare for the deployment of CryoSat-2 and plan for a laser altimeter successor to ICESat.
- Foster development of Arctic and Southern Ocean–Antarctic observing systems, including their ocean and terrestrial and atmospheric components such as Arctic-HYCOS (Hydrological Cycle Observing System).
- Develop observer networks for river ice, lake ice, and snow, via schools and native communities.
- Create a global 2-dimensional glacier inventory as a reference for assessing glacier change.
- Establish an IPY data management structure (or Data Information System) and standardize metadata principles (e.g. unique meta-tagging of all IPY legacy data for archive retrieval).
- Identify and initiate data rescue and reprocessing of historical benchmark datasets.
- Assist WMO and ICSU in establishing a Global Cryosphere Watch.

Adopting these recommendations will ensure that IPY legacy data sets are available as benchmarks for gauging future climate change, that important in situ observational networks are reinvigorated, that plans are made for follow-on programs for key spaceborne sensors (e.g., passive microwave imaging systems), and that innovative data management systems deliver data and GIS services to the science community, policy makers, and the public.

Mid Term (2010-2015):

- Develop integrated, operational analysis products based on cryospheric data assimilation, models, satellite, and in situ data, and develop an operational cryospheric forecasting capability.
- Implement a dual and high frequency radar mission for snow water equivalent and an extension to the Global Precipitation Mission (GPM) for solid precipitation.
- Develop an integrated data processing capability for cryospheric products from a SAR virtual constellation.
- Launch a high latitude radar altimeter successor to CryoSat.
- Implement recommendations of the International Conference on Arctic Research Planning (ICARP) Working Group on Terrestrial Cryospheric and Hydrologic Processes and Systems. Augment selected supersites, and extend essential geographic networks to obtain appropriate measurement density and distribution, for representative data. Employ station autonomy and near real-time telemetry to facilitate data assimilation and data exploitation for satellite calibration and validation.
- Adopt GCOS climate monitoring principles (GCMP) for all operational satellites and in situ sites.
- Train local community observers and recruit schools for observations of freshwater ice and snow.
- Implement standard data formats for distributed web/Earth data visualization services.
- Recover and reprocess long time series archived data relevant to the development and construction of cryospheric fundamental climate data records (FCDRs).
- Assure that there is adequate temporal overlap to inter-calibrate satellite sensors for consistent time series.
- Collate, digitize and analyze the long-term ice record contained in historic regional ice charts produced by various Northern Hemisphere countries in order to document historic variability and trends in the sea-ice state and the climate over the past 1000 years.
- Undertake extensive reprocessing of all cryospheric variables based on an IPY legacy dataset and better calibrated and validated retrieval algorithms. Initiate an Antarctic reanalysis project.
- Implement an Antarctic Radarsat Geophysical Processing System.
- Ensure that high spectral resolution optical sensors are planned for future satellites.

Adopting these recommendations will solidify our observational understanding of how the cryosphere and climate are changing and form the basis for testing and evaluating predictive models of future climate change along with its consequences for sea level rise and local weather.

Long Term (beyond 2015):

- Develop seamless integration and distribution of cryospheric data products, including data fusion products (e.g., mass balance of sea ice, land ice, snow cover)
- Establish operational, international SAR satellite constellation for all-weather cryospheric remote sensing, retaining essential modes for large-scale mapping, InSAR, and sea-ice charting.
- Ensure continuity in multi-frequency, high-resolution (<12km) passive microwave radiometry – including C-band channel for all-weather surface temperature observations.
- Operationalise satellite SWE and time-variable gravity measurements.
- Implement the P-band microwave concept for ice-sheet sounding, taiga biomass estimation, and potential permafrost applications.
- Evaluate in situ cryospheric reference network (CryoNet) and supplement it with new sites, and retire others, as needed. Ensure that CryoNet is an acknowledged and supported component of the WMO Integrated Global Observing System.
- Develop a large network of autonomous robots, equipped to measure surface energy and mass flux.
- Assimilate cryospheric products in next-generation Earth-system Global Circulation Models (GCMs), operational medium range and seasonal-interannual forecasting models and climate models.
- Develop interannual forecasting capability for ice sheet dynamics, mass-balance changes, and sea level rise rate estimates.

Adopting these recommendations will ensure a required stream of data into models that accurately forecast how the cryosphere will respond to changing climate and how changes in the cryosphere will drive local, regional and global changes in climate.

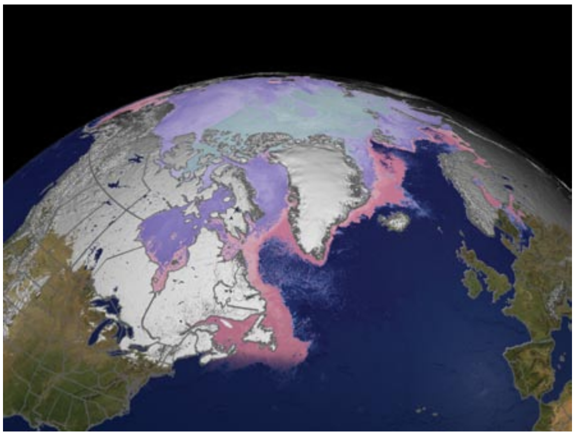
In addition to recommendations on cryospheric observations, the report also proposes more general recommendations on other environmental observations:

- With regard to the surface-based network, initiation of an inventory should be proposed by IGOS for all observing stations and platforms belonging to IGOS Partners, research networks, academies of sciences, and engineering communities, with a view of augmenting their programs with additional multidisciplinary observations. Reporting procedures of these observations should also be considered, noting the capabilities of the modern observational and data relay systems, such as the WMO Integrated Global Observing System and WMO Information System. Data transmission, acquisition, archival, preparation, acceptance and monitoring of adherence to reporting standards need to be reviewed. This activity will be ambitious and difficult, but it needs to be started. The Group on Earth Observation (GEO) is the appropriate organization to initiate the process. Assemblage of a data set of multidisciplinary surface-based and airborne observations during the IPY period could provide the necessary understanding of capabilities of such a system, at least for the polar regions.

- For the space-based system, the most general recommendation of CryOS is to proceed, as quickly as possible, with inter-agency coordination of research and operational missions, so that as complete as possible a data series from multiple sensors is available for users. The Global Inter-agency IPY Polar Snapshot Year (GIIPSY) project is an important step in this direction during the IPY period.

- CryOS recommends the systematic development of standardized distributed environmental data processing, together with the development of commonly accepted standards for data visualization and quality control and assessment.

Initial co-ordination of recommended activities will be undertaken by the World Climate Research Programme's Climate and Cryosphere (CliC) project and by ICSU through the Scientific Committee for Antarctic Research (SCAR) in close cooperation with relevant IPY projects and IPY coordinating structures and bodies. Specific implementation will require involvement of the broader scientific community, national and international organizations and agencies involved in cryospheric observation. ■



Analogous to the CryOS vision for the terrestrial cryosphere, there is high potential to realize a complete picture of marine cryosphere components within the next 10-15 years. This example of snow cover and sea ice temperature over the Arctic from MODIS illustrates one current capability that can be integrated with others to realize this potential. (*Image courtesy of NASA/Goddard Space Flight Center Scientific Visualization Studio*)

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Chapter 1 defines the cryosphere, the objective of the theme, and the scope of the report.

Chapter 2 describes the use of cryospheric data for weather and climate research and for societal applications. Examples of cryosphere-related hazards are given.

Chapters 3-10 list current capabilities and requirements for observing essential climate variables in the major domains of the cryosphere. Each of these chapters contains domain-specific recommendations.

Chapter 11 reviews the cryospheric observing system by observation type; i.e., in situ, satellite, and airborne. Data management objectives are detailed.

Chapter 12 discusses implementation issues and presents implementation actions in three phases.

1 The Cryosphere Theme

1.1 The Cryosphere

The term “cryosphere” traces its origins to the Greek word ‘kryos’ for frost or ice cold. It collectively describes the elements of the Earth system containing water in its frozen state, and includes sea ice, lake and river ice, terrestrial snow cover, solid precipitation, glaciers, ice caps, ice sheets, permafrost, and seasonally frozen ground. The cryosphere exists at all latitudes and in about one hundred countries (Figure 1.1) and has profound socio-economic value due to its role in water resources, and impact on transportation fisheries, hunting, herding and agriculture. Scientific research confirms the pivotal role of the cryosphere, and in particular the polar regions, in climate due to their influence upon surface energy, moisture, gas and particle fluxes, clouds, precipitation, hydrological conditions, and atmospheric and oceanic dynamics. The cryosphere not only plays a significant role in climate; it is a sensitive and informative indicator of climate change.

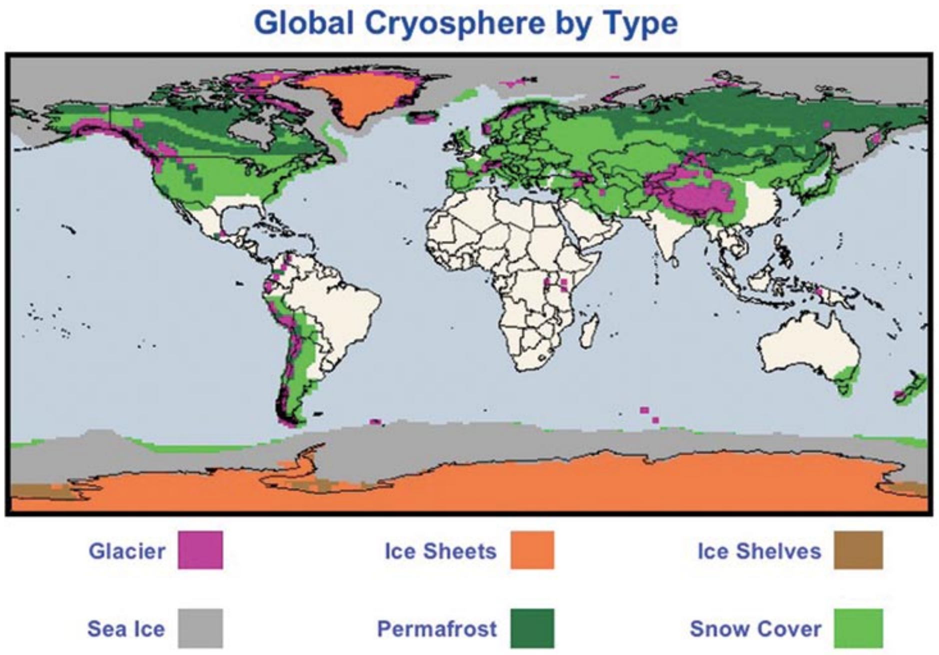
Processes and phenomena involving the cryosphere operate over a wide range of spatial scales from meters to thousands of kilometers. The residence times of water stored in different cryospheric domains (or “elements”) largely involve three time-scales: seasonal-interannual, decadal-centennial, and millennial or longer. Snow cover extent and lake and river fresh-water ice are mostly seasonal, reaching their maximum extent in winter in each hemisphere. Most sea ice is seasonal, except for the central Arctic basin and some locations around Antarctica, where perennial ice may survive to reach several years of age. Water in glaciers, ice sheets, or ground ice, by contrast, may remain frozen for 10 to 100,000 years or longer, and deep ice in parts of East Antarctica may have an age approaching 1 million years. In terms of areal extent, Northern Hemisphere winter snow and ice comprise the largest area, amounting to an average 23% of total hemispheric surface area. Seasonally and intermittently frozen ground occupies 57% of the exposed land area of the Northern Hemisphere. Most of the world’s ice by volume is in Antarctica, principally in the East Antarctic Ice Sheet.

1.2 Scope and Objectives of the Cryosphere Theme

The Integrated Global Observing Strategy (IGOS) Cryosphere Theme is an activity of the IGOS Partnership. Its goals are to determine requirements for cryospheric observations and to prepare recommendations on the comprehensive and efficient ways of developing, coordinating and maintaining those observations and related data. After the recommendations in this report are approved, the cryosphere observing system (CryOS) will enter the implementation stage.

In polar and mountain regions, the cost of in situ observations is very high, and satellite monitoring is able to address only a partial suite of key geophysical variables. Therefore, there is considerable merit in sharing observations that can serve the needs of various user communities and nations. Ultimately, there is also a need to improve the coordination of resources provided by national and international institutional structures responsible for cryospheric observations, and to facilitate the transition of research-based products into sustained monitoring systems. The likelihood of achieving these goals would be significantly enhanced if there was a comprehensive, integrated and coherent approach to the development and international coordination of cryospheric observations by research, long-term scientific monitoring, and operational programmes, and for the generation of data and information needed for both operational services and

Fig. 1.1. Global distribution of the various components of the cryosphere.



research. The Cryosphere Theme will address the major domains of cryospheric observations and data applications: terrestrial, alpine, and marine.

Through the IGOS Partnership there is a potential to develop a comprehensive system of validated remote sensing and in situ observations. For the terrestrial cryosphere, CryOS envisions the capability of providing a complete picture of solid precipitation, snow reserves, river and lake ice, permafrost, glaciers, ice caps, ice sheets and seasonally frozen ground. Elements of such a system already exist (Figure 1.2). In addition to its high value for operational use (e.g., water supply management, flood forecasting, drought prediction, crop forecasts, construction stability assessment, sea level estimates, etc.), this system will bridge meteorological and hydrological applications related to the cryosphere, and ensure the incorporation of appropriate variables in the next generation of climate and hydrological models.

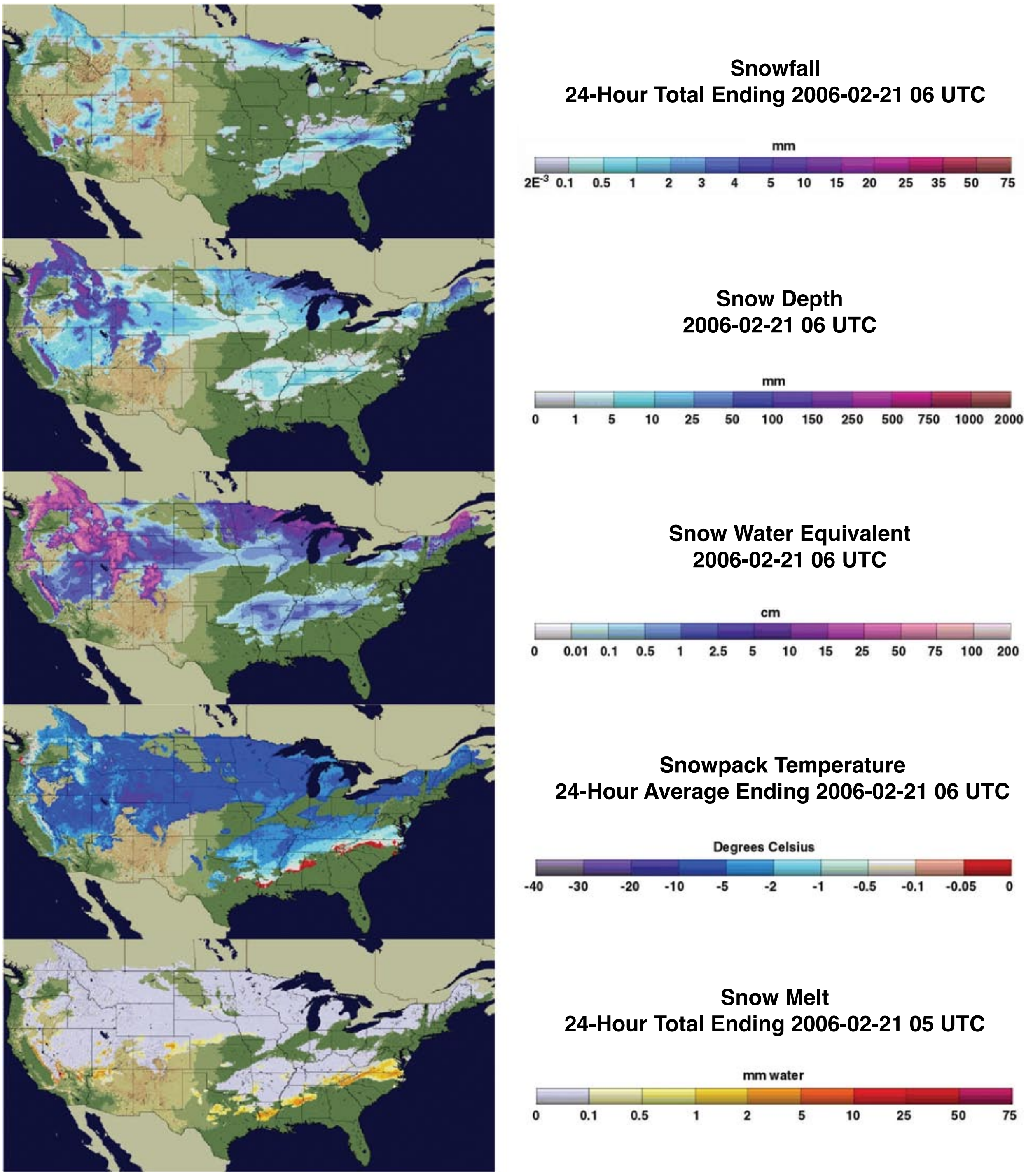
There is a need for a significantly enhanced mountain and plateau cryosphere monitoring system for ice sheets, ice caps, glaciers, and permafrost. The basic challenge here is to transform research-based systems into a sustained, truly global system, complementing the Global Terrestrial Network for Glaciers, and producing data with the accuracy required for the estimation of sea level rise, water management, and disaster mitigation.

For the ocean, CryOS envisions comprehensive observations of sea ice and ice shelf characteristics, the efficient exchange of these data, their use in operational services, and subsequent processing to generate data for research applications and climate studies. The system should incorporate modern advances in satellite systems and air reconnaissance, as well as surface-based and subsurface segments such as ice profiling sonars, sea-ice buoys, ship-borne, and coastal observations. Observations of ocean temperature and salinity from ice-tethered platforms, from moorings, and from the use of 'Argo'-type floats under the ice, plus deployment of novel data collection systems, may close the existing gaps in the polar oceans and turn operational oceanography into a truly global venture.

Many studies require information from all the cryospheric domains. Methods of observation may be similar for the land- and ocean-based cryosphere, and the same satellite sensors and in situ platforms may be used. The principal challenge for CryOS is to identify ways to develop, coordinate and maintain cryospheric observations within the various observing systems and to work through existing coordinating and implementing bodies so that

- the set of cryospheric products to be developed meets most of the identified user requirements, within a 10-15 year time frame,
- arrangements are made to ensure that existing cryospheric data and products are known, available and made openly accessible to the users in an interoperable way,
- resources are identified to improve observations as requirements and technology evolve, and
- there is a stronger commitment by observing system operators to sustain essential cryospheric components of the observing systems. ■

Fig. 1.2. **The CryOS vision of providing a complete picture of the terrestrial cryosphere is demonstrated, to a limited extent, by the National Snow Analyses, produced operationally for the conterminous U.S. by NOAA's National Weather Service.**



A land surface modelling and data assimilation framework, forced by downscaled numerical weather analyses, is used to fuse all available ground observations of snow depth and SWE, airborne SWE observations, and observations of snow cover from multiple satellites into a comprehensive suite of hourly snow information products at 1-km resolution. Development of such approaches to information integration is a key for exploiting the cryosphere observing system.

2 Applications of Cryospheric Data

Cryospheric data are required for weather and climate research and in many types of practical applications such as engineering, services to society, and various types of land- and marine-related resource management.

2.1. Weather and Climate

Cryospheric variables such as solid precipitation, snow cover, snow water equivalent, snowstorms, icing, and river-, lake-, soil-, and sea-ice freeze-up and break-up times are components of weather forecasting in cold climate regions. Ice services provide forecasts for navigation and offshore activities. The performance of numerical weather forecasts strongly depends on the accuracy of initial conditions for predictive models. For example, the European Centre for Medium Range Weather Forecasting (ECMWF) estimates that during the spring season there is decrease in accuracy of the initial conditions for atmospheric temperature and humidity due to problems of satellite retrievals over meltponds in the ice in the Arctic Ocean. This reduces the length of practically useful numerical prediction for Europe by approximately one day (A. Hollingsworth, pers. comm.). Consequently, progress in the remote sensing of sea ice, detection of meltponds, and retrieval of air temperature and humidity profiles over the ice are important concerns for weather prediction.

Links between the cryosphere and climate are numerous. Major factors are the high albedo of snow and ice surfaces, the latent heat associated with the phase changes between ice and liquid water, and the insulating effects of snow cover. The delaying effects of seasonal snow and ice cover on annual energy and water cycles, the fresh water stored in ice sheets and glaciers, and the greenhouse gases locked up in permafrost are also very important. Through these factors and associated feedback processes, the cryosphere plays a significant role in global climate.

A model of the interactions between the physical, biological, and economic systems of the Arctic was proposed by Overpeck et al. (2005), and is shown in Figure 2.1. The left side of the figure gives the current state. Precipitation minus evaporation (P-E), the thermohaline circulation (THC), sea ice, and terrestrial ice are the drivers of Arctic climate, the strongest being P-E and sea ice (based on the number of other hubs they affect). Feedbacks start with the driver hubs and loop back to amplify or dampen an initial change. There are two positive feedbacks: sea ice/THC/P-E and terrestrial ice/THC/P-E. Given the recent decline in sea ice extent, these feedbacks imply that the trend will continue, resulting in the system state illustrated on the right side of the figure.

Beyond the temporal limit of weather predictability (i.e., two weeks), there are several time scales on which the cryosphere significantly affects atmospheric and oceanic circulation and vice versa. Anomalies in snow cover, particularly on the Eurasian continent, and sea-ice distribution are known to affect atmospheric circulation on intra-seasonal to seasonal time scales (Watanabe and Nitta, 1998; Honda et al. 1999; Gong et al., 2003a, b). Prominent modes of climate variability such as El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Northern and Southern Annular Modes (NAM and SAM) are associated with anomalous temperature, precipitation, and atmospheric circulation, which in turn alter the state of the cryosphere (Kwok and Comiso, 2002; Turner, 2004; Ukita et al., 2006). One of the major science questions for climate research is prediction of the future state of all cryosphere elements on the decade to century time scales. That predictability depends in part on the ability of the climate models to represent all the feedbacks associated with the cryosphere.

Key science questions on the role of the cryosphere in climate include:

- What will be the magnitudes, patterns and rates of change in the terrestrial cryosphere on seasonal to century timescales in the 21st century? How will this affect the water cycle?
- What will be the major socio-economic consequences of changes in the cryosphere?
- What is the contribution of glaciers, ice caps and ice sheets to changes in the global sea level on decadal-to-century time scales?
- What will be the nature of changes in sea-ice distribution and mass balance in response to climate change and variability?
- What will be the impact of changes in the cryosphere on the atmospheric and oceanic circulation?
- What is the likelihood of abrupt or critical climate and/or earth system changes resulting from processes in the cryosphere?

Detailed records of past climate are preserved in layers within the ice preserved in glaciers, ice caps and ice sheets, from which we can determine annual variations in atmospheric dust content, atmospheric chemistry, and the isotopic fractionation of oxygen in rain and snow. We can invert the physical and chemical signatures of ice cores to obtain estimates of climatological variables such as surface temperature and annual accumulation, to infer changes in the source regions of deposited water, and even to detect evidence for changes in human agricultural practices. The paleoclimate record from ice cores is particularly significant today because it provides us with a baseline for establishing the context of changes observed in atmospheric chemistry and temperature since the start of industrialization, and the natural variations in the Earth system. The response of the ice to climate change is of interest on time scales from decades to millennia and enables us to address issues ranging from the long-term habitability of the planet to the risk of recurrence of catastrophic events.

2.2. Importance of the Cryosphere for Society

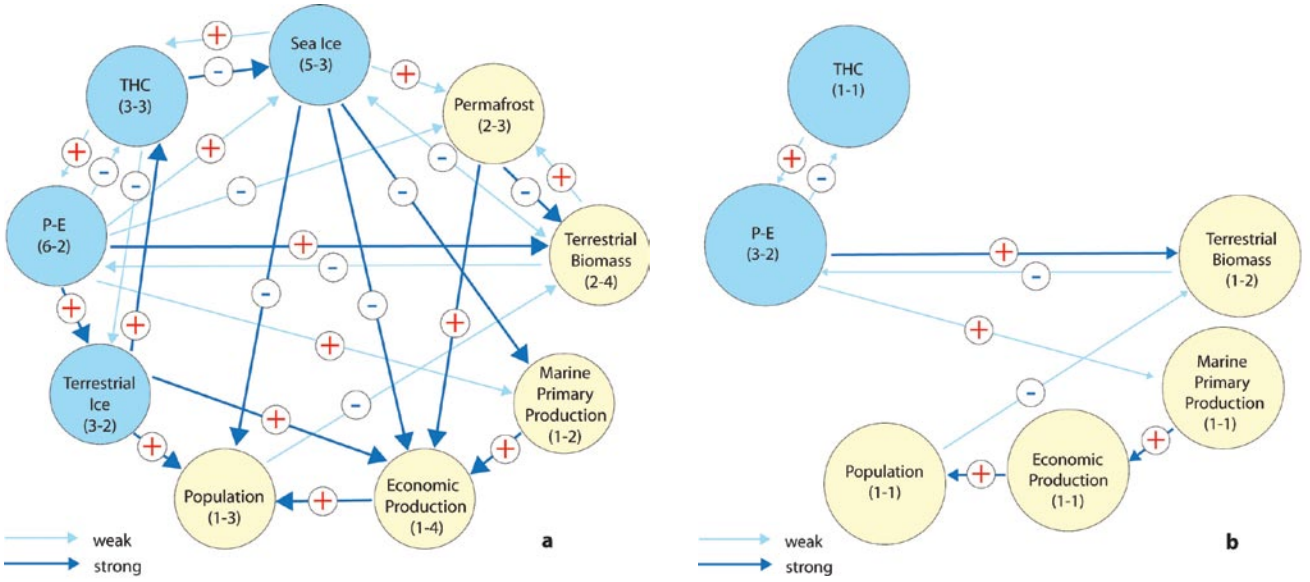
CryOS will contribute to all societal benefit areas of the Global Earth Observation System of Systems (GEOSS). It will

- help reduce the loss of life and property from natural and human-induced disasters,
- provide a better understanding of environmental factors affecting human health and well-being,
- improve management of energy and water resources,
- help us understand, assess, predict, mitigate, and adapt to climate variability and change,
- improve weather forecasting and hazard warnings,
- improve the management and protection of terrestrial, coastal and marine ecosystems,
- help support sustainable agriculture, and
- improve our ability to monitor and conserve biodiversity.

The capacity for better cryospheric observations will facilitate assessments of the socio-economic and environmental impacts of changes in the cryosphere for national and international policy making. Several examples of how the cryosphere affects human activities and life support systems are presented below.

Water Supply: As much as 75 percent of water supplies in the western United States come from snowmelt. The amount of snow and the rate of snowmelt help to govern the timing of spring runoff and the characteristics of annual runoff. Some countries rely on snowmelt forecasting to predict floods and snowmelt runoff and to provide flood alerts. Changes in the amount and timing of melt runoff from mountain snow packs and glaciers will affect water resources in many dry climates, such as the western United States, northwestern China, central Asia, and the Andean countries. They will also affect hydropower operations in the Alps, Scandinavia, Canada and New Zealand and some other regions. For example, in the hot, dry European summer of 2003 (Schär et al., 2004) water shortages and heating of larger rivers had adverse effects

Fig. 2.1. **Schematic of the essential components (or hubs) of the present Arctic System.**



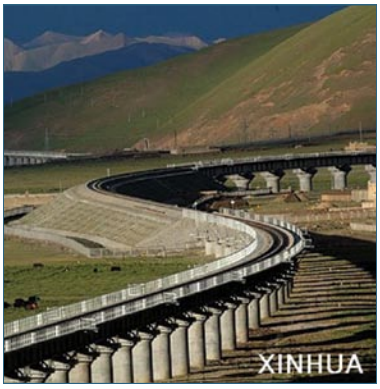
The main interactions between hubs are denoted by arrows: single or double arrowheads indicate one or two-way interactions. Interaction strength is designated by arrow thickness, and the sign (+ or -) indicates whether a change in one component produces a change in another of the same (+) or opposite (-) sign. Numbers in parentheses within each hub indicate the number of interactions going out of, and coming into, that hub. Driver hubs are blue; recipient hubs yellow. The right figure shows the Arctic System in the future after loss of substantial permanent ice.
(*From Overpeck et al., 2005*)

on the cooling of nuclear power plants and subsequent energy production. Millions of people rely on this water resource, and shortages might have severe impacts on economic stability. In addition to the socio-economic impact, there will be direct effects on the functioning of ecosystems in these regions (Barnett et al., 2005).

Sea Level Rise: Sea level rise is a major concern for heavily populated coastal areas and is critical for a number of small island nations. Possible impacts include the relocation of peoples from several atolls in the Pacific Ocean and the flooding of large parts of Bangladesh. While the highly publicized melting of sea ice and the disintegration of massive floating ice shelves do not contribute directly to sea-level rise, the removal of ice shelves may cause previously dammed glaciers to move more quickly from land to the ocean. Although the volume equivalent of glaciers in terms of global sea level rise is small (0.5 m) compared to that of the ice sheets of Greenland (7 m) and Antarctica (about 70 m), their actual contribution to current global sea level rise may be much larger than that from the ice sheets (Church and Gregory, 2001). Modern global climate and ice sheet models suggest that ice sheets will make little contribution to sea level rise in this century, because melting at their edges may be balanced by accumulation in the interior. Nevertheless, recent research suggests that ice sheets can degrade mechanically as well as by surface melting, and that ice sheets can be lubricated at their beds by subglacial streams. Neither mechanical degradation nor subglacial hydrological systems are treated adequately in modern models of ice sheet behaviour, leaving us with the possibility of rapid and currently unpredictable changes in sea-level once certain thermal thresholds are passed.

Coastal Erosion: Arctic coastal soils in many areas include large quantities of ice-rich permafrost. Wave-induced undercutting of the permafrost leads to collapse of coastal bluffs and subsequent erosion by the action of waves and currents. Reduction of the sea ice cover, and especially of the fast ice, also corresponds, in general, to increased fetch of waves allowing them to grow and become more destructive as they approach the coast. Shortened periods of seasonal ice-cover, and later development of the fast ice and its earlier break up, expose coastlines to more severe storms that occur during transition seasons. A very dangerous phenomenon is the ice storm, which occurs when the action of waves and wind puts ice floes and broken ice into motion. Navigation in such conditions is extremely dangerous.

Transportation: Transportation is affected by changes in snow cover, fresh-water and sea ice extent and thickness, and the degradation of permafrost. Persistent reductions in Arctic multi-year sea ice cover would allow marine operations through normally ice covered regions, such as the Northern Route and Northwest Passage. This will benefit marine transportation and related socio-economic developments, such as the exploitation of hydrocarbon resources in the Arctic shelf seas, but represents a risk for marine ecosystems. Snowfall frequency and magnitude directly affect road and rail traffic and aircraft operations. River ice and lake ice provide winter roads for access to remote areas. Thawing of permafrost may lead to the degradation of roads and railroads.



Engineering: The design of buildings and infrastructure in cold climates must consider the presence of permafrost and seasonally frozen ground. Knowledge of thermal and ground ice conditions is critical for sound land use planning and engineering design in permafrost regions. Special design and construction techniques are employed to prevent the thawing of ice-rich permafrost and subsequent thaw settlement and loss of soil strength (which may have implications for infrastructure integrity). In recent years it has become customary to consider the impact of climate warming in engineering design, especially for large structures or those where the consequences of failure are significant (e.g., mine tailing containment facilities, oil and gas pipelines). The development of oil and gas deposits in ice-covered seas and shelves largely depends on the ice regime there and the presence of icebergs, which together determine the economic feasibility of exploration and production projects.

Wildlife: Regional climate change will affect the polar marine environment and wildlife populations on land and sea, including fisheries. Fresh-water ice can have a significant influence on aquatic and riparian ecosystems, geochemical processes, and sediment transport (Ferrick and Prowse, 2000).

Other economic sectors such as recreation (e.g., skiing, snowmobiling, ice fishing) and tourism are significantly affected by short-term and long-term changes in snow and ice conditions and the scenic contributions of glaciers and alpine snow. The insurance industry is also becoming affected by increasing risks associated with changing cryospheric phenomena.

2.3. Examples of Cryosphere-Related Hazards

Avalanches and the collapse of glaciers are well known cryospheric hazards. A particular threat to large regions in the Himalayas and tropical Andes originates from fast growing pro-glacial lakes that are subject to sudden outburst floods (GLOFs), for example triggered by calving or ice avalanches (see Richardson and Reynolds, 2000a for an overview). Stagnant, flat and often debris-covered glacier tongues have been subject to rapid decay in recent decades (Ageta et al., 2000, Watanabe et al., 1995), with meltwater ponds at their surface coalescing to form rapidly growing lakes, often only damned by glacial till having limited stability and the potential for complete rupture (Benn et al., 2000; Richardson and Reynolds, 2000b). Although large-accumulations of snow do not seem as dramatic as avalanches, they may lead to catastrophic spring floods.

(Courtesy of Northwest Territories Transportation, Canada
From: http://www.thedieselgypsy.com/Ice%20Roads-3B-Denison.htm)

Frozen lakes are commonly used for wheeled transportation at high latitudes. The increased variability in break-up and freeze-up dates, as well as the decrease in the time that the lakes are frozen in recent decades, makes such transportation routes dangerous.

The instability of slopes underlain by permafrost may present additional hazards. There may be more slope failures such as active-layer detachments and landslides where permafrost warms and thaws because vegetation has been removed by human activity, by forest fires or by climate change. In the high-mountains, for example, slope stability is often controlled by the presence of permafrost (Davies et al., 2001; Haeberli et al., 1997). Global warming increases the risk of thawing permafrost, threatening people and infrastructure in densely populated valley floors below (Dramis et al., 1995; Haeberli and Beniston, 1998). Numerical models suggest that this destabilization will accelerate (Gruber et al., 2004, Haeberli, 2005).

Icebergs present an extreme hazard to ships because of their large mass, the hardness of the ice and the unpredictable nature of their motion. If they are detected at sufficient range, they can be easily avoided, but detection becomes more difficult in poor visibility and high sea states. Bergy bits and growlers (pieces of larger icebergs) are particularly hazardous in this regard because they are smaller and lower in the water. Offshore platforms, which are less manoeuverable, are at greater risk and, in bergy waters, employ tow vessels to deflect icebergs away from the rigs.

Icebergs, pressure ridges, and grounded pressure ridges (“stamukhas”) can gouge and scour the sea bottom and damage cables, pipelines, and other objects based on the bottom or buried in it. Estimating the risk of sea-ice bottom gouging is necessary for determining safe burial depth for marine cables and pipelines. Greater depths result in safer conditions but the construction costs increase significantly. The optimal burial depth takes into account the expected lifespan of the construction and risks associated with environmental conditions.

Table 2.1 summarizes the priority observations associated with the weather/climate and societal applications described above. The Societal Benefit Areas (SBA) of the Global Earth Observing System of Systems (GEOSS) are indicated. Information on the cryosphere is most relevant to the Disasters, Climate, and Water GEOSS SBAs, but also contribute in the areas of Energy and Agriculture. The link to the Health SBA is primarily through hazards. There are many other socio-economic impact areas not explicitly covered by the general GEOSS headings, such as the impact of the cryosphere on the indigenous communities via impacts on water resources management, hunting, herding, fisheries, and shore-line erosion. ■

Table 2.1. **Applications of cryospheric data and priority observations. GEOSS Societal Benefit Areas are underlined.**

Application	Priority Cryosphere Observations
Monitoring Climate Variability and Change	Long-term, consistent records of all cryosphere variables; advanced in situ observations; medium- and high-resolution optical and microwave imagery and altimetry, interferometry
Weather and Climate Prediction	High spatial and temporal resolution fields of snowfall, snow water equivalent, depth, albedo, and temperature; mapping of permafrost and frozen soil; mapping of river-, lake- and sea-ice characteristics
Water Resources, Energy	In situ observations of glacier characteristics, snow cover, snow water equivalent, river- and lake ice thickness; high spatial and temporal resolution fields from satellite radars of glacier facies, snow water equivalent; mapping of permafrost and frozen soil; temperature; mapping of river- and lake-ice characteristics
Sea Level Rise and the Loss of Coastal Land	High spatial and temporal resolution optical and microwave observations of ice shelves, ice sheet, and land ice mass balance, melt, motion, glacier calving, and fast-ice formation; frequent in situ observations and mapping of ice-rich coastal permafrost
Transportation	Very-high resolution maps of snow depth near transportation routes; long-term, consistent records and improved observations of snowfall frequency and magnitude; river-, lake- and sea ice extent and thickness; monitoring of permafrost status and degradation
Construction and Engineering	Mapping of permafrost and frozen soil and temperature; long-term consistent analyses of snow water equivalent for snow loading design and legislation; mapping of grounded sea ice, sea-ice geometry, depth, strength and drift velocity; river-ice jams
Fisheries and Habitat Management; Ecosystems; Biodiversity	Monitoring of snow and snowmelt runoff to rivers and input to oceans; monitoring of lake- and river ice thickness and dynamics
Agriculture	Monitoring of snow and snowmelt runoff to rivers and input to oceans; mass balance of glaciers
Recreation and Tourism	High spatial and temporal resolution fields of snow depth; land, river, and sea-ice state; monitoring of lake- and river ice thickness
Disasters, Hazards	In situ monitoring of snow microphysical and mechanical properties; high-resolution optical and microwave imagery of avalanche regions, glacial melt water pond characteristics, river-ice characteristics; glacier retreat with lake formation; monitoring of coastal permafrost and status on slopes

3 Terrestrial Snow

Terrestrial snow has the largest geographic extent of the cryosphere components. It covers nearly 50 million km^2 of the Northern Hemisphere in winter, affecting heavily populated mid-latitude regions as well as higher latitudes. Snow is a crosscutting component of the cryosphere that influences surface water and energy fluxes, atmospheric dynamics and weather, frozen ground and permafrost, biogeochemical fluxes, and ecosystem dynamics. The high albedo of snow reduces solar energy inputs and promotes lower surface temperatures. The low thermal conductivity of snow allows it to insulate the land surface from large energy losses in winter and reduce the severity of soil frost. Snow smoothes the land surface, reducing wind resistance and modifying energy exchanges with the atmosphere. These interactions and the large latent heat of fusion strongly influence the land-surface energy budget, with local and regional effects on atmospheric circulation that are now known to propagate globally. The magnitude and timing of snow accumulation and melt are also primary controls on ecosystem carbon exchange in many seasonally snow-covered areas. By constraining the length of the growing season and affecting water availability and the soil thermal regime, snow accumulation and melt directly control the timing of carbon uptake by vegetation and the magnitude of winter CO_2 efflux from soil, and indirectly control rates of carbon uptake through freeze-thaw controls on soil decomposition, respiration and nitrogen availability. Snow must be accurately represented in water, weather and climate, and ecosystem models for a wide variety of science and decision-support applications. Observations of several key snow properties are essential to support these models.

The high sensitivity of snow to changes in temperature and precipitation makes it a primary indicator of climate change and implicates it in climate change hypotheses concerning redistribution and acceleration of the water cycle. Reduced snow accumulation and changes to the seasonal timing of accumulation and melt are projected. Evidence suggests that these changes may already be occurring, but this is complicated by the characteristically high variability of snow regimes throughout a wide range of spatial and temporal scales. Observations revealing this variability are particularly important for understanding variability and change and for validating hypotheses of future snow conditions.

Several snow properties must be observed to support the many different Earth-system science and socioeconomic applications (Figure 3.1). Observations of snow cover, water equivalent, depth and albedo are widely applied. Observations of snow density, temperature, microphysical properties, and chemistry are comparatively uncommon, but the need for these is rapidly increasing with the widespread use of more sophisticated snow models in water, weather and climate applications and with expanding interest in the role of snow in the carbon cycle, water quality and ecosystem dynamics.

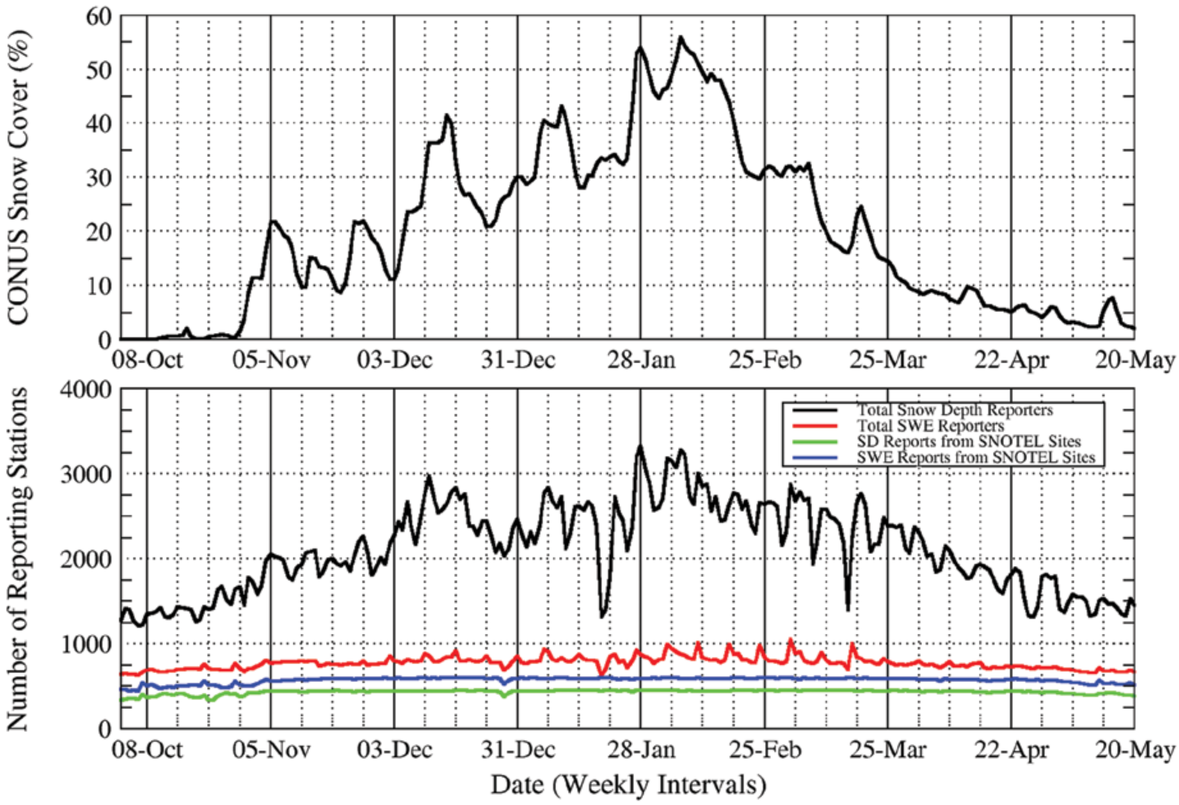
Observation of the *daily geographic extent of snow cover* is essential because it enables inference of several first-order effects of snow on many Earth systems. It is used in many models as a fundamental control on hydrologic, atmospheric and ecosystem processes. Observation of *snow water equivalent* (SWE; the total water content) is also essential. Unlike snow-cover extent, SWE provides quantitative information about both mass and energy that defines the volume of water storage and establishes "memory" and first-order predictability for hydrologic and atmospheric systems. SWE is the principal snow observation needed for most water resource applications and it complements precipitation observations. Observation of *snow depth* is required for many applications and holds the greatest popular interest. Snow depth is used by atmospheric models to estimate surface roughness and is a key factor in determining the insulative properties of the snowpack for soil and ecosystem applications. Depth observations lack direct information about water content, but can be used with coincident observations (or estimates) of *snow density* to calculate water storage. Observation of *snow albedo* is required to accurately determine radiation and energy budgets. Snow albedo varies widely (between 35-95%) and is sensitive to dynamic snow conditions that can be difficult to model and are not normally observed, including grain size and contamination by dust and soot. Snow albedo observations help avoid these difficulties. Observation of *snow temperature* is also important for determination of energy budgets and related processes such as snowmelt. Modelled temperatures for the snow surface and internal volume are sensitive to errors in model forcings and fluxes; they propagate to subsequent radiative and turbulent fluxes, impacting estimates of water and energy budgets and the timing of snowmelt. Accurate temperature observations help constrain such errors and increase confidence in model results.

Observation of several additional microphysical and mechanical snow properties is important, including *grain size, grain shape, stratigraphic structure, hardness, liquid water content, strength* and *stability*. These are required for evaluation of avalanche hazards and are important for many other applications. Because all snow processes (including electromagnetic interactions that govern remote sensing observations) depend fundamentally on these properties, model development, parameterization and testing, process understanding, and advancement of snow observing systems depend on observation of microphysical properties of snow. Finally, observation of the *chemical and nutrient constituents* within snowpacks is required to assess biogeochemical fluxes and estimate potential impacts on water quality and ecosystems when these constituents are released through snowmelt. Acidic constituents from precipitation ("acid snowfall") are stored in the snowpack and preferentially flushed out in the initial stages of snowmelt, resulting in an ionic pulse with acid concentrations many times higher than averages for the whole snowpack. Observation of *trace gas fluxes* through the winter snowpack is essential for determining the net carbon balance of snow-covered ecosystems. Winter respiratory carbon dioxide losses from these ecosystems are high, and over half of the carbon assimilated by photosynthesis in the summer can be lost the following winter. Measurements of atmospheric CO_2 amount over the snowpack are necessary to provide accurate estimates of the annual net ecosystem exchange of carbon and of carbon sequestration/emission.

3.1. Status of Observations

Snow properties are observed using a wide variety of instruments and systems on surface, airborne and space-borne platforms. Some of the surface-based methods include: graduated probes and stakes, acoustic snow-

Fig. 3.1. Percentage of snow-covered area within the conterminous U.S. during the 2003-2004 season with corresponding unique snow depths and SWE.



The upper plot shows the percentage of snow-covered area within the conterminous U.S. during the 2003-2004 season. The lower plot shows the corresponding number of unique observations of snow depth (black line) and SWE (red line). The number of snow depth observations is highly correlated to the amount of snow cover, while the number of SWE observations is relatively constant and remains near 800 per day, nationwide. Compared to most regions, this constitutes a dense network of snow-reporting stations, although it represents a density of only one station per 6000 km^2 for the snow-affected portion of the country.

depth sounders, snow coring devices, snow pillows (pressure transducers), and excavation of snow pits with detailed sampling using various instruments. Some of the remote sensing methods include observation of terrestrial gamma radiation from low-flying aircraft, observations of visible and infrared radiance from aircraft and both low Earth-orbit (LEO) and geostationary (GEO) satellites, and observations of microwave emissions and backscatter using passive and active sensors on aircraft and LEO satellites. These observations are used and combined in many different ways, depending on the application, required scales and accuracies and the types of observations available. Current measurement accuracies and requirements are given in Appendix B, Table B.1. In addition to the standard parameters listed (snow cover, depth, and water equivalent), there are other snow parameters that are not in the table but are important for some applications, e.g., layer snow temperature, layer boundaries, hardness, grain form, grain size, density, strength, and stability.

Worldwide, many surface-based snow-observation networks have diminished or have been completely lost. Those that remain provide valuable snow observations. Most are small networks operated at relatively local scales, and often are heavily dependent on cooperative observers (usually volunteers) to collect and report observations. There are important exceptions, such as the National Resource Conservation Service SNOTEL network, that provide automated SWE observations hourly or daily at over 600 stations in the western U.S. Overall, snow observations are sparse. The most common observation is snow depth. Far fewer SWE observations are available, and observation of other snow parameters is extremely limited.

Most surface-based approaches result in a single snow measurement at individual points. Numerous measurement tools and instruments are used, with widely varying accuracy and precision and with sampled area ranging from less than 1 cm^2 to a few square meters. This is a problem because the fine-scale spatial variability in snow properties is characteristically large due to effects of wind drifting and underlying vegetation and topography. Point observations are only representative of relatively small areas. Furthermore, some measurement approaches are destructive, including probes, coring devices and snow pits, and require that subsequent observations be made in adjacent locations. Relocation of the measurement point in conjunction with the fine-scale variability contributes noise to time series records. Multiple point measurements (e.g. snow courses) can overcome sampling problems associated with spatial variability, but the number of samples required can be prohibitively large.

Remote sensing offers greater spatial coverage and sampling over larger, more representative areas. Airborne measurements of naturally occurring terrestrial gamma radiation have been used for more than 30 years to observe SWE along flight line transects, and are still used operationally in the U.S. by the National Weather Service. Gamma radiation emitted from isotopes in mineral soil is measured from low-flying aircraft during both snow-free and snow-covered conditions. The attenuation of gamma radiation by water (in any phase) is well known; by accounting for attenuation by soil moisture and atmospheric water vapor, the difference in observed radiation can be attributed to SWE. The insensitivity to the phase of water can be advantageous over some surface-based approaches, which do not always effectively sample solid ice layers, extremely wet snowpacks, and snowpacks with loose grains. The approach cannot work from space, however, because the relatively weak terrestrial radiation signal is fully attenuated by the tropospheric water column.

Observations of snow-cover extent from visible, near-infrared, and microwave sensors on Low Earth Orbit (LEO) and Geostationary (GEO) satellites have been widely used since 1966. Since that time, NOAA has mapped the areal extent of snow cover in the Northern Hemisphere on a weekly basis using optical satellite imagery (e.g., Advanced Very High Resolution Radiometry (AVHRR) and Geostationary Operational Environmental Satellites (GOES)). This data set is the longest satellite-derived record (> 30 years) of snow extent. It has been used as the basis for many analyses of snow cover variability and change on a hemispheric and continental basis (e.g., Robinson et al., 1993). The first-order importance of snow cover in several land-surface processes makes this long-term record extremely valuable. Continuation of this record is based on AVHRR and Moderate Resolution Imaging Spectroradiometer (MODIS) optical/infrared data and Special Sensor Microwave/Imager (SSM/I), and Advanced Microwave Scanning Radiometer for EOS (AMSR-E) is expected in the future. Visible and near-infrared sensors aboard several LEO satellites also provide observations of broadband snow albedo with 5-10% accuracy. Space-based capabilities for observing snow depth and SWE are much more limited. Microwave sensors appear ideal for this purpose, but current sensors lack optimal combinations of frequencies and resolutions. Observations of upwelling microwave radiance at two frequencies (typically 19- and 37-GHz) using passive microwave radiometers have provided useful estimates of both snow depth and SWE, but their low spatial resolution is an important limitation and is poorly suited for mountainous areas. Moreover, current approaches are somewhat under-determined, as microwave sensitivity to other snow and land-surface properties (e.g. grain size and forest characteristics) complicates interpretation of the signals. Currently the most accurate estimates are obtained from region-specific empirical algorithms, where limiting the geographic domain helps to reduce the variation of sensitive factors. SAR observations overcome the resolution problem, but current sensors operate at frequencies too low to be useful for most snowpacks.

3.2. Shortcomings in Current Observations

Surface-based observations are essential for many applications and remain the only available means of observing many snow properties. However, they cannot provide the comprehensive coverage needed. Moreover, their effective use and integration is challenged by several major problems that contribute to high uncertainties in the data.

In situ capabilities have declined, with a decrease in networks and the relative lack of detailed in situ data undermining the validation of automated sensor data. There are significant data gaps in latitudes north of 60° N and in all southern latitudes, with sparse in situ measurements and resultant difficulties in validating remote sensing retrievals.

Although SWE is critically important, at best SWE observations are very sparse and are totally absent in many regions. Large observation gaps result. In the context of large spatial variability, interpretation of a few isolated snow observations is very difficult. The lack of nearby supporting observations increases the uncertainty of available observations. Furthermore, many applications require numerous observations to assess water storage or interpret patterns, variability and change. Sparse SWE observations limit interpretation to large regions and don’t resolve important local-scale variability.

Following snow depth and SWE, the observation of other snow properties is rare and occurs primarily within the realm of research studies or specific applications such as avalanche hazard assessment. Energy- and mass-balance snow models, now widely used for many applications, are highly nonlinear and include several interacting variables. These models are under-constrained by mass-oriented observations of SWE or snow depth alone. Snow temperature observations are necessary to constrain the energy states of these models. Observation of a broader set of snow microphysical and chemical properties is becoming increasingly important for coupled modelling of climate, ecology and carbon cycling.

The value of snow observations is often substantially reduced by large inconsistencies in measurement methods, observation frequency and reporting times and standards. Daily mosaics of observations at national and global scales are both spatially and temporally incoherent and noisy. Accumulation of observations over larger regions and time periods is one solution, but the loss of resolution is unacceptable for many applications.

Many surface-based snow observations lack sufficient metadata. Often, little more information than a geographic location is available. Validation of station location information often reveals compelling evidence that available metadata is incorrect. Confidence in snow observations is very dependent on accurate and comprehensive metadata. The value of an observation is greatly diminished without it.

Snow observation sites are often not representative of surrounding areas. This results in observation biases that can be easily propagated to large regions through modelling and data assimilation. In some cases, entire networks are intended for specific purposes that do not require unbiased observations. In others, the cause may be programmatic (e.g. many snow depth observations are collected at relatively windswept airports where other meteorological data are collected), or simply a matter of where observers are available. Such biases are common and can be quite large, but the magnitude is most often unknown. The problem is exacerbated when metadata is lacking for evaluation.

Growing awareness of the effects of vegetation growth near observation sites has significant implications for climatological interpretation of snow observations. Trees and other vegetation strongly affect local snow accumulation patterns, with both increasing and decreasing snow accumulation depending on the size, type and configuration of vegetation. Credible interpretation of long-term snow accumulation trends demands accounting of changing vegetation conditions, but such changes are poorly documented at most snow observation sites. Reconstruction of past vegetation change on a site-by-site basis would require a major effort.

Most surface-based snow-observing systems exist for specific users and applications without larger purpose or oversight. Internationally accepted observation standards and guidelines exist, but awareness of these is often low. Network operators and observers are under little or no obligation to follow them and may have valid reasons not to. A lack of coordinated focus on snow and other cryosphere observations among major organizations responsible for surface-based observations perpetuates these problems. Consequently, while surface-based snow observing systems may meet specific needs, they lack the ability to provide large-scale estimates for hydrological and climatological analyses and models.

Remote sensing observations are required to augment and complement surface observations. Future routine measurement of snow areal extent is dependent upon the successful launch of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Visible Infrared Imager Radiometer Suite (VIIRS) and Conical Scanning Microwave Imager/Sounder (CMIS), which are delayed, and similar sensors on the European Meteorological Operational (MetOp) satellite series. Space-based observations are the only viable means of filling gaps in surface networks and can provide additional information not easily observable on the ground. The consistent, systematic, nature of satellite remote sensing helps overcome some of the functional inconsistencies of surface-based observations.

However, there are important shortcomings in remote sensing capability as well. Validation remains a challenge for estimates of snow depth/snow water equivalent using satellite passive-microwave data. Algorithms require regional tuning to account for variable landscape and physical properties effects.

A major challenge in remotely mapping snow cover is the successful identification of contributions to the measured signal from vegetation, snow, and the underlying soil. This is not possible using a single-frequency scatterometer alone. One thing that could possibly help in the future with this problem is a scatterometer that operates at multiple frequencies and a dual-frequency radar altimeter, e.g., Envisat.

The operating resolution of most snow and land-surface modelling has far surpassed that of microwave sensors with significant capability to observe SWE and snow depth. Over the past decade, predictive modelling has been driven to high resolutions by the importance of local-scale understanding and the need to include fine-scale processes in models, and has been enabled by rapid computational advances and cost reductions. Large-scale hydrometeorological models operating at 1-5 km resolution are now common, and further resolution improvements are expected within the next few years that will be important for coupling with carbon and ecosystem models. High-frequency microwave sensors necessary to observe SWE and snow depth have not improved commensurately. Available active and passive sensors with appropriate frequencies, such as QuikSCAT, SSM/I and AMSR, were not developed for terrestrial applications and have spatial resolutions of 20 km or more. This significantly limits their use in contemporary terrestrial modelling applications. It also complicates retrieval of snow properties in many environments, especially in mountainous regions.

The skill of SWE and snow depth retrievals using available microwave sensors and algorithms is generally insufficient. This is due partly to the low resolution of the sensors and the complexly mixed signals that result from sub-footprint variability in snowpack and land surface characteristics. Regional tuning of empirical algorithms has been successful in some cases, but this approach has not been widely adopted and has some of the same risks of inconsistencies as surface-based networks. Some regions lack sufficient surface-based snow observations needed for tuning. The lack of skill also results from fundamental limitations of the algorithmic approach commonly used, which is generally under-determined and is limited on physical grounds to SWE less than approximately 20 cm. The satellite observations have greater potential than is currently achieved. Advancements in retrieval methods need to use microwave and ancillary observations more effectively.

Observation of snow cover extent is reasonably mature, but there are remaining difficulties in discrimination of snow and clouds. The spectral resolution, bandwidth and dynamic range of available optical sensors on both LEO and GEO satellites are fundamental constraints. Improved multi-spectral imaging is needed to address this problem. Observation of cloud motion from GEO sensors can improve discrimination. In this case improved spatial resolution is needed to resolve textural differences.

The observation of broadband snow albedo from space-based sensors, including AVHRR, MODIS, and Multi-angle Imaging SpectroRadiometer (MISR) is sufficiently accurate (5-10%) for many applications, but snow energy exchanges can be sensitive to small albedo differences. Increasingly, modelling applications require both visible and shortwave-infrared albedo, which is achieved now by compositing multiple scenes with an associated loss of resolution due to geo-registration limitations. Improvements in optical sensors and geo-registration accuracy are required to support multi-band albedo with sufficient resolution.

Remotely sensed surface temperatures could be very useful to help constrain the energy components of contemporary snow and land-surface models, but the currently attainable accuracies over snow are insufficient for this purpose. The nonlinear behaviour of snow near 0^{o}C and the tendency for propagation of errors in snow surface temperature requires observation accuracy on the order of 1^{o}C or less. ■

Recommendations: Development of Snow Observations

R3.1 A coordinated plan for surface-based snow-observation networks must be developed, first at the national, then at the international level. The plan should address the needs for improved consistency in observation methods and reporting standards and for improved exchange of data. It should address current and emerging needs for measurement of other snow properties besides snow depth and SWE. A consistent approach to compiling and using considerably improved metadata for snow observations is needed.

R3.2 The capability of satellite observations must be improved. The development/validation of satellite remote sensing techniques, including the validation of existing products, support of new systems (e.g., European Global Precipitation Mission (E-GPM)/CGPM and CloudSat for solid precipitation), and support of algorithm development is required. High-frequency active and passive microwave observations, which are uniquely well-suited to observing SWE and snow depth, have low spatial and spectral resolution. Improved instruments with higher spatial and spectral resolution are required. High-frequency (Ku, X-band) SAR should be considered a priority for global SWE observation.

R3.3 Priority should be given to research and development of algorithms and new sensors to measure SWE, under a wide range of vegetation conditions. Furthermore, it may be possible to design improved algorithms to more effectively use existing data sources. Further research is necessary to realize the retrieval of SWE from SAR data, with their higher spatial resolution; SAR is the only instrument capable of mapping wet snow cover at the fine spatial resolution required in mountainous terrain (where the hydrology is dominated by the melting snow pack).

R3.4 Techniques must be developed to merge *in situ* measurements and satellite retrievals. Targeted field projects should be conducted to deal directly with the measurement of snow in multiple environments. These should seek to advance coordinated remote sensing of snow albedo and surface temperature (i.e. optical measurements) together with SWE and snow depth (i.e. microwave measurements). Study areas for intensive field campaigns should be established with long-term plans to maintain them as “Super Sites” to improve knowledge of snow processes and to provide reference targets for multi-sensor remote sensing and modelling applications.

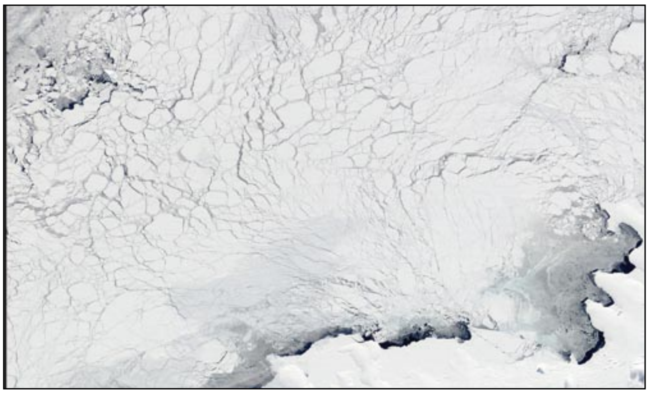
R3.5 Integrated multi-sensor data fusion and global analysis systems that blend snow observations from all sources must be improved. The ideal global snow observing system will use observations from all relevant sources in coherent, consistent high-resolution analyses of (at a minimum): the extent of snow cover, snow depth, SWE, snow wetness, and albedo. No current system provides global coverage, and a more complete system would include snow albedo and temperature, microphysical properties, and chemical constituents. Improved algorithms for the objective, optimal combination of snow observations from widely disparate sources must be developed. These must address both mass and energy considerations of snow models.

4 Sea Ice

A significant fraction of the world's oceans is covered by sea ice. Its areal extent varies seasonally from 7 to 16 x 106 km^2 in the Northern Hemisphere and from 3 to 19 x 106 km^2 in the Southern Hemisphere accounting for ~10% of the hemispheric surface area at respective winter peaks. Level sea ice in the Northern Hemisphere is up to 2 meters thick in the seasonal ice regions and averages up to 4 meters thick in the perennial ice regions. It is about half as thick in the Southern Hemisphere. The characteristics of sea ice vary regionally, particularly between the Arctic and the Antarctic.

Sea ice is considered a key component of the climate system for several reasons. It limits exchanges of heat and moisture between the ocean and the atmosphere. Because of the large difference in reflectivity between ice (which is bright) and ocean (which is dark), a reduction in the extent of sea ice will result in more heat being absorbed by the ocean instead of reflected back into the atmosphere. This is likely to amplify the effect of warming in high latitudes, making the extent of sea ice a potential early and sensitive indicator of climate change. Sea ice also redistributes salt and freshwater, as it rejects brine when it freezes. Brine rejection in turn produces saline, cold, and thus dense water in convective regions and polynyas, mainly in the subpolar North Atlantic and the coastal region of Antarctica. The seasonal sea-ice zone is highly productive biologically, which makes sea ice a key component in the carbon cycle. Fast ice, regions of non-moving sea ice attached to the coast or to ice shelves, provides important habitats for wildlife, and the shear zone between fast and drifting ice frequently results in open water in these regions, to the benefit of the biota.

For the Arctic, observations over the last few decades indicate significant decreases in the total area and extent of sea ice (Parkinson et al., 1999; Bjørgo et al., 1997) and in its thickness (Rothrock et al., 1999; Wadhams and Davis, 2000; Tucker et al., 2001), both in summer and year round (Figure 4.1) (e.g. Serreze et al., 2003; Comiso, 2002). In contrast, there is no overall decrease in sea ice cover around Antarctica, although regional patterns are evident, with growth in sea ice cover in the Ross Sea and declines west of the Antarctic Peninsula (e.g., Parkinson et al., 1999). The rapid decline of the Arctic perennial ice cover reported by Comiso (2002) and projected by the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (*IPCC, 2001. Climate change: The scientific basis*) and the Arctic Climate Impact Assessment (ACIA, 2005), suggest that the Arctic sea ice could become seasonal. Such a change would have profound climate implications, and would deeply affect the Arctic ecosystem and Arctic residents.



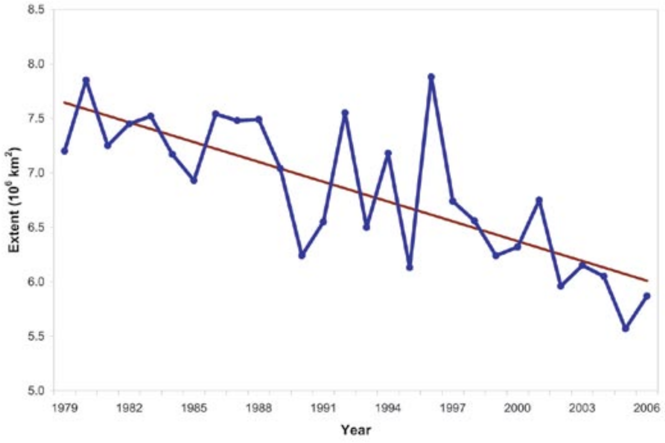
Observations of sea ice are needed to support a range of scientific and socio-economic applications. Although surface observations provide the best quality data, the high spatial variability in sea-ice properties means that local surface observations may not be representative of the surrounding regions. Observations from ships and aircraft cover larger areas, but cannot cover entire ice-covered seas. Spaceborne observations do provide such cover, but have limited spatial-temporal resolution, suffer from inconsistencies between datasets, and lack rigorous validation.

Basin-scale observations of sea ice *concentration/extent, thickness distribution, motion, melt, albedo,* and *temperature* are required to understand the large-scale dynamic and thermodynamic evolution of sea ice cover seasonally and from year to year. Continuous time series of these parameters can be used to detect long-term trends in sea ice cover. Along with a precise knowledge of the *ice edge location* and *ice age/type* (or *stage of development*), these parameters are also required for safe navigation and operational support in ice-covered waters (discussion of operational ice observation needs can be found in WMO, 2006). Ice concentration, thickness distribution, and motion are also required for calculations of ice mass balance.

Other parameters such as *sea ice thickness, snow cover, meltponds, leads, and ridges*, and their distributions also play a key role in the large-scale evolution of sea ice, as well as in the local surface energy budget, but are difficult to measure except at the local scale. Observations of these parameters at the local scale are needed for navigating through the ice with icebreakers, and under the ice with submarines.

Even smaller-scale properties, such as *sea ice texture, brine content,* or *frost flowers*, are important for understanding the local thermodynamics of ice growth, the role of sea ice in chemical interactions with

Fig. 4.1. **Arctic sea ice extent trend for September 1979-2006, from passive microwave sensors (SMMR-SSM/I).**



The linear trend, -8.9%/decade, is denoted by the blue line. (*Data courtesy National Snow and Ice Data Center*)

the atmosphere, and the development of the radiative properties of the ice as detected by remote sensing instruments. Better observations of these small-scale parameters will help resolve ambiguities in the larger-scale satellite data products. Observations of *biological and chemical constituents* are important for understanding the ecosystems associated with sea ice, but are currently limited.

Observations of sea ice are needed not just in their own right, but also as key inputs to numerical models of the sea-ice system on the one hand, and of the ocean-ice-atmosphere system and climate on the other hand. Operation models are now available for synoptic (24-120 hour) and seasonal (1-6 month) forecasting.

4.1. Status of Observations

Sea-ice properties are observed by surface, ship, airborne, and spaceborne systems (Lubin and Massom, 2006). The location of the sea ice edge in some parts of the Arctic has been observed for over a thousand years. In contrast, the first quantifiable observations of sea-ice properties came from ships sailing in and near ice-covered regions in the early to mid 1800s. The early observations were widely scattered, collected by inconsistent means, and limited in quality. Modern ship observations of sea ice have been standardized for the Southern Ocean through the Antarctic Sea Ice Processes and Climate (ASPeCT) protocol (Worby and Ackley, 2000). That standard has not yet been applied to the Arctic. National ice services began routinely producing ice charts for the Arctic in the 1950s. Antarctic ice charting began in the 1960s. Until the 1970s ice charts relied upon ship and aircraft observations, after which remote sensing from space began and has continued to grow. Submarine sonar observations of ice draft under the Arctic sea ice began in earnest in the 1950s, though the data are sparse and remained classified for decades. Upward-looking sonars (ULS) give thickness and volume flux estimates from below. Electromagnetic (EM) sensors mounted on ships, surface vehicles, low flying helicopters or fixed-wing aircraft can give thickness estimates from above the surface. Surveys using new airborne lidar methods can now provide thickness data for large regions. Other sensors on helicopters or aircraft provide observations at scales between surface and satellite observations, which are particularly useful for highly variable properties such as snow and meltponds. More recently, near-surface observations have been taken from autonomous underwater vehicles (AUV), which are essentially small, unmanned submarines, and from unmanned aerial vehicles (UAV), although their small size limits the type of sensor that can be carried.

Manned Russian “North Pole drifting stations” have operated from the Arctic sea ice between 1937-1991 and since 2003. Several temporary field camps have been established on the ice, between the Arctic Ice Dynamics Joint Experiment (AIDJEX) in 1975 and the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment during 1997-1998. More of such expeditions will occur during the International Polar Year. Though sporadic in time and space, these field expeditions obtain intensive observations from a focused area, providing fine-scale estimates useful for calibration, validation, and parameterization development, as well as for understanding physical processes. Autonomous buoys were deployed in the Arctic during the 1950s, within the Russian Drifting Automatic Radio-Meteorological Station (DARMS) programs, and since 1970s within the International Arctic Buoy Programme (IABP), providing observations of Lagrangian ice drift and meteorological conditions at scattered locations. More recently, deployments of Antarctic buoys have begun through the International Programme for Antarctic Buoys (IPAB), while in the Arctic mass balance buoys are now being deployed to obtain ice/snow thickness and internal temperatures.

Surface and near-surface based approaches are limited in their coverage, with single measurements or a small suite of instruments distributed over a limited area for a short duration. Because sea ice varies over short spatial scales, point or transect measurements are rarely representative of the surrounding conditions. Nonetheless, such approaches are valuable for understanding processes that occur at scales that cannot be resolved by satellite. They also provide key information for sensor calibration and validation and for developing parameterizations for sea-ice models.

Satellite-borne visible/infrared sensors obtain observations of albedo, temperature, snow cover and radiative fluxes. They can also obtain information regarding extent, concentration, motion, and melt, but coverage is limited due to frequent cloud cover. The NOAA AVHRR provides a time series of products from 1981 at spatial resolutions of 1-5 km. The NASA Earth Observing System (EOS) MODIS sensor, operating since 1999, yields significant improvements over AVHRR in both number of channels and spatial resolution (250-1000 m). MODIS is a research sensor, not designed for use in routine operational applications, though it has been successfully employed to this purpose for some parameters. The NPOESS VIIRS sensor is planned to follow MODIS, but has been delayed.

Satellite-borne dual-polarized, multi-frequency passive microwave radiometers began operating in late 1978 and have continued since, providing near-complete daily coverage of the polar regions under all sky conditions for geophysical parameters such as concentration/extent, motion, melt, albedo, and temperature. These time series extend back to late 1978 from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) through a series of Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) sensors, providing more than a quarter century record that can track inter-annual trends and variability. However, there are several uncertainties with these records. The time series combine data from several sensors. Slight variations in instrumentation and orbit (e.g., diurnal effects due to different crossing times, orbital decay) necessitate inter-sensor calibration for a consistent time series. Unfortunately, in some instances there was minimal sensor overlap for inter-calibration. Another issue is that relevant geophysical parameters are not directly observed but instead must be derived from the sensor-measured properties (e.g., radiance, brightness temperature). The geophysical parameters are derived empirically providing generally accurate results in areas where the emissivity of sea ice is predictable and well defined (as in dry and relatively thick seasonal and perennial ice) but the errors can be considerable in newly formed ice and in melt and melt-ponded areas. There are several sea ice concentration products all derived from the same sensor data, none of which is demonstrably superior in all conditions. Finally, the spatial resolution of these products (10-25 km) cannot obtain important detailed information of the ice cover, such deformation, melt-pond and lead formation, and ridging. Nonetheless, these sensors provide a continuous, reasonably consistent data set that needs to be continued into the future and improved to track the impacts of climate change on sea ice.

The Japanese Advanced Microwave Scanning Radiometer for EOS (AMSR-E) on the NASA Aqua satellite provides more than double the spatial resolution of SSM/I, additional channels, improved products, and entirely new products such as snow depth over seasonal ice and ice temperature (though these new products have not yet been rigorously validated). However, like MODIS, AMSR-E was designed for research, not routine operational observations, though it has shown some utility for such applications. A second AMSR sensor on the Midori-2 satellite failed within months of launch and there are no plans for future AMSR sensors. The NPOESS Conical Scanning Microwave Imager/Sounder (CMIS) was planned as a follow-on, but mission delays make it unlikely that CMIS will overlap with AMSR-E. Passive microwave sensors on Japanese Global Change Observation Mission (GCOM) satellites could fill potential gaps. The newest passive microwave technology is the polarimetric sensor, like the new WindSat/Coriolis instrument, but it is not yet known what enhancements to sea-ice knowledge such instruments could provide.

New technologies have recently been applied to satellite-borne sea-ice remote sensing, including SAR, scatterometry, and altimetry. SAR provides detailed images of the ice cover at spatial resolutions as high as 30 m. The advent of SAR revolutionized the capabilities of the operational centers, allowing much higher quality analysis including information on lead location/orientation, ice type, new ice formation, and ice thickness. SAR instruments on ERS-1/2, Radarsat, Envisat, and Advanced Land Observing Satellite (ALOS) provide useful high-resolution information on deformation, leads, ridging, and new ice production (Figure 4.2). All these parameters are needed to understand the small-scale evolution of the ice cover. Radarsat-2 will continue the Radarsat mission with a launch in 2007. Scatterometry provides information at a similar spatial scale as passive microwave, but can provide better information on perennial ice cover as well complementary information on other properties due to different sensitivities to differences in the ice surface (e.g., melt, snow). The Seasat scatterometer first demonstrated the benefits of such data in 1978 but its mission was short-lived. The ERS-1/2 and NASA (NSCAT) scatterometers launched in the early and mid 1990s, respectively, began the scientific application of routine scatterometer data to operational applications including sea ice. The SeaWinds instrument on the NASA QuikScat and the Japanese Advanced Earth Observing Satellite (ADEOS) have since provided routine polar Ku-band observations since 1999, and the 2006 launch of MetOp-1, the first in a series of three satellites, ensures continuity in the C-band time series of Advanced Scatterometer (ASCAT) measurements for the next 15 years.

The "holy grail" of sea-ice observations is basin-wide surface topography combined with ice and snow thickness distribution. In situ, ship, submarine, and EM observations of thickness are limited spatially and temporally. Airborne lidar can now provide more coverage, but satellites provide the only platform from which frequently sampled basin-scale thickness estimates are possible. The NASA EOS ICESat sensor, launched in 2003, can provide estimates of sea-ice surface elevation, but ICESat has some limitations when it comes to sea ice. Sensor problems have limited operations to three or four short (4-6 weeks) operational periods per year instead of the planned continuous operation. ICESat carries a laser altimeter, and is thus subject to cloud contamination, limiting the geographic coverage of useful surface data at times. The ICESat altimeter measures the elevation at the top of the surface, including the overlying snow cover; accurate estimates of ice thickness require good knowledge of snow depth and density. ICESat was designed primarily for ice sheet and glacier detection, not sea ice, and was originally to have flown in parallel with CryoSat, whose SAR altimeter was optimized for this purpose. Although ICESat may not be sensitive enough to obtain precise ice thickness estimates, it has made a significant step towards routine observation of ice thickness from space, with reasonable basin-wide thickness distribution fields having been produced during intervals of laser operation. Beginning in 2009, CryoSat-2 will enable all-weather sea ice thickness measurements to be continued, with an orbit inclination and sampling pattern allowing measurements closer to the North Pole. **Current measurement accuracies and requirements for sea ice are given in Appendix B, Table B.2.**

4.2. Shortcomings in the Current System

The current sea-ice measurement system has enhanced our knowledge of sea ice. Limitations contribute to lingering uncertainties as follows:

1. There is a need for well-documented operational sea-ice products on a global scale from national ice services that can be easily assimilated in coupled numerical models. There is a need for standards for measurement protocols, data exchange, and data presentation (XML-based, ISO-approved standards).

2. The existence of sea ice concentration products from several passive microwave algorithms has led to confusion among users. The strength of each data product for the various applications should be properly documented and if possible the number of products should be reduced to a minimum, preferably, one. Rigorous evaluation and consolidation of products are needed together with rigorous formal estimates of algorithm uncertainties/errors. Inter-sensor calibration was done only for short overlap periods and seasonal effects are not addressed.

3. Passive microwave and scatterometer-based products are too coarse to obtain fine-scale details of the sea ice cover. The coarse resolution results in many uncertainties due to mixed surface types within a sensor footprint, particularly at the ice edge and near the coast where coastal polynyas are important. AMSR-E reduces this problem, but these issues still remain.

4. SAR provides the best high-resolution data from satellites and is crucial for operational support. With a wide-swath SAR mode capability, global coverage is possible at repeat intervals of only 1-3 days. Nevertheless, there are significant ambiguities in the single polarization backscatter signature, making interpretation difficult at times. Lack of receiving capacity has limited the amount of data available, particularly in the Antarctic.

5. ESA CryoSat was lost at launch in 2005, leading to a potential gap in altimetry for basin-scale thickness measurements. CryoSat-2 is planned as a replacement in 2009, though it is unlikely that ICESat will still be operational at that time. An ICESat replacement is currently under consideration.

6. Most polar-orbiting satellite data are sun-synchronous, and do not allow optimal sampling of processes driven at sub-daily timescales. Orbital configurations should be optimized to prevent aliasing of diurnal or semi-diurnal polar processes such as tides.

7. Basin-scale thickness measurements from satellite are just beginning and need to be further developed. Snow depth and density are major uncertainties in deriving total ice thickness from freeboard observations. Rigorous validation of snow depth and ice thickness is needed using combinations of moored and submarine ULS data and airborne sensors.

8. Surface properties, such as snow characteristics (depth, SWE, grain size) and meltponds, are not well sampled even though they influence the surface energy balance and the surface radiative properties that affect the remote sensing signal. Their spatial and temporal variability is difficult to sample from the ground. However, they vary at too small a scale to be directly observed by satellite sensors. Satellite-derived snow cover estimates are limited to seasonal ice and are not yet well validated. A

strategy is needed to characterize these properties using in situ and airborne observations. We need a consistent protocol for making such observations.

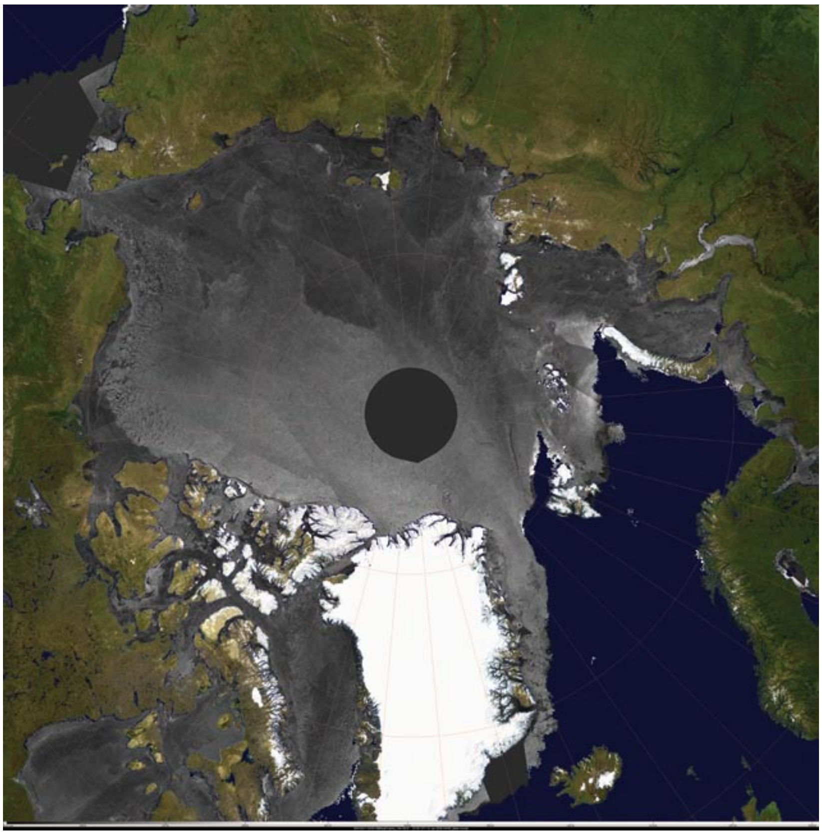
9. The role of small-scale properties – for example, brine content, frost flowers, texture, and chemical and nutrient content – in the ecosystem, and chemical exchanges with the lower troposphere are not well understood.

10. Observations are not well suited for model assimilation because error structure (spatial and temporal variability) is not currently provided. The unknown surface emissivity impedes the efficient assimilation of sounding data over sea ice in Numerical Weather Prediction (NWP) models.

11. Coordination between nations and sometimes even between national programs is often lacking in planning field expeditions, limiting the achievements of such expeditions. Historical records from many such endeavours have not been widely distributed.

Systematic, consistent observations of the sea-ice component of the cryosphere are critical for the operational community, whose primary task is to reduce shipping hazards. Operational ice services also make extensive use of satellite passive microwave ice concentration data (from the DMSP SSM/I and EOS Aqua AMSR-E), ice extent and type data from visible-thermal IR imagery (e.g., NOAA AVHRR, DMSP Optical Line Scanner [OLS] and EOS MODIS), and radar scatterometer data e.g., from QuikScat. A major issue for navigation in the Southern Ocean is that the operational monitoring of ice there is given a low priority and has recently been scaled back by the US National Ice Center. As a result, ice charts are unavailable in a timely fashion, and ships operating around Antarctica must largely rely on their own satellite reception and processing systems for safe navigation. It should be noted that these data in themselves form a unique dataset and often fill in large gaps in Antarctic observations. ■

Fig. 4.2. Envisat ASAR and visible (MERIS) composite mosaic from 14 January 2006.



(*Courtesy of Microsoft Vexcel UK, ESA PolarView Consortium*)

Recommendations: Development of Sea-ice Observations

R4.1 The continuity of the passive microwave and visible/infrared time series needs to be assured with an effective overlap period (at least one year) between sensors for quality inter-sensor calibration. Polarimetric passive microwave instruments (i.e., WindSat/Coriolis, Surface Moisture/Ocean Salinity (SMOS)) should be investigated for possible utility for sea-ice studies.

R4.2 The passive microwave concentration data records should be reanalyzed/reprocessed and validated with other available data. This should include improved inter-sensor calibration (using longer overlaps), rigorous evaluation of current algorithms, and development of data fusion methods to obtain optimal combined products. A CDR-quality passive microwave concentration product, with well-quantified error estimates accounting for spatial/temporal variability, is feasible and should be produced.

R4.3 Rigorous validation and enhancements to other passive microwave products need to be pursued, particularly snow depth estimates and ice age/type. Strategies need to be developed to account for varying spatial scales and temporal sampling when combining in situ and airborne small-scale measurements for validation of the satellite products. There should be collaboration with land snow researchers to develop improved snow estimates over sea ice.

R4.4 Proper coverage of ice-covered regions by SAR sensors for operational support needs to be continued in the Arctic. For the Antarctic, detailed coverage is lacking and needs to be improved. Enhanced spatial/temporal coverage, either from wider swath instruments or increased number of instruments, is needed in order to provide more frequent repeat coverage to track small-scale, short-term variation in the ice cover.

R4.5 New methodologies should be developed to take advantage of the capabilities of dual-polarized SAR sensors that will soon be available.

R4.6 Continuity of satellite altimeter missions and enhancement of techniques is critical for monitoring basin-wide thickness and surface topography estimates. Coordination between radar and laser altimeter missions to obtain near-coincident data will help resolve uncertainties in thickness retrievals.

R4.7 Continuing surface observations are essential for satellite validation and calibration, development of model parameterizations, and process studies. Enhanced technologies should be pursued for continuous automated observations. In particular, mass balance buoys and moored ULS provide useful autonomous information and such programs should be expanded if possible. There should be better coordination with oceanographic observation programs to leverage ocean buoy deployments (e.g., develop combined ocean Argo buoys for ice measurements as well).

R4.8 Targeted field camps should be organized to gather a variety of coincident data to understand interactions between parameters. International coordination is crucial to obtain the maximum benefit. Permission should be granted to access waters in national economic zones for maximum scientific value from research during the upcoming IPY and beyond.

R4.9 New technologies such as UAVs, AUVs, broadband radars, and airborne lidars, which have great potential, should continue to be pursued. Increasing payload capabilities and/or decreasing sensor weight will allow more sensor types (e.g., passive and active microwave on UAVs) to be deployed.

R4.10 Historical records should be sought and compiled into consistent data records to extend the newer, more complete records back in time to provide a better understanding of long-term trends and variability. Many existing ULS data and field measurements of snow and ice thickness still have not been distributed to the community at large (e.g., through data centers).

R4.11 Sea-ice scientists should coordinate with those studying ice cores, chemistry, and biology to better integrate physical data with ecosystem studies (e.g., krill, benthic communities).

R4.12 Development of emissivity and backscatter models will aid the assimilation of remote sensing data in models, and may improve retrievals of surface properties.

R4.13 Satellite-based snow depth products should be extended to perennial sea ice. Dual frequency SAR sensors may offer new and independent estimates to complement passive microwave techniques.

R4.14 The continued provision of timely satellite data is critical to allow national ice services to provide comprehensive and detailed ice mapping of the marine cryosphere. Gaps and future operational requirements include:

- High-resolution coverage in the form of SAR follow-on missions, multiple satellites for revisit and operational redundancy and multi-polarization data for sea-ice classification and (small) iceberg detection.
- Sea ice thickness observations at operational spatial and temporal scales.
- Routine data fusion/integration products, e.g., microwave plus optical/thermal (AVHRR/MODIS/MERIS-type sensors), and radar scatterometer plus a passive-microwave radiometer. Methods will need to address resolution, coverage and temporal differences between data types.
- Quantitative retrievals for model assimilation, requiring validation of algorithms and determination of error characteristics.

R4.15 International cooperation between ice agencies is increasing and should be encouraged. It should include data access and sharing, and agreemenet on standards in nomenclature, analysis practices and data exchange. Such cooperation should also extend to the research community and national funding agencies.

R4.16 Satellite data from the Southern Ocean commonly fill in large gaps in Antarctic observations, and their acquisition by, and archiving at, the Arctic and Antarctic Research Center (Scripps) should be continued. An important new satellite-based initiative is the European PolarView programme; it is strongly recommended that this continues to operate in both polar regions.

R4.17 It is critical that the requirements of the ice services are recognized and met in the long-term strategies of cryospheric observation missions. The socio-economic benefits of ice information are enormous. Meeting ice service requirements in future missions will help ensure continuing benefits, and the realization of even more.

5 Lake and River Ice

Lake and river ice play a key role in the physical, biological, and chemical processes of cold region freshwater. The presence of freshwater ice also has several economic implications ranging from transportation (ice-road duration, open-water shipping season) to the occurrence and severity of ice-jam flooding which often causes serious damage to infrastructure and property (Bonsal et al., 2006). In response to the increasing recognition of the ecological and economic significance of freshwater ice, scientific concern has been expressed regarding climate change impacts on future freshwater-ice regimes (e.g. Anisimov et al., 2001).

In the arctic and sub-arctic regions of the Northern Hemisphere, lakes are a major component of the terrestrial landscape. Estimates of their areal coverage range from 15 to 40% depending on location. The lakes range from those which are little more than 1 m deep, but often several square kilometers in surface area, to those which are very deep and very large (e.g. Lake Baikal, Great Slave Lake and Great Bear Lake). Lakes of all sizes have the highest evaporation rates of any high latitude surface. Shallow lakes warm quickly in spring and have very high evaporation rates until they freeze in the fall. Large deep lakes take substantial periods to warm, but stay thawed into early winter, and their total evaporation amounts are significantly greater. Intermediate-sized lakes display characteristics that lie between these extremes. The frequency and size of lakes greatly influence the magnitude and timing of landscape-scale evaporative and sensible heat inputs to the atmosphere and are important to regional climatic and meteorological processes (Rouse et al., 2005). The duration of lake ice in particular, controls the seasonal heat budget of lake systems thus determining the magnitude and timing of evaporation. Because lakes are such a major component of most northern atmospheric and hydrologic systems, the ability to determine their annual energy and water budgets is critical to our ability to forecast high latitude weather, climate, and river flow patterns. Recent investigations have shown the importance of lake ice cover (obtained through numerical simulations or from satellite observations) for modelling the energy and water balance of high-latitude river basins, for boreal climate modelling, and for improving numerical weather prediction.

River ice is also one of the major components of the cryosphere. It affects an extensive portion of the global hydrologic system, particularly in the Northern Hemisphere where major ice covers develop on 29% of the total river length and seasonal ice affects 58% (Prowse et al., in press). It is also an important modifier of numerous biological, chemical, and hydrologic processes, and is capable of causing extensive and costly damage to infrastructure. River-ice duration and break-up exerts significant control on the timing and magnitude of extreme hydrologic events such as low flows and floods (Prowse et al., 2007). Given the broad ecological and economic significance of river ice, scientific concern has been expressed about how future changes in climate might affect river-ice regimes (e.g., Anisimov et al., 2001).

Seasonal ice cover grows and decays in response to heat transfers through the ice surface layer that are affected by net radiation, surface albedo, on-ice snow depth and density, air temperature, wind speed, water heat flux, etc. Although freshwater-ice formation and decay processes are influenced by numerous physical and climatological factors acting on a variety of spatial and temporal scales (e.g. wind speed, air temperature, net radiation, surface albedo, on-ice snow depth and density, water flux) it has been determined that the timing of break-up and freeze-up correlates best with air temperature during the preceding weeks to months of the event (e.g. Palecki and Barry, 1986). Empirical and modelling studies have shown that dates of lake and river freeze-up and break-up dates (FU/BU) are well correlated with air temperature during the transition seasons, with changes of approximately 4-7 days for every degree Celsius change in air temperature.

There is now ample evidence that shows the robustness of freshwater ice as a proxy indicator of climate variability and change (e.g., Magnuson et al., 2000; Lacroix et al., 2005; Duguay et al., 2006). Long series of lake-ice observations can serve as a proxy climate record, and the monitoring of FU/BU trends has been shown to provide a convenient integrated and seasonally specific index of climatic perturbations. The utility of lake and river-ice observations for climate monitoring has clearly been demonstrated by Magnuson et al. (2000) who found significant trends towards earlier BU and later formation of ice on lakes across the Northern Hemisphere from 1846 to 1995. Trends and variability in lake- and river-ice cover have shown some relations to large-scale atmospheric and oceanic circulation patterns or teleconnections (e.g. Bonsal et al., 2006). Given the importance of freshwater ice as a climate indicator, and its influence on energy, water and biochemical cycling, and on aquatic ecosystems, the Global Climate Observing System (GCOS) calls for the monitoring of dates of complete freeze-over and water clear of ice to an accuracy of ±1-2 days for several hundred medium-sized lakes (~100 km^2) and selected large lakes in middle and high latitudes.

5.1. Status of Observations

Ice concentration is the fraction of the water surface that is covered by ice. It is typically reported as a percentage (0 to 100 percent ice), a fraction from 0 to 1, or in tenths (0/10 to 10/10). Ice concentration on lakes is not determined at the satellite pixel-scale as is done operationally for sea ice from passive microwave-based algorithms. Rather, it is estimated over various areas of a lake, as is done for the production of ice charts by NOAA for the Great Lakes of southern Canada/northern United States, or over the entire lake surface, as done by the Canadian Ice Service (CIS).

NOAA began synoptic ice chart observations for the Great Lakes in 1960. Composite ice charts, a blend of observations from different data sources (ships, shore, aircraft, and satellite) that cover the entire area of the Great Lakes for a given date have been produced starting in the 1970s. A 30-winter (1973-2002) set of composite ice charts has been digitized, and a multi-winter statistical analysis of the climatology of the ice cover concentration has been completed (Assel, 2003). The ice charts and weekly and daily time series over the 30-year period are available on CD/DVD from NOAA (the NOAA Great Lakes Ice Atlas at http://www.glerl.noaa.gov/data/ice/atlas/index.html).

The Canadian Ice Service (CIS) began operational weekly monitoring of ice extent on large lakes in 1995 using NOAA AVHRR (1.1 km) and RADARSAT ScanSAR (100 m) imagery in support of the Canadian Meteorological Centre's (CMC) needs for lake-ice coverage in numerical weather models. The amount of ice on each lake (in tenths) is determined by visual inspection of AVHRR and RADARSAT imagery. The program started with 34 lakes (in 1995) and has now reached 136 lakes (mostly in Canada with a few in the USA). The current lake-ice monitoring program is limited to roughly 200 RADARSAT frames a year due to the high cost. It is possible to derive dates of complete freeze-over (CFO), and when water is clear of ice (WCI) with an accuracy of ±1 week using this dataset. The accuracy of the information in the CIS lake-ice coverage database depends on the amount of cloud cover over a particular lake (NOAA AVHRR imagery is cloud dependent) and the frequency of RADARSAT coverage. RADARSAT data also have some limitations - lake ice is smoother than sea ice, and at times the lack of features on some lakes makes ice difficult to see; strong winds which roughen the lake surface, and therefore increase radar backscatter, can also make the discrimination between floating ice and ice-free areas of a lake difficult at times.

The 'extent' measure defines a section of a water body as either ice-covered or ice-free. From remote sensing data, each pixel is usually coded in binary mode with a value of 1 (ice) or 0 (no ice). Extent is frequently described in terms of area (in square kilometers) covered by at least some ice. Currently, MODIS data from the Terra and Aqua satellite platforms are used to produce snow-cover products from the automated SNOWMAP algorithm at the Goddard Space Flight Center (GSFC) (Hall et al., 2002). The snow cover maps also show ice on medium-size to large lakes that are not eliminated from analysis by the land/water mask. Data on ice on lakes is provided in a binary mode at 500-m spatial resolution. The MODIS snow-mapping algorithm is fully automated which makes the results consistent from scene to scene. The land/water mask does not differentiate between lakes or rivers, so all inland water bodies are processed by the snow algorithm. Based on the land/water mask, pixels that fall on an inland water body are processed using the same criteria tests for snow as used on land. If snow is detected, the inland water is mapped as snow-covered lake ice in the output product, otherwise inland water is mapped. The lake-ice algorithm does not attempt to differentiate ice types or other characteristics of lake ice. It is designed only to detect the presence of snow-covered ice.

In 1997, the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) started to generate a daily snow and ice product at a resolution of about 24 km with the Interactive Multisensor Snow and Ice Mapping System (IMS). The IMS incorporates a wide variety of satellite imagery (AVHRR, GOES, SSMI, etc.) as well as derived mapped products (USAF Snow/Ice Analysis, AMSU, etc.) and surface observations. The coarse resolution of the 24 km product allowed mapping of ice extent only on the largest lakes of the Northern Hemisphere. Since February 2004, a higher resolution product at approximately 4 km resolution became available, which allows us to determine ice extent on smaller lakes. The two products described above have yet to be validated and used to derive freeze-up and break-up dates, and ice cover duration.

Freeze-up and break-up dates from lakes and rivers have traditionally been determined from surface-based observations. Unfortunately, surface-based lake and river-ice observations have been steadily declining since the 1980s to a point where networks almost disappeared in many countries. In Canada, freeze-up and break-up observations were reported for only 12 water bodies (lakes and rivers) across the entire country during the 2000-2001 ice season. Financial cutbacks and the automation of meteorological stations in the vicinity of lake and river-ice observation sites are the two main reasons for the drastic decline in the surface-based networks (e.g. Lenormand et al., 2002). Remote sensing has been seen for several years as the technology that would eventually supersede surface-based observations of freeze-up and break-up dates. However, this transition has not yet been realized in any country.

Knowledge of ice thickness is important for the determination of trafficability on lakes and rivers in winter, and for the planning of winter ice roads in the North. Ice thickness measurements have primarily been through field observation programs established by federal and state/provincial government agencies. For example, in Canada, CIS maintains a database of lake, river and sea-ice characteristics as part of the National Ice Archive. However, observational networks such as the one operated by CIS are generally sparse and the number of sites has been steadily declining since the 1980s; a network status which is similar to that of the surface-based freeze-up and break-up observations (Lenormand et al., 2002).

Ice thickness has been estimated with some success using numerical ice growth models (e.g. Duguay et al., 2003) and through the synergistic use of optical and SAR data on shallow Arctic lakes (e.g. Duguay and Lafleur, 2003). With its field of view of 43 x 75 km, the 6.9 GHz frequency channel of AMSR-E offers a promising means to obtain lake ice thickness from very large lakes. It might also be possible to obtain the total thickness of snow and ice on medium to large lakes from snow surface elevation data acquired by spaceborne lasers such as the one on ICESat (Jeffries et al., 2005). Except for shallow rivers, where SAR has some potential for ice thickness determination, the successful application of other techniques (e.g. passive microwave) to river ice seems unlikely in view of the large footprint of the sensors and the relatively narrow width of even the broadest river channels (Jeffries et al., 2005).

Snow depth (and density) on ice is important for the estimation of winter conductive heat loss from lakes. Field measurements of snow depth on ice are usually made along with ice thickness measurements as described above. The potential to derive snow depth on floating ice by remote sensing has been demonstrated by Markus and Cavalieri (2000) who used the 85 GHz SSM/I channel to estimate snow depth on Antarctic sea ice. The high frequency channel (89 GHz) on AMSR-E offers the same possibility, and with an Instantaneous field of view (IFOV) of 4 x 6 km it could potentially be used to obtain data for medium- to large-sized lakes (Jeffries et al., 2005).

Many shallow lakes and low flow rivers of the Arctic completely (or partly) freeze to their bed in winter. Knowing which lakes and rivers freeze to their bottom (grounded ice) or not (floating ice), and when this occurs during the course of the winter period, is critical for mapping and monitoring water availability and fish over-wintering habitats, and for planning winter ice roads. The potential of ERS-1/2 and RADARSAT SAR imagery has been demonstrated for such purposes on the North Slope of Alaska and the Hudson Bay Lowland of Canada (Jeffries et al., 1996; Duguay et al., 2002; Duguay and Lafleur, 2003). However, these applications are not yet operational.

Aufeis, also known as river icings or naleds, form when water overflows onto a river-ice surface from tributaries or from below the ice, and from groundwater springs (Jeffries et al., 2005). It represents temporary aboveground storage of water discharged during the winter; the stored water is released by melting of the aufeis during the following spring and summer. Large aufeis may thus cause significant inter-seasonal redistribution of water resources. Aufeis can be monitored best with high-resolution optical imagery such as Landsat, SPOT, and the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), or higher resolution sensors like Ikonos and QuickBird. The potential of SAR, and in particular the use of interferometric SAR (InSAR), has also been demonstrated. Where groundwater springs exist, open water areas on rivers and lakes can persist for the entire winter period. Open water areas can be easily detected with SAR or optical imagery (Pietroniro and Leconte, 2005). Higher spatial resolution data (e.g. 15-30 m) is preferred since it allows detection of narrow river channels.

Ice in reservoirs is invariably being monitored by good in situ facilities. There is no exchange of such data despite its possible significance for regional modelling and other potential applications. The significance of such data for climate monitoring is low because the water regime in reservoirs is largely controlled. However, significant climate variations may make such control more costly or less efficient.

Current measurement accuracies and requirements for freshwater ice are given in Appendix B, Table B.3.

5.2. Shortcomings in Current Observations

Surface-based observations were once the most important source of information regarding lake and river-ice conditions. The declining state of the surface-based networks since the mid 1980s, particularly in Canada and Russia, has led to serious geographical and temporal gaps for several lake and river-ice parameters.

Some lake- and river-ice observations from various countries have been compiled into the Global Lake and River Ice Phenology Database (GLRID) at NSIDC. The database contains records for 748 sites, but again the number of sites reporting ice observations has plummeted since the 1980s (Figure 5.1). A similar effort in Canada, the Canadian Ice Database (CID), reveals a similar trend. No national or international funding is currently available to support updating of these databases and to re-establish, at least part of, the surface-based observational ice networks.

Satellite remote sensing can provide some of the parameters that are no longer observed in situ. Some surface-based measurements, however, are still needed to validate remote sensing approaches and to refine models of lake-ice growth and river-ice dynamics.

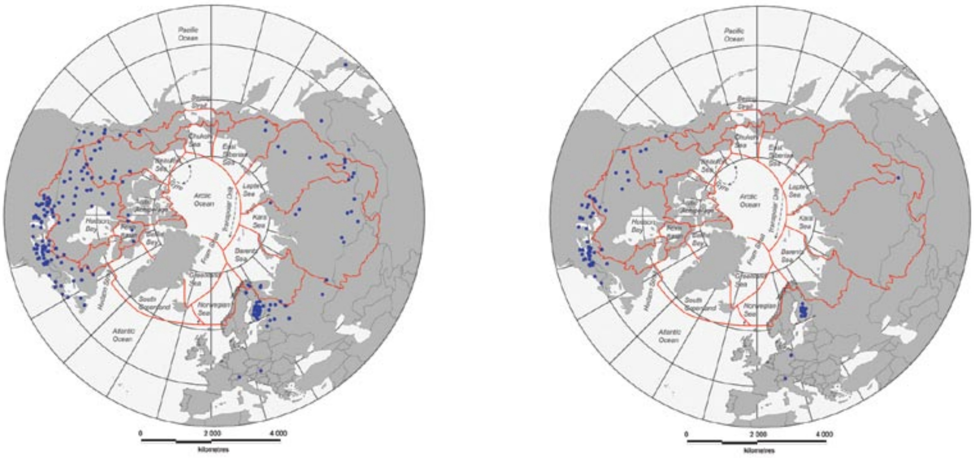
Lake-ice observations are available via some remote sensing derived products (e.g., MODIS Snow, the Interactive Mapping System (IMS), CIS). However, the observations are limited spatially and/or temporally. Climatically and hydrologically relevant parameters, such as the dates of the first appearance of ice, complete freeze-over, beginning of thaw, and when the water body becomes completely free of ice, are currently not available from these products.

The MODIS 500-m daily snow product is of particular interest for lake ice and river ice (large rivers) monitoring. However, this product has not yet been validated for lakes or rivers. Extensive cloud cover and periods of darkness in early winter at high latitudes limit its use during the freeze-up period. Active microwave, SAR and scatterometer data, and the higher frequency passive microwave available on AMSR-E (89GHz) may help during both the freeze-up and break-up periods.

The spatial resolution of most satellite sensors providing high (daily) temporal resolution is simply too coarse for the monitoring of the majority of river-ice parameters listed in the table. Some studies have shown the potential of AVHRR and MODIS to monitor break-up dates on very large rivers of the Northern Hemisphere (Pavelsky and Smith, 2004). The value of higher resolution RADARSAT imagery (8 m) has also been demonstrated for the mapping of river ice types (Weber et al., 2003). However, the cost associated with the acquisition of such imagery is a major impediment.

No satellite mission currently provides lake and river ice thickness and snow depth on ice measurements. ■

Fig. 5.1. Lake-ice observations in 1970 (left) and 1995 (right).



Recommendations: Development of Freshwater Ice Observations

R5.1 A major data rescue effort for Russia (and other countries) must be undertaken and submitted to the World Data Centre for Glaciology at the National Snow and Ice Data Center (NSIDC), to accompany existing historical records archived there. Several regional archives (part of the network) are needed.

R5.2 A set of target regions and lakes/rivers (some of which were part of an existing historical network) must be identified for future long-term ice monitoring.

R5.3 The status of ice observations at largest reservoirs should be reviewed and provisions of data exchange considered.

R5.4 Existing lake-ice or river-ice sites need to be reactivated and new observation sites added. The establishment of networks of volunteers and schools must be encouraged. These networks can provide a framework for educating young students (future decision makers) and teachers, as well as the general public, as to the importance of freshwater ice monitoring. Such observational networks have recently been established in the Canada (IceWatch: http://www.naturewatch.ca/english/icewatch/ and Alaska (Lake Ice and Snow Observatory Network, or ALISON: http://www.gi.alaska.edu/alison/).

R5.5 A set of lake and river experimental sites must be established for remote sensing algorithm development and testing (ground-based, airborne, and satellite). Initial sites include the Great Slave Lake/Mackenzie River area, Hudson Bay Lowland/Churchill River area, and more southern (temperate climate) locations.

R5.6 Conventional (surface-based) observations of freeze-up and break-up need to be compared with satellite-derived time series, starting in the 1970s-1980s with AVHRR data. This would ensure some continuity in the transition between the surface-based and satellite observations (i.e. post 1980s when many of the lake/river ice sites were lost).

R5.7 Mapping ice on lakes and rivers requires a finer spatial resolution than for most sea-ice mapping applications, because of the small size of some lakes and narrow river channels. On larger lakes and rivers, like the Great Lakes and St. Lawrence River, polar orbiting visible infrared sensors provide useful information on the ice cover. The MODIS 500-m snow product needs to be validated for lake ice. The development of a composite lake-ice product from the combination of MODIS Aqua and Terra data (i.e. increasing the number of MODIS swaths) should be examined along with the possible improvements that can be made with the integration of passive and active microwave data.

R5.8 SAR is the optimal sensor class because it has a higher spatial resolution and is able to image through cloud and in darkness. The latter characteristic is important for episodic events such as river and lake-ice break-up. It has been shown that SAR can be used to map ice cover and areas of open water on rivers and lakes, and to identify areas of floating and grounded ice. The development of operational methods based primarily on the use of high-resolution SAR imagery is needed.

R5.9 The potential of passive and active microwave data to map ice cover (concentration and extent), open water, ice thickness, and snow depth on ice on large lakes needs to be examined.

R5.10 Integrated multi-sensor data fusion and numerical model output must take place to improve estimates of ice parameters and for ice forecasting.

R5.11 The development of lake-ice products for data assimilation into numerical weather prediction (and regional climate) models is needed.

6 Ice Sheets

An ice sheet is a continental-scale body of ice that flows under its own weight towards the ocean. Two major ice sheets remaining from the last ice age blanket most of Greenland and Antarctica. They contain enough ice to raise sea level by 7.2 m and 62 m, respectively, if melted. The inland ice rests on bedrock. Ice shelves are the floating extensions of the inland ice and directly link the ice sheet with the ocean. Ice is carried from the inland ice to the ice shelves via fast flowing ice streams and outlet glaciers that breach the mountainous barriers surrounding Greenland and Antarctica. Ice sheets are thickest near the ice divides, where the thickness exceeds 4 km in East Antarctica and 3 km in Greenland, and thinnest at the ice fronts where they can be as thin as 200 m.

The shape, extent and volume of the ice sheets are controlled largely by the balance between the amount of snow added to the surface, the rate of ice flow in the ice streams, and the amount of ice lost from the ice shelves through melting at their bases and iceberg calving from their fronts (Jacobs et al., 1992). A small amount of mass is also lost through surface melting, and some subglacial water is known to reach the ocean, although the exact amount is not known. Current estimates of mass loss from the Antarctic ice sheet are highly uncertain, with values of about 0.15 to 0.40 mm/year suggested recently as the contribution to global sea level for the period 1961-2003. Iceberg calving is the largest mass loss term in Antarctica. While large iceberg calving events are necessary for maintaining the mass balance of the ice sheet, the concern is that these events might become more frequent in response to atmospheric and oceanic warming, thus tipping the system out of mass balance.

Ice sheets are important archives of past climates on Earth. Ice cores collected from the ice sheets provide detailed information about past climate and environmental conditions on timescales from seasons to decades to hundreds of millennia, depending on the rate of accumulation. They are the only means of showing how closely climate and greenhouse gas concentrations were linked in the past, and in demonstrating that very abrupt climate changes can occur. Because ice cores provide proxies for climate variables, they are used as a tuning tool for models of the future climate change scenarios based on the changes that took place in the past.

Until recently, ice sheets were assumed to evolve slowly with dynamic response times of centuries to millennia. Satellite remote sensing studies have radically altered this perception. Airborne and spaceborne radar and laser altimetry studies show that much of the perimeter of the Greenland Ice Sheet (Krabill et al., 2000) and substantial portions of West Antarctica (Wingham et al., 1998) are thinning, in some areas at rates of meters per year. Recent surveys of Antarctica's ice mass budget suggest that the ice sheet is losing mass (Zwally et al., 2005). Recent analysis suggests that more than 0.3 mm per year of the current increase in sea level rise is attributable to mass loss from the Greenland and Antarctic Ice Sheets (Rignot and Thomas, 2002). A major outstanding question about ice sheets is how the ice sheet contribution to sea level rise will change in the future. Ice sheet models are currently not able to predict this accurately, in part because they are not realistically coupled to ocean models.

In Greenland, observations of velocity change include a mini-surge, and a near doubling of velocity of Greenland's largest outlet glacier, Jakobshavn Isbræ. Decadal-scale acceleration (Rignot and Kanagaratnam, 2006) and deceleration (Joughin et al., 2002; Stearns et al., 2005) have been observed in West Antarctica. InSAR also has been used to detect the migration of grounding lines, which is a sensitive indicator of thickness change. InSAR observations have also shown that loss of ice shelves often leads to dramatic acceleration of the grounded ice, which directly affects sea level. These snapshots of temporal variation have been too infrequent to ascertain whether they constitute normal ice-sheet variability or indicate long-term change. The controls on fast ice flow are still the subject of active investigation and debate (Alley and Bindschadler, 2001).

Ice shelves are important components of the ice sheets, and processes leading to their demise need to be well understood. Recent studies have shown that the ice shelf collapse can be very short (seconds-months) or long (decades-centuries) (Shepherd et al., 2003), and that occasional observations may not suffice to further our understanding of the phenomenon. It is therefore important to monitor ice shelf elevation and thickness, surface and basal melt rates, grounding line locations and iceberg calving events, and to learn more about the processes involved so that they can be incorporated into ice sheet prediction models.

Icebergs are found all around Antarctica, and can drift considerably farther north than the sea ice. In the Arctic, large numbers are found around Greenland, throughout Baffin Bay and southward along the east coast of Canada as far as the Gulf Stream; they are found less frequently elsewhere in the Arctic. The size of icebergs range from small "bergy bits" the size of a piano to massive table bergs hundreds of square kilometers in area and tens of meters high above the waterline. Large icebergs like these can significantly affect the oceanographic conditions through fresh water inputs from melting. Smaller icebergs pose significant dangers to navigation.

Fig. 6.1. Antarctic Mapping Mission (AMM-1) RADARSAT image of Antarctica in 1997.

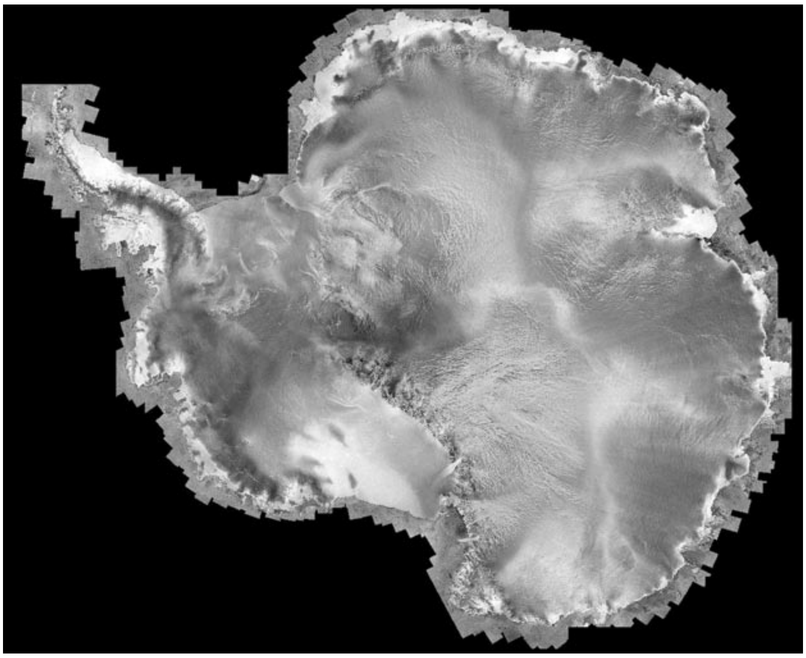


Image from http://earthobservatory.nasa.gov/Study/RampingUp/

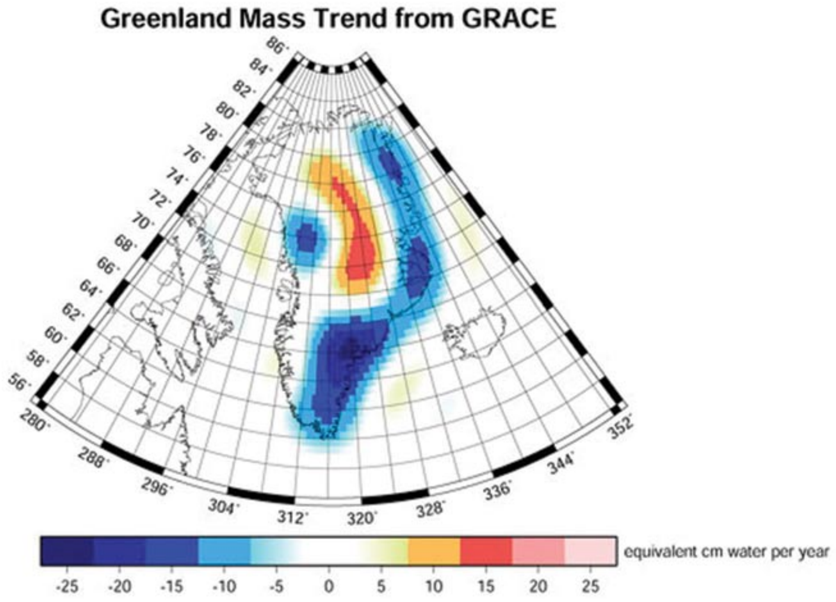
6.1. Status of Observations

Geophysical techniques used to study ice sheets include measurements of physical properties (temperature, borehole deformation) and chemical properties (isotopes, dust) in ice cores. Such measurements have been made in several boreholes drilled through both polar ice sheets. Snow pits are used to measure near surface temperature, snow and firn density, crystalline structure, surface accumulation and, when coupled with GPS repeat measurements of accumulation poles, surface velocity. In situ reflection and refraction seismological experiments are used to measure ice thickness, near surface density, the crystalline fabric of the ice and the properties of the glacier bed. Surface and airborne radars are used to map internal reflecting horizons interpreted as chronographic markers, to measure ice thickness and to identify areas where the bed is wet. Most recently, wideband radars have been used to estimate accumulation rate, and the latest radars enable us to image the glacier bed in three dimensions. Airborne photographic observations of ice sheet extent, and in situ observations of accumulation and motion to determine ice sheet mass balance, together provide important historical records of the state of ice sheets. **Current measurement accuracies and requirements for ice sheets are given in Appendix B, Table B.4. Iceberg measurement requirements are addressed in Table B.5.**

Over the last three decades, observations and studies of ice sheet physical properties and dynamical behavior have shifted away from in situ observations and towards airborne and spaceborne techniques (Massom and Lubin, 2006). This occurred in part because of technological improvements in sensors and the ability to acquire data over vast areas of remote terrain, during the day or night and in all weather conditions. Exploitation of satellite data began during the early 1970s. For example, the Coastal-Change and Glaciological Maps of Antarctica map series is a collaborative effort between the U.S. Geological Survey, Scott Polar Research Institute (SPRI), the British Antarctic Survey (BAS), and other national Antarctic institutions to use satellite images to define changes in the cryospheric coast of Antarctica for the past 30 or more years. Landsat MSS, Landsat TM, RADARSAT, Terra and Aqua MODIS images are used in the compilation (cf., Williams et al., 1995; http://pubs.usgs.gov/factsheet/fs17-02 and http://pubs.usgs.gov/factsheet/fs/2005/3055). Visible image data including high-resolution SPOT, Landsat and ASTER data are also useful for accurate estimates of ice sheet motion and for deducing the shape of the ice sheet surface using shape-from-shading techniques. Even earlier data were acquired by reconnaissance satellites starting in 1962 but only made available to the science community in the mid 1990's. These panchromatic images collected by the Corona, Argon and Lanyard satellites provide a treasure of historical data for gauging subsequent changes in the positions of shear margins, grounding lines and glacier terminae (Zhou and Jezek, 2002; Kim et al., 2001).

Passive microwave observations of ice sheets are used to measure the onset, duration and extent of ice sheet surface melt. Time series observations compiled from the SMMR

Fig. 6.2. Trend in the mass of the Greenland ice sheet, as estimated from GRACE. (*Courtesy Luthke et al.*)



and SSM/I data sets show that melt extent is increasing with time across Greenland (Abdalati and Steffen, 2001). The situation is different in Antarctica where the net annual melt extent is decreasing. Examined on a monthly basis, melt extent is increasing during February. Passive microwave data have also been inverted to estimate average annual accumulation (Zwally and Giovinetto, 1995). Bolzan and Jezek (2000) developed an empirical approach to estimate annual variations in accumulation rate for the dry snow zone in Greenland. Winebrenner et al. (2004) investigated how passive microwave data can be used to estimate near surface temperature. This is complementary to the analysis of infrared temperature data by Comiso (1994) and by Shuman and Comiso (2002).

Changes in ice sheet surface elevation averaged over large areas can be interpreted as measures of changing ice sheet volume. Since the SEASAT mission of the late 1970s, satellite radar altimeters continue to be invaluable tools for measuring ice sheet elevation. The U.S. Navy's Geosat operated to 72°S during 1985-89 in a 17-day orbit; ESA has flown three radar altimeters in a 35-day orbit to 81.5°S: ERS-1 (1991-2000); ERS-2 (1995-2003); and Envisat (2002-present). The radar altimeter has a large footprint (~2-3 km over flat ice for ERS), so steep slopes on the ice streams cause tracking problems, limiting its vertical accuracy. The multi-decadal records of elevation changes detected using both airborne (Krabill et al., 2000) and spaceborne altimeters demonstrate that much of the perimeter of the Greenland ice sheet is thinning. More marked changes are observable in local sectors of Greenland and West Antarctica where thinning rates of meters per year have been reported. A laser altimeter is used on the ICESat satellite to accurately measure and re-measure ice sheet topography. A major advantage of the laser altimeter is the small footprint that mitigates slope migration and tracking problems. This enables better sampling in the sloping regions of the ice sheet and the ice margins where, at least in Greenland, the greatest changes are occurring. ICESat also extends coverage of the ice sheet to 86ºS, compared to 81.5ºS for ERS. Satellite radar and laser altimetry data also provide information on sub-glacial water movement beneath the ice sheets (Wingham et al. 2006; Fricker et al. 2007).

Synthetic aperture radar (SAR) complements other remote sensing instruments through high-resolution observations of microwave radar backscatter. SAR image data acquired during the 1997 RADARSAT-1 Antarctic Mapping Project (Jezek, 1999, 2002; Jezek et al., 2003) were compiled into the first high-resolution radar mosaic of the southern continent (Figure 6.1). The mosaic has been used to map the ice margin (Liu and Jezek, 2004) and to estimate ice margin changes in comparison with earlier data sets (Kim et al., 2001), and to compare radar and passive microwave measurements of snow facies extent (Liu et al., 2006a, 2006b). SAR interferometry (InSAR) is capable of measuring ice motion and has revolutionized the science of glaciers and ice sheets. For example, acceleration of inland ice following collapse of Antarctic Peninsula Ice shelves demonstrates the buttressing effect long conjectured to allow ice shelves to modulate the flow of the grounded ice cover. In conjunction with ice sheet models, the InSAR data provide a powerful means to investigate controls on glacier flow. Coupled with airborne measurement of ice thickness, InSAR velocities can be used to compute the net outflux of ice. When compared with the estimated surface accumulation, this led to the conclusion that the Greenland Ice Sheet discharge is in net deficit by about 167 km^3 (Rignot and Kanagaratanam, 2006) and that the West Antarctic Ice Sheet is in net deficit by about 48 km^3 (Rignot and Thomas, 2002).

Satellite gravity provides direct measurements of ice sheet mass change (Figure 6.2). Data from the GRACE satellite show that the Greenland Ice Sheet is losing mass at an equivalent rate of sea level rise of about 0.54 mm/yr (Chen et al., 2006).

Most recent major field campaigns, such as the Program for Arctic Regional Climate Assessments in Greenland, the West Antarctic Ice Sheet Project in West Antarctica, the International Trans-Antarctic Science Expedition (ITASE) across Antarctica, and the U.S. NSF Science and Technology Center for Remote Sensing of Ice Sheets (CReSIS) in both Greenland and Antarctica integrate in situ, airborne and spaceborne observations to acquire detailed pictures of past climate, the present mass balance and the changing dynamics of the polar ice sheets.

Icebergs form from calving of glaciers and ice sheets. The necessity of iceberg monitoring came to the forefront after the sinking of *Titanic* in 1912. Shortly thereafter, the International Ice Patrol was formed to track North Atlantic icebergs. Early iceberg detection was conducted from vessels traversing the shipping lanes in the North Atlantic and later by aircraft reconnaissance. With the establishment of permanent bases in Antarctica during the 1950s, it became important to track Antarctic icebergs, now done for large icebergs by the U.S. National Ice Center (NIC). Since the 1970s, satellite technologies have tremendously improved iceberg monitoring, particularly with the advent of SAR and Side-Looking and Forward Looking Airborne Radar (SLAR/FLAR) sensors that can see through clouds. Very large Antarctic icebergs can be detected and tracked with optical satellite sensors such as AVHRR and, since the mid-1990s, with scatterometers, which can see through clouds where visible/infrared imagery are not viable. However, smaller icebergs are very difficult to detect from space. In the western north Atlantic, C-Band Synthetic Aperture Radar has been successfully used to detect large icebergs (>130 meters in length) and even medium icebergs (65-130 meters) provided the sea is relatively calm. Discriminating icebergs from other small targets such as fishing boats, still poses a significant challenge to incorporating this technology operationally. Other primary platforms for observing icebergs are low altitude aircraft (1000-3000 meters). Side-Looking and Forward Looking Airborne Radar (SLAR/FLAR) on aircraft are used operationally to identify icebergs but, since iceberg targets may be confused with vessels, visual confirmation is relied upon for unambiguous detection. Marine radar on ships and offshore platforms is commonly used for close range detection up to 20 km.

6.2. Shortcomings in Current Observations

The current ice sheet measurement system has generated some significant discoveries about ice sheets over the past decade, leading to a greater understanding of the complex processes involved in ice sheet dynamics and improving our predictive capability. Satellite remote sensing has contributed to the majority of these discoveries. There are, however, some vital measurements that can currently only be made in situ, and such measurements are sparse due to the vast size of the ice sheets. There are also gaps (both temporal and spatial) in the current suite of remote sensing observations.

Ice thickness is routinely measured using surface based and airborne mounted radars operating at frequencies from ~5 MHz to ~500 MHz. These systems provide reliable information about ice thickness, internal radar reflecting layers, and the reflectivity of the glacier bed. However since they are currently only used on the surface or from an aircraft the spatial coverage is limited, and there are still large gaps in the ice thickness maps, especially for Antarctica. To efficiently fill these gaps, there is a need to install such instruments on a long duration aircraft (manned or unmanned) or a spacecraft. Lacking from both airborne and spaceborne techniques, and only recently suggested as possible from surface experiments, is an ability to image the glacier bed using a SAR type approach. Image information about the glacier bed is critically important for understanding the basal conditions that control glacier flow.

Ice sheet motion is optimally measured using InSAR techniques that can yield fine spatial resolution measurements of ice sheet surface velocity on continental scales. When used in conjunction with in situ and other measurements of surface velocity and topography, this approach yields highly accurate (several meters per year) estimates of ice sheet motion. There are four civilian SAR satellites providing cryospheric SAR data: ERS-2, Envisat, Radarsat-1 and PalSAR. These will were joined in 2007 by TerraSAR-X (launched 15 June 2007). The new satellites will provide an unprecedented opportunity to improve our ability to monitor and study change in the cryosphere. Instead of being restricted to only C-band (~5.3 GHz), results will also be available at L-band (~1.3 GHz) from the Japanese PalSAR on ALOS, and X-Band (~10 GHz) from the German TerraSAR-X satellite. Other countries are also planning SAR satellites, including constellation coverage, so that in the coming decade the future is bright for SAR satellite data coverage. Repeat-pass InSAR is now the standard technique for mapping ice movement. The limitation is that planned systems are not optimized for acquiring interferometric data over the ice sheets. Moreover, an integrated observations program for maximizing the use of these satellites while minimizing the burden on any single operator is yet to be developed.

Existing digital elevation models (DEMs) are a fundamental requirement for many aspects of land cryospheric monitoring and research, but existing DEMs are of limited accuracy and spatial resolution in many regions of the ice sheet. Even the first high resolution mapping of Antarctica (Jezek, 1999) depended on the existence of a complete continental DEM (Liu et al, 2006a, 2006b). The requirements for ice elevation vary with application from the very high accuracy necessary for mass balance change, to the more moderate requirements for mapping and InSAR estimation of glacial ice movement.

The TerraSAR-X tandem mission is a German initiative to derive a high resolution (post spacing ~ 12m) global DEM with ~2m vertical accuracy. The proposal will use two TerraSAR-X satellites flying in a tandem configuration to form an across-track interferometric pair. Currently a Phase A study is being performed and it is hoped that a follow-on proposal will lead to a TanDEM-X launch in late 2008. Such a DEM would be very valuable for many aspects of cryospheric monitoring, modelling, and enhancing inventories.

Satellite radar and laser altimeter data have provided an invaluable quasi-continuous time series of ice sheet elevation data from 1978 through to the present. However, there will be a gap between laser altimeter observations between the current ICESat mission and its follow-on mission, ICESat-2. Similarly there may be a gap in observations between ICESat and the advanced radar altimeter to be carried by CryoSat-2.

Ice sheet thinning rates are estimated by using radar-derived ice thickness and InSAR-derived ice velocities to compute the difference between horizontal mass fluxes and area-integrated accumulation rates. Accurate accumulation rate measurements can only be obtained from direct, in situ observations, however, so that the information is sparse. Airborne-radar depth-measurements of dated internal layers provide a new method for obtaining more spatially extensive multiyear average estimates of accumulation rate. Spaceborne techniques have been used to estimate average accumulation and recently, techniques have been proposed to obtain annual estimates. A key objective is to extend the amount of data collected by airborne platforms, to use that data to refine spaceborne observations, and to use spaceborne data in combination with meteorological models to derive annual and seasonal accumulation rate fields.

The grounding lines of the ice shelves have been well mapped in some places using InSAR and also recently using ICESat. However there are some regions where the grounding line location is not well known. The sea floor topography beneath the ice shelves is poorly known in most areas of Antarctic and Greenland. This is because the sub-ice-shelf cavity is difficult to access, since it is covered by several hundred meters of ice. Point-wise access has been achieved by hot-water drilling from the surface (e.g., Nicholls & Jenkins, 1993) and some spatial coverage by use of an autonomous underwater vehicle (AUV) (Nicholls et al, 2006). The available data thus far is sparse and this represents a major limitation for modelling the ice-ocean interaction, including the ocean tides within the cavities.

Basal melt rates have been estimated for the major ice shelves of Antarctica using mass flux calculations (Rignot and Jacobs, 2002; Joughin and Padman, 2003). However these only represent a snapshot at one time, and little is known about how basal melt rates vary inter-annually or seasonally. Numerical models of the ocean circulation within an ice-shelf cavity (e.g., Holland et al, 2003) do provide estimates of basal melt, including the spatial pattern. Such models are limited in the their parameterization of the basal melt process, which is based on observations taken from sea-ice studies and not from the ice-shelf cavities. Direct observation of the melting process in the ice-shelf cavities is required, and could be achieved through development of automated ice-ocean vertical profilers.

Surface melt patterns and duration are successfully measured on an almost daily basis using passive microwave techniques. A future objective is to combine extent and duration maps with other observations, such as thermal infrared estimates of surface temperature, to estimate melt volume.

Vertical temperatures measured in boreholes through the volume of the ice are inverted to reconstruct paleoclimate and near surface (10 m) temperatures are monitored in shallow boreholes as indicators of short-term climate changes. In the future, low frequency (L and P-band) passive microwave radiometers may be able to provide some information on the internal temperature of the ice because of the dependence of microwave emission on the physical temperature and the penetration depth of these lower frequencies.

Meteorological measurements from Automated Weather Station (AWS) networks remain important as key means of estimating net water vapor flux to and from the surface (Box and Steffen, 2001). Sublimation/evaporation is highly sensitive to these fluxes, and represents a key yet poorly understood component of ice-sheet mass balance, removing snow and ice and/or adding mass by condensation/deposition. These measurements should be maintained and spatially extended to key regions on both ice sheets.

Valuable information covering the last several hundred thousands years has been obtained from a number of deep ice cores drilled through the Greenland and Antarctic ice sheets. However, the Antarctic ice sheet spans an area comparable to the size of Europe and it covers a correspondingly wide range of both climatological and glaciological regimes. A network of ice cores is required to sample paleoclimates across the whole continent. ■

6 Ice Sheets

Recommendations: Development of Ice Sheet Observations

R6.1 Implement a C-band synthetic aperture radar optimized for SAR interferometry and capable of measuring the velocity field of the whole of the Greenland and Antarctic Ice Sheets. Data from this system would also provide new estimates on grounding lines, ice edge and shear margin positions.

R6.2 Continue surface elevation measurements from polar orbiting altimeters. Continuous observations with new altimeter instruments including CryoSat-2, ICESat, and ICESat-2 are necessary to extend the time series. Increased spatial resolution of surface topography should be obtained using TANdem-X interferomerically derived topography.

R6.3 Continue passive microwave observations of ice sheet surface melt through the re-inclusion of a passive microwave radiometer on NPOESS. As new or replacement sensors are deployed, it is essential that observations overlap so that the derived surface melt records can be reconciled for changes in calibration and viewing geometries. Passive microwave data in combination with wide-bandwidth nadir sounding radars may also be useful in refining estimates of surface accumulation rate.

R6.4 Increase the density of ice thickness measurements, particularly in East Antarctica where data are sparse. Ice thickness measuring radars should be evolved into systems that provide spatial information on the glacier bed, in particular, to identify where the bed is wet or where pooled subglacial water exists. Fixed wing aircraft, UAV and satellite implementations of advanced ice sounding synthetic aperture radars should be explored.

R6.5 Continue the acquisition of high (10 m) and moderate (250 m) resolution optical imagery for detecting rapid changes in ice shelves, ice streams and outlet glaciers and for measuring surface velocity as a complement to InSAR. Continue acquiring low-resolution (1 km) thermal infra-red data for measuring surface temperature.

R6.6 Time series GPS based observations of surface displacement should be made on several outlet glaciers and ice streams (for example, Jacobshavn Glacier, Kangerdlussuaq Glacier, Peterman Glacier, Byrd Glacier, Thwaites Glacier and Whillans Ice Stream). In combination with passive seismic event monitoring systems, this network will help identify the physical processes behind unexpected observations of rapid (hours to days) changes in local ice sheet motion.

R6.7 Continue the time series of spaceborne gravity observations for monitoring changes in ice sheet mass and the contribution of ice sheet mass loss to sea level rise. Spaceborne observations should be complemented by surface based gravity networks.

R6.8 Collect deep ice cores for paleoclimate studies. Acquire the oldest climate and greenhouse gas record from an Antarctic ice core (~1.5 M years). Investigate the last interglacial and beyond with a northwest Greenland deep ice core drilling project. Establish a 40,000-year network of ice cores to provide a bipolar record of climate forcing and response. Boreholes through ice sheets should be continued into bedrock so as to measure geothermal heat flux in places where the glacier is frozen to the bed. New ice core drilling technologies must be investigated.

R6.9 In situ observations of snow accumulation on ice sheets should be expanded. These include firn and ice cores, snow pits, ultrasonic sounders, stakes (single, lines, farms), and shallow ground-penetrating radar.

R6.10 Develop instrumentation to observe the basal melting of ice shelves. This can be achieved through further development of autonomous underwater vehicles to provide spatial sampling. Likewise, development of vertical profilers would allow for sustained temporal sampling, albeit at a limited number of sites. Such data can be used as a foundation for building a parameterization of ice-shelf basal melting and for direct validation of basal melting inferred from other observational techniques, such as satellite sensing.

7 Glaciers and Ice Caps

The total number of glaciers has been estimated by statistical scaling to about 160,000 (Meier and Bahr, 1996), covering an area of about 785,000 km^2 (Dyurgerov and Meier, 2005). Most of these ice masses are glaciers of cirque, mountain or valley type, whereas ice caps of varying size exist on many of the Canadian and Eurasian Arctic Islands. While ice caps are defined as a dome-shaped ice mass with radial flow, larger ice masses with their thickness not sufficient to obscure the subsurface topography are termed ice fields (e.g., IUGG(CCS)/UNEP/UNESCO, 2005a). Large ice fields are found in Alaska (e.g. the Bagley Ice field, covering 5200 km^2), and in the southern Andes (e.g. the Southern Patagonia Ice field, covering about 13000 km^2). Glaciers and glacial environments are sensitive indicators of climate change, and, in many mountain regions, important component of the hydrological cycle. The response time of glaciers to adjust their length to changed climatic conditions mainly depends on their mean slope and size. Small mountain glaciers react rapidly to climatic forcing. Typical response times of valley glaciers are 20 to 50 years (Oerlemans, 1994). In spite of the fact that glaciers and ice caps account only for 0.5% of the total land ice, their contribution to sea level rise during the last century exceeded that of the ice sheets. For the last three decades the vast majority of glaciers worldwide retreated; the average specific mass balance of all glaciers and ice caps for that period has been estimated at –265 mm/year, corresponding to 0.4 mm/year sea level rise (Ohmura, 2004). However, this estimate still carries significant uncertainty.

Studies of glacier mass balance and dynamics are not only important for climate research, but are of great concern for socioeconomic reasons, related to effects of glacier retreat on water supply. In many mountain ranges glaciers provide a significant portion of runoff during the dry season, so are vital for drinking water, irrigation and industry. Severe adverse consequences for future water availability are expected from accelerating glacier and snow cover retreat, in particular in regions where fresh water is already limited. Most critical regions with vanishing glaciers are China, India and other Asian countries, as well as the South American Andes (Barnett et al., 2005), with hundreds of millions of people affected. But the supply of meltwater from glaciers has significant environmental and economic value during the summer season also in other regions, including the European Alps and the Rockies of North America.

Understanding and modelling the response of glaciers to atmospheric forcing requires data on glacier mass balance, glacier/atmosphere interaction, and ice dynamics. In addition to field surveys, studies of glacier/climate interaction are based on forward modelling, relating meteorological conditions to mass balance and glacier advance or retreat, to learn how glaciers respond to greenhouse warming scenarios and contribute to sea level rise, as well as on inverse modelling to derive climate signals from glacier fluctuations in the past. Modelling has focused on few well-studied glaciers where multi-year time series of field measurements are available. It is expected that satellite-based glacier observations will enable more comprehensive studies and extend existing data in space and time.

7.1. Status of Observations

The global terrestrial network for glaciers (GTN-G) within GCOS and the Global Terrestrial Observing System (GTOS) is designed to provide quantitative and understandable information about glacier change to the scientific community as well as to policy makers, the media and the public. The network is operated by the World Glacier Monitoring Service (WGMS) and follows a global hierarchical observing strategy (GHOST). This integrative approach is based on detailed (index) in situ measurements of mass balance at Tier 2 (Tier 3) sites and length change measurements at Tier 4 sites, combined with global information from remote sensing data (glacier inventories) at Tier 5 sites (Haeberli, 2006). Currently, there are about 50 Tier 2 / 3 sites and about 550 Tier 4 sites that are maintained due to their integration in an international observing program. Glacier inventories comprise basic information on physiographic properties of glaciers, including glacier boundaries and surface topography. Systematic compilation of inventories at regional or national scale started in the 1940s, based on aerial photography. These activities peaked in the 1970s and 1980s. From approximately 160,000 glaciers about 44% (71,000) are currently stored in the World Glacier Inventory (WGI) (IAHS(ICSI)/UNEP/UNESCO, 1989). The data are available in digital form from the World Data Center for Glaciology/NSIDC. Stored data include glacier code, name, geographic location, total area, length, minimum and maximum elevation in most cases. Many regions are still not included in the WGI although data have been compiled (e.g. Arctic Canada). However, for assessment of glacier changes at a global scale the WGI provides the most comprehensive data set. While data on glacier fluctuations are reported regularly by the WGMS (e.g., IUGG(CCS)/UNEP/UNESCO/WMO, 2005a and 2005b) the recent review by Barry (2006) summarizes the currently observed changes in glacier area.

The emergence of Earth observation satellites opened up the prospect of achieving a complete global inventory of glaciers. A first initiative in this direction was the “Satellite Image Atlas of Glaciers of the World” (U.S. Geological Survey Professional paper 1386-A-K). Compilation of the 11-volume atlas involves more than 100 scientists, using Landsat MSS images from 1972-1981 to establish a baseline of the areal extent of all glaciers on the Earth (http://pubs.usgs.gov/fs/2005/3056). Each volume includes the comprehensive history of observations of the glaciers in each glacierized region (e.g., Antarctica, South America, Europe, etc.). The atlas series is a nearly completed 20-year effort. When completed in 2008, it will provide a baseline reference for future satellite-image-based research, such as the Global Land Ice Measurements from Space (GLIMS) Project (Bishop et al., 2004; Kargel et al., 2005), which has started to compile glacier inventory data sets in standardized format in close cooperation with NSIDC and WGMS (http://www.glims.org/MapsAndDocs/). The aims of GLIMS are to establish a global inventory of land ice, including surface topography (DEM), to measure the changes in the extent of glaciers and, where possible, surface velocities. It aims also to establish a digital baseline inventory of ice extent during the period 2000-2005 for comparison with inventories created at earlier and later times. This will in turn lead to improved information on the global extent of glacier retreats/advances in recent decades and centuries. The related glacier mapping techniques from threshold ratio images could be automated to a high degree (Paul et al., 2002). First surveys for various regions in the world indicate strongly accelerated glacier decline during the past 20 years (Khromova et al., 2003; Paul et al, 2004).

Topographic data can be obtained from single-track interferometry measurements by the Shuttle Radar Topography Mission (SRTM), which provides almost complete coverage of surface topography between 60° N and 56°S (http://www2.jpl.nasa.gov/srtm/). The standard SRTM Digital Elevation Model (DEM) is available in a horizontal grid of 90 m, with nominal absolute vertical accuracy (90% linear error) of 16 meters and nominal absolute horizontal accuracy of 20 m. Comparisons of glacier surfaces from the SRTM with existing DEMs allow estimations of changes in glacier thickness where accurate topographic data from previous years are available (e.g. Rignot et al., 2003). However, a detailed comparison between standard and existing DEMs should first be carried out to eliminate potential bias (Berthier et al., 2006; Surazakov and Aizen, 2006). The along-track stereo sensor ASTER and similar sensors such as SPOT5-HRS or ALOS provide alternative means of generating DEMs over glaciers. Airborne laser surveys can also be used for precise topographic mapping of glaciers, but the cost is high.

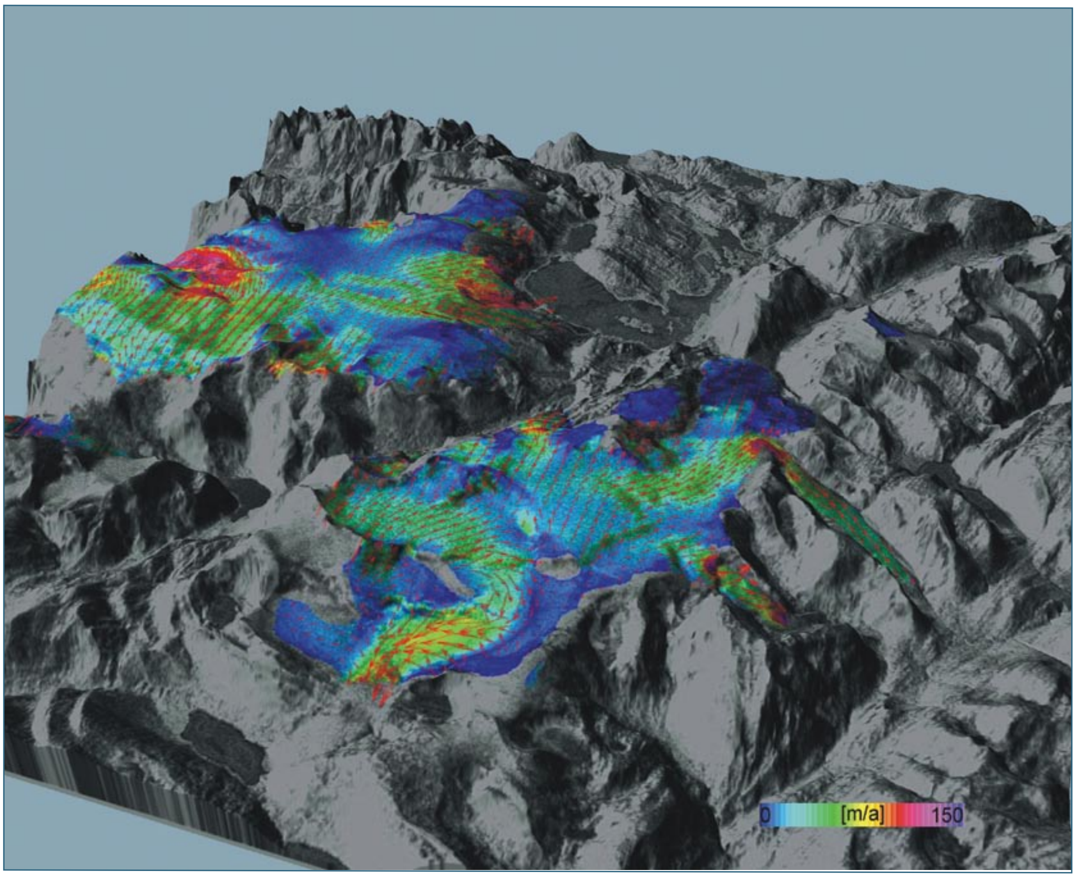
Repeat pass (differential) interferometry (D-InSAR) can also be used to map glacier surface topography, and also provides maps of surface motion (Figure 7.1). At least two independent interferograms are needed to separate the interferometric signals of motion and topography. Single interferograms can be used where a DEM from other sources is available. Interpretation of interferometric velocities is not straightforward, because InSAR provides only one component of the velocity vector, and because the motion is usually retrieved over a short time interval (Mohr at al., 2003). InSAR can measure short-term velocity events (Björnsson et al., 2001). For retrieving annual ice fluxes and the state of balance of an individual glacier, InSAR measurements at different dates are advisable to account for possible seasonal variations (Rabus and Fatland, 2000). Repeat-pass InSAR over snow and ice is hampered by temporal changes in the surface signal due to precipitation, melting or wind. That is why most InSAR applications over mountain glaciers have been based on short repeat-pass periods, in particular the one-day repeat-pass Tandem Mission of ERS-1/ERS-2 (1995-1999), and some limited 3-day repeat-pass periods (the ice phase) of ERS-1 in 1992 and 1994. Another option for velocity mapping, although less accurate than InSAR, is to use image correlation techniques applied to the backscattering amplitude of SAR images acquired typically over time intervals of several weeks to months (Strozzi et al., 2002). This technique requires distinct and conservative features, and so is usually not applicable in accumulation areas. Correlation of repeat-pass optical images can also provide velocity measurements (Kääb, 2005a). Applied over a time period of a few weeks it can map the two-dimensional displacement field on a glacier with good accuracy, depending on sensor resolution and stability of surface features (Berthier et al., 2005; Kääb, 2005b). Correlation of optical images acquired one year apart provides velocity measurements in the ablation zone, where surface features are trackable. This better represents the state of balance of the glacier, and can be used to monitor its dynamic response to climatic change.

Relationships between the global climate system and glacier extent are complex. In order to understand and model a glacier’s response to climatic forcing, we need to know its mass balance. Continuous annual mass balance measurements made over relatively long periods (more than 20 years) based on field measurements of accumulation and ablation are only available from about 50 glaciers world-wide, and from just a few regions (Dyurgerov and Meier, 1997). The selection of glaciers is often driven by accessibility, and small glaciers are preferred. For historical reasons many glacier regions have no mass balance observations, which biases the network of mass balance sites strongly towards Europe, Scandinavia and North America. The global distribution of glacier length change measurements (Tier 4 sites) that are of vital importance for calibrating glacier flow models is much more representative. This series started in 1894 and is a key source for modelling past and future glacier behavior, and for climatic variables (Oerlemans, 2005). Glacier runoff is also important, both for climate research applications and for water management tasks. Runoff gauges are usually not available at glacier streams, because of the difficult terrain and remoteness. Glacier mass balance modelling in daily time steps can be used to calculate glacier runoff (Hock, 2005).

In order to augment the mass balance data set, models are used to calculate mass balance as function of meteorological and physiographic data. The models range from simple correlations with climate data up to spatially distributed models that consider the physical processes determining the exchange of energy between the glacier surface and atmosphere. Calibration of these models is supported by mass balance measurements (in particular at Tier 2 sites) for glaciers in most climate zones. Satellite data on surface albedo and temperature, can be used to extend these models spatially. Maps of diagenetic glacier facies obtained from optical and SAR images are also useful as inputs to distributed mass balance models. The main source of error in glacier mass balance modelling is the lack of information on snow accumulation. Spatial extrapolation from precipitation measurements at climate stations and from numerical meteorological models is problematic, because orography strongly affects the deposition of snow, especially on mountain glaciers.

Regular surveys of glaciers are also needed to detect glacier-related hazards, such as outburst floods of lakes dammed by glaciers or moraines, and ice avalanches. At times, a chain of processes, e.g. an ice avalanche, entraining debris down stream and thus triggering a major slide/mud-flow or causing outburst floods of glacier lakes along its path may cause a major catastrophe. Presently, hazardous glaciers are observed on a case-by-case basis. The main risk zones are in the South American Andes and the Himalayas, where there are major gaps in regular observations. An inventory of potentially dangerous lakes is available for Bhutan and Nepal and can be used to assess rapid changes.

Fig. 7.1. Ice motion of glaciers in the Svartisen area (Norway), derived from ERS InSAR data. (*Courtesy ENVEO IT*)



To describe the response of glaciers to climate change, ice flow models are used to calculate changes in glacier geometry as a function of mass balance forcing. Inputs to the model include the shape of the glacier bed, basal flow conditions, and the material properties of the ice. For the most part, ice thickness measurements come from surface-based radars, as borehole studies of ice deformation properties and of subglacial till are rare. To provide appropriate inputs for these complex models we need simpler, more robust approaches. Ice coring in the cold firn of glaciers and ice caps is also needed to extend the climate archive obtained by coring on the ice sheets. **Current measurement accuracies and requirements for glaciers and ice caps are given in Appendix B, Table B.6.**

7.2. Shortcomings in Current Observations

A comprehensive glacier observing system must be based on synergy of ground-based and satellite-borne observing systems, complemented by airborne surveys for special studies. Representative surveys of glaciers and ice caps will only be possible by using satellite observations. This has already been taken into account in the GLIMS initiative. Field measurements will also be required – for instance measurements at anchor stations for calibrating and validating satellite-based observations and process models. It will be essential to maintain the World Glacier Monitoring Service (WGMS) as the only reliable (i.e. quality checked) source of standardized data on global glacier mass balance and length changes.

The synergistic use of the different glacier-observing subsystems and the integration of their various measurements is still in an early stage, and is hampered by shortcomings including:

1. There are large gaps in the global glacier inventory database. High-resolution multispectral optical sensors (Landsat, SPOT, ASTER, etc.) are the most efficient means for glacier mapping. The compilation of the first global glacier inventory is hampered by the lack of resources for analyzing available satellite data sets, including high data costs for some satellite data. Repeat inventories are required at 5 to 10 year intervals for global change studies, assessing change of water resources, etc. Low cost satellite data are required for this task.

2. Formal establishment of the responsibility of the GLIMS project for Tier 5 observations is required to ensure a fully integrated and multilevel observing strategy for glaciers within GTN-G. Regular assessments of glacier changes (mass, length, velocity, etc.) by remote sensing techniques should be reported in the 'Fluctuation of Glaciers' reports.

3. The glacier topography database is fragmentary and/or of poor quality. Space based data are needed to improve it. The Shuttle Radar Topography Mission (SRTM) has helped, though coverage is not global. Improved accuracy and spatial resolution of the future DEM observations are required for accurate estimates of mass changes.

4. Glacier mass balance data are sparse and unsuitable either for regional and/or global assessments or for water management. It would seem unrealistic to call for a major increase of in situ mass balance studies. Methodologies should be further developed for estimating mass balance from meteorological data, in synergy with remote sensing data (topography, glacier facies, albedo, accumulation, etc.) to give a more comprehensive picture of mass balance in various climate zones and globally.

5. Remote sensing is required for measuring snow accumulation on glaciers. Field measurements are tedious and extremely sparse, and extrapolations from meteorological stations and numerical weather models are flawed.

6. Comprehensive data are required on glacier velocity. Extensive global data sets on surface velocities of glaciers were collected by the interferometric ERS tandem mission between 1995 and 1999. In order to assess the dynamic response of glaciers to global warming, a similar mission is required within the next few years.

7. More data are required to monitor glaciers for hazards. Continuous observations are needed from optical, medium and high spatial resolution sensors. Satellite radars enable daily observations, but costs are high. ■

Recommendations: Development of Glacier and Ice Cap Observations

R7.1 For climate research, priority needs include the completion of the global glacier inventory and the improvement of models that link meteorology to glacier mass balance and dynamic response.

R7.2 Downscaling techniques need to be developed for feeding such models with GCM data. Remote sensing data are needed to initialize and validate these models. Water management tools for glacier runoff will also benefit from these developments.

R7.3 In order to achieve these objectives, on the space infrastructure side long-term continuation of Landsat/SPOT type missions, providing data at favorable costs, are needed to obtain global inventories of glaciers and their changes in time intervals of 5 to 10 years.

R7.4 A dedicated mission for precise mapping of glacier topography is a high priority for determining the evolution of changes in glacier mass directly or from distributed mass balance models. Single pass or short-repeat InSAR will provide coverage of all glaciers worldwide. Such an InSAR mission would also provide ice motion data. For the mass balance and hydrological modeling and for downscaling of circulation models a satellite mission providing spatially distributed information on accumulation should be implemented, such as the candidate CoreH_2O Earth Explorer mission concept based on dual frequency (Ku- and X-band) SAR that is considered in ESA's Living Planet Programme.

R7.5 In parallel with advancing the space infrastructure it is essential to maintain a solid ground-based glacier observation network. Drivers for this are continuation and improvement of long time series of key climate parameters such as mass balance (seasonal data) and glacier length, which includes resuming long-term observation series on several glaciers, as well as the use of these observations as anchor stations for calibration and validation of process models and satellite-derived glacier products.

R7.6 The coordination of global glacier monitoring activities by WGMS and generation of a standardized database of glacier measurements is of high priority. Support of already established monitoring networks like GTN-G needs to be strengthened by establishing an adequate share of international and national funding to guarantee the continuation of the operational services, to maintain the international network, and to face the challenges of the 21st century.

R7.7 A global 2D glacier inventory (polygon outlines, cf. GLIMS initiative and GlobGlacier project) is needed as a reference for glacier change assessment within the framework of GTN-G.

8 Surface Temperature and Albedo

Surface temperature and albedo are the key parameters that determine the energy transfer between the surface and the atmosphere, including the net surface radiation flux, surface turbulent sensible and latent heat fluxes, and the transport of energy below the ocean surface. These two quantities are easier to measure than turbulent fluxes, and should therefore be part of the cryospheric observing system. Although basically two independent parameters, they are related in that one can significantly affect the other. For example, increases in surface temperature of snow or ice would cause the initiation of surface melt that in turn affects the surface albedo. Also, a decrease in albedo would cause the absorption of more shortwave radiation by the surface that in turn would cause an increase in the surface temperature. These two parameters are relevant to all the cryosphere domains, and are therefore addressed separately.

Surface temperature is arguably one of the most important parameters needed in cryospheric studies. It provides direct information about the state of the snow, ice, land, or ocean surface. It requires the least amount of interpretation in terms of relationships to global climate change. Many cryospheric processes are directly related to surface temperatures. For example, the onset of melt and of freeze-up is dictated by temperature. Surface temperature thus provides the means to identify these events and directly assess the length of the melt period. Increases in melt period can be critical over some regions, (e.g., the Greenland ice sheet) since it would cause more melt water to percolate to the bedrock and serve to lubricate the latter causing the ice sheet to surge more rapidly than normal. Increases in melt period would also cause decreases in the volume and hence thickness of the sea ice cover resulting in declines in ice extent. Furthermore, any increase in melt length would change the state of the permafrost, glaciers, and snow cover.

Albedo is defined as the fraction of incident short wave radiation that is reflected from the surface. A more general term is the total or broadband albedo, which is the integral of the contribution from the entire visible spectrum, i.e., 400 to 1500 nm (Perovich, 1996) or 300 to 3000 nm (Hanesiak et al., 2001). It is the relatively high albedo of ice and snow compared to that of other surfaces that makes the cryosphere very special in climate change studies. Albedo controls the heat exchange between the surface and the atmosphere, and it is mainly because of ice-albedo feedback that climate change signals are expected to be amplified in the polar regions. It is also albedo, together with temperature, that determines the rate of surface melt in the snow and ice and how fast the latter retreat in the summer (Curry et al., 1995). Because of its role in radiation balance, it is also considered as a critical parameter in sea ice and global models.

The albedo of ice and snow varies considerably throughout the year. The reflected radiation includes scattering and absorption within the snow and ice that varies with the dielectric properties of the material, thickness of snow and ice, size of scatterers, and wetness of the surface. The albedo thus increases as the ice thickens in autumn and as the surface acquires a snow cover, while the albedo decreases in the summer as the snow surface melts and turns into slush and eventually into meltponds. Albedo is therefore useful for assessing the characteristics of the surface and the condition of the snow cover. Fresh snow usually has high albedo while old snow, which is grainy, has lower albedo. Albedo over snow and ice is also decreased by contaminants such as soot.

8.1. Status of Observations

Surface temperature has been a basic measurement at meteorological stations around the world for decades. They typically measure air temperature 2 m above the surface rather than the actual surface skin (radiating) temperature. There are, unfortunately, very few measurements on sea and land ice. Because of the vast expanse and general inaccessibility of ice sheets and sea ice, the only practical way to produce spatially detailed maps of surface temperature is through use of satellite remote sensing. Thermal infrared measurements are quite useful for this purpose, because the emissivity of snow and ice surfaces is uniform and close to unity. Passive microwave systems can be used as alternatives (Shuman and Comiso, 2002), because they penetrate thick clouds, and hence provide good surface data for day and night under practically all weather conditions. However, the application is limited because knowledge of the emissivity of the surface almost on a pixel-by-pixel basis is needed before we can estimate surface temperatures from the measurements. Such information is not available due to the large spatial variability of surface ice emissivity at the microwave frequencies.

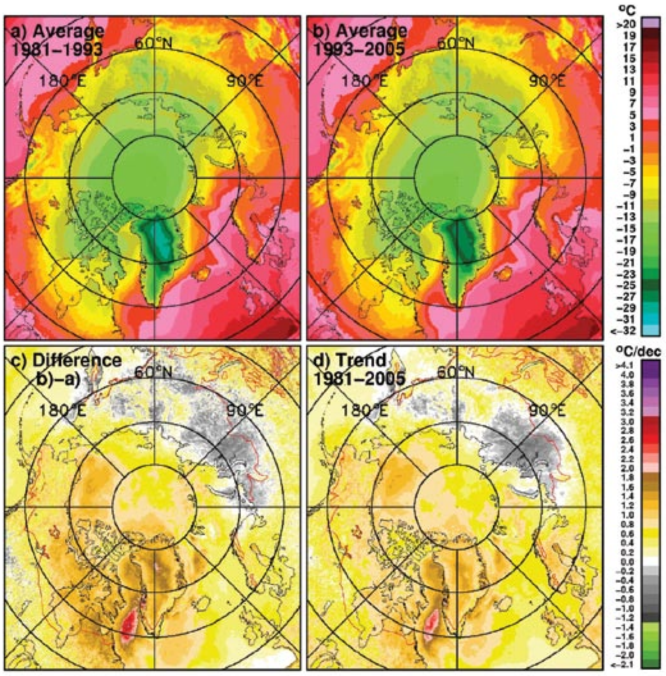
One of the main problems with infrared sensors is that they provide surface temperatures only where there are no clouds. An effective cloud masking technique is thus required, which is hard to implement because clouds can be difficult to distinguish from snow and ice. While clouds may be persistent they are not always present. Given the high frequency of observation by polar orbiting satellite sensors, the chances of getting surface measurements for a particular area are thus relatively high. Weekly and monthly averages of the data have been generated with practically no gaps over ice-covered areas. Because of the clear-sky sampling bias, the resulting maps are regarded as surface temperature maps for these conditions only. At any one time the differences between clear and cloudy sky surface temperatures can be 5ºC or more, but on a monthly basis the differences are smaller.

Snow and ice surface temperature has been estimated from satellites using the Temperature Humidity Infrared Radiometer (THIR) on board the Nimbus satellites (Comiso, 1994), and from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA operational satellites. Other systems (e.g., ENVISAT/AATSR and EOS/MODIS) provide improved capabilities and more accurate retrievals. MODIS has 36 visible and infrared channels and provides continuous coverage at 1 km resolution while AATSR has more limited coverage but provides two look angles for improved accuracy. The record lengths of data from these sensors are still relatively short but they offer a promising future for climate studies.

These infrared sensors all measure the temperature of the top layer (the “skin”) of the ice surface. Comparative analysis of surface temperatures derived from AVHRR data with co-registered and coincident in situ measurements confirms that the thermal infrared data capture the same variability in surface temperature as the ground values. Errors associated with the retrieval of surface temperatures have been evaluated and estimated to range from 2º to 3ºC (Steffen et al., 1993; Key and Haefliger, 1992; Comiso, 2003; Shuman and Comiso, 2002). These errors include problems with cloud detection. The uncertainties in the algorithms are lower, on the order of 1º C.

The AVHRR sensor has been used to generate monthly average temperature maps of high latitude regions of the Northern and Southern Hemisphere from 1981 to the present. Compared to other sources of regional surface temperature data (e.g., NCEP or ECMWF), the infrared data provide a more realistic representation of the spatial distribution of surface temperatures in areas where there are no in situ measurements. For example, the retrieved data are coherent with the expected variations in surface temperature with elevation in Antarctica and in Greenland, whereas models reflect spatial temperature patterns poorly over the ice sheets. Some unique surface features over land and sea ice that are not in other data sources have also been identified.

Fig. 8.1. Surface temperature of the Arctic from AVHRR.



(a) Average surface temperature from August 1981 to July 1993; (b) Average surface temperature from August 1993 to July 2005; (c) Difference between (b) and (a); (d) Surface temperature trend for the period August 1981 to July 2005.

Figure 8.1 illustrates the use of the relatively long AVHRR time series for recent climate change studies. It shows that the changes between two time periods, 1981-1993 and 1993-2005, are overwhelmingly positive, indicating warming, with the most positive data located in the western Arctic (i.e., Beaufort Sea) and North American region. An unexpected result is the detection of large areas of cooling in parts of Russia, which have subsequently been verified using in situ data. Other analyses of AVHRR data show even stronger cooling in the eastern Arctic in areas for which there are no surface measurements. This indicates that global monitoring is important and that trend studies should not rely solely on measurements from ground stations, especially if the latter are sparsely distributed.

Albedo is the non-dimensional ratio of the radiation reflected by a surface to the incoming radiation. Most commonly it is based on irradiance, which removes much of the directional reflection component. However, there is still a directional component in the downwelling irradiances, which is dominated by the sun angle. The atmosphere also plays a role, scattering the direct solar beam. Therefore, there are really two components to the albedo: the directional hemispherical, or "black sky", at some solar angle, and the diffuse, or "white sky" albedo. To estimate the surface albedo from space, radiance measurements in narrow spectral bands need to be converted to broadband estimates of irradiance.

A number of investigators have performed surface-based measurements of wavelength-integrated and spectral albedos for a wide variety of ice types and conditions (cf, Perovich et al., 2002a; Hanesiak et al., 2001). Airborne observations (cf, Tschudi et al., 2001; Perovich et al., 2002b) have been limited to a few campaigns in different locations and show high variability in summer sea ice albedo. Snow and ice albedo is routinely generated from space instruments, particularly the AVHRR and MODIS (Lubin and Massom, 2006).

Current measurement accuracies and requirements for snow/ice surface temperature and albedo are given in Appendix B, Table B.7.

8.2. Shortcomings in Current Observations

Meteorological stations conducting measurement of surface temperature in cold regions are not uniformly distributed. As a result their spatial coverage is too poor to allow accurate assessment of spatial variability and trends in temperature over the polar regions. The paucity of stations is associated with logistic difficulties in setting up and maintaining them in the adverse polar environment.

The most practical technique for obtaining skin depth surface temperatures over snow and ice covered regions is through the use of thermal infrared satellite sensors. The technique is far from ideal in the polar regions, because of the high frequency and persistence of clouds, which makes temporal monitoring of the surface impossible on a daily basis despite the high frequency of satellite passes. Because of relatively large diurnal variability during the summer, even the daily maps may not represent daily averages well, because different areas represent measurements during different times of the day.

Detecting clouds by satellite in the polar regions is not easy. Cloud detection is complicated by low sun angles, long periods of darkness, bright surfaces, and low thermal contrast between cloud and the background. Inaccuracies in cloud detection have a significant impact on surface temperature estimates from space. Quantifying atmospheric effects on the retrieved surface temperature data, including those of water vapor and aerosol, is also a challenge.

The main concern associated with the development and analysis of a long-term temperature record is the relatively short lifespan (typically 5 years) of each AVHRR sensor. The archived composite record is actually a collection of data from several AVHRR sensors with no overlap coverage between sensors. The lack of overlap has made it difficult to compare the performance and compatibility of the different AVHRRs. For lack of a better solution, in situ data have been used to improve calibration and ensure consistencies in the derived temperatures from the different sensors.

Validation of satellite retrievals using surface measurements of temperature is problematic because most meteorological stations report air temperature at a height of 2 m, not the surface skin (radiating) temperature. Biases between the air temperature and the skin temperature are generally small, perhaps 1° C on average, but can be large in the presence of strong inversions.

The AVHRR has only two channels useful for albedo retrieval, and they do not have on-board calibration. This is a particularly problem for climate studies. In order to partially alleviate the problem, vicarious calibration is used. The uncertainty in albedo estimates is primarily due to calibration uncertainty. MODIS data provides an improvement, but work is needed to make the calibration of the different channels internally consistent. As with surface temperature estimates from space, satellite estimates of surface albedo are restricted by cloudiness, which can exceed 80% during Arctic summer (Intrieri et al., 2002).

Validation of satellite data is needed to ensure that retrieved products are accurate. Airborne observations of albedo are beset with challenges due to aircraft orientation. Recent developments in stabilized platforms help to address this problem, but are not yet available for UAV deployment. Unfortunately, few meteorological stations measure upwelling and downwelling shortwave irradiance, so in situ albedo measurements are sparse.

■

Recommendations: Development of Surface Temperature and Albedo Observations

R8.1 There should be a continued production of unified, consistent time series maps of surface temperature and albedo to add to the existing record from NOAA AVHRR that extend back to the early 1980s.

R8.2 The surface network of radiation measurements must be expanded to validate satellite-derived surface albedo and temperature measurements. Surface albedo datasets should capture the progression of large-scale melt-freeze at sufficient resolution for surface energy budget evaluations and model validation. Future airborne deployments of albedo and reflectance instruments, as well as surface-based measurements, are essential to evaluate the accuracy of satellite albedo estimates.

R8.3 The MODIS daily snow albedo product should be extended to include sea ice.

R8.4 The fusion of infrared and passive microwave data would help to improve accuracy and spatial as well as temporal coverage. The microwave data are most valuable when done over areas where the emissivity of the surface is well known. In those areas, spatially detailed measurements from passive microwave data could be used with infrared data to obtain surface temperature maps that have high temporal resolution and spatially consistent values.

R8.5 Multi-angular satellite measurements e.g., from MISR and PARASOL, are required to better characterize the bidirectional reflectance functions (BRDF) of snow and ice.

R8.6 Vicarious calibration efforts of AVHRR visible channels from all NOAA satellites need to be continued.

R8.7 Methods for estimating the spectral albedo of snow and ice from satellite should continue to be developed. Future satellites should carry spectrometers.

9 Permafrost and Seasonally Frozen Ground

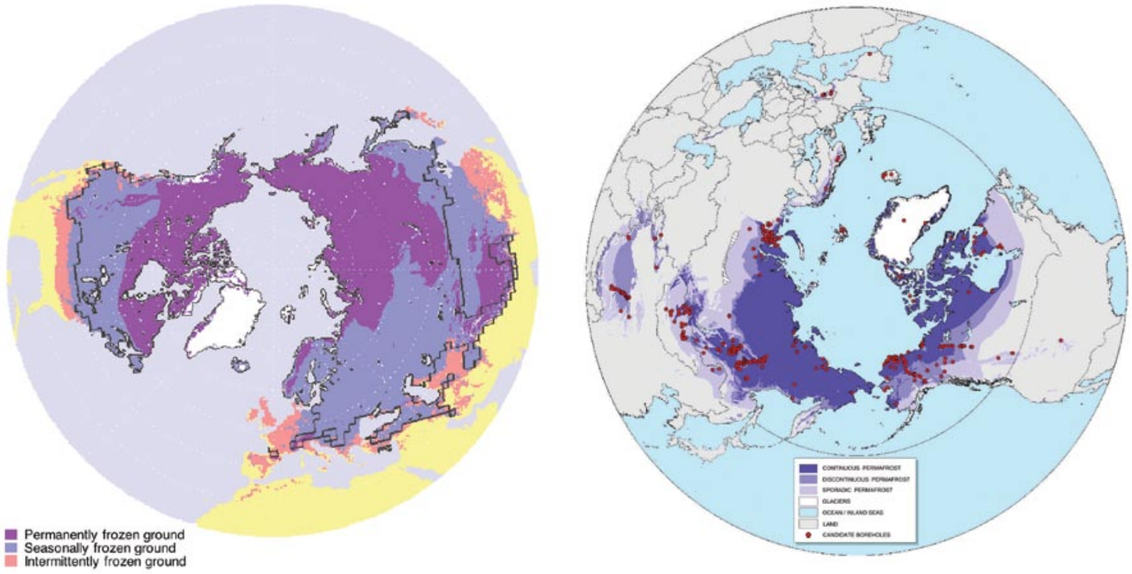
Permafrost, defined as sub-surface earth materials that remain at or below 0°C continuously for two or more years, is widespread in Arctic, sub-Arctic, and high-mountain regions, and in ice-free areas of the Antarctic and sub-Antarctic. In the Northern Hemisphere, permafrost regions cover approximately 23 million km^2 with actual land area underlain by permafrost occupying between 12 and 17 million km^2 (Brown et al., 1997; Zhang et al., 2000). The uppermost layer of seasonal thawing is termed the "active layer". Seasonally frozen ground combined with intermittently frozen ground occupies approximately 54.4106 km^2, or 57% of the exposed land areas of the Northern Hemisphere and includes the active layer over permafrost and soils outside the permafrost regions (Zhang et al., 2003) (Figure 9.1). The importance of permafrost and seasonally frozen ground to natural and human systems in the polar and sub-polar regions is discussed in detail in the ACIA (2005) and IPCC (2001) reports. The recent report on Arctic Observing Networks (NRC, 2006) includes requirements for permafrost observations.

9.1. Status of Observations

The Global Terrestrial Network for Permafrost (GTN-P) identifies permafrost thermal state (i.e., ground temperature) and the active layer thickness as the key variables for monitoring (WMO, 1997; Brown et al. 2000; Burgess et al., 2000). The temperatures measured in the permafrost provide an indication of the integrated changes in the ground surface energy balance, and thus preserve a record of recent changes in surface climate for a given area. The GTN-P consists of two international monitoring components: the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring (CALM) networks, whose developments have been coordinated by the International Permafrost Association (IPA) starting in the 1990s. Both TSP and CALM have regional components for the Antarctic in cooperation with IPA and the Scientific Committee for Antarctic Research (SCAR). GCOS regional workshops and action plans for South American and Central Asia recommend expanded GTN-P sites in these mountainous regions (GCOS, 2005).

The key TSP parameter is the measurement of borehole temperatures to establish the mean annual temperature at the depth of zero amplitude change (approximately 20-metre depth). Many permafrost temperature records are of short duration and discontinuous, with fewer sites having 20- to 40-year time series. Currently about 400

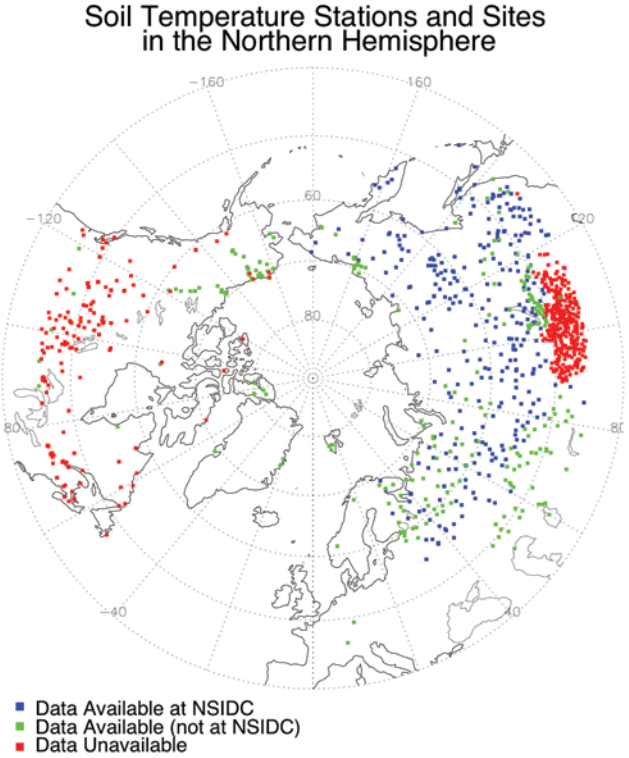
Fig. 9.1. Northern Hemisphere maps of zones of permafrost and seasonally frozen ground (left) and locations of candidate boreholes (dots) for the IPY TSP project and GTN-P (right).



boreholes in more than 15 countries are listed in the GTN-P database. Although there is no formal network that specifically covers mountain and plateau permafrost, national and regional programs exist such as Permafrost and Climate in Europe (PACE over the period 1997–2001: Harris et al, 2001), Permafrost Monitoring Switzerland (PERMOS), and an extensive monitoring program across the Qinghai-Tibet Plateau in China. The CALM program has been in operation for more than a decade. There are currently over 140 sites that report seasonal thaw and in some cases soil temperatures, moisture and frost heave and subsidence.

Field observations of depth and distribution of seasonally frozen soils are generally derived or modelled from soil temperature measurement. No formal international network exists for these soil temperature or moisture observations, although several programs compile and make available some data (see GTOS Terrestrial Ecosystem Monitoring Sites (TEMS; GTOS (2005) and NSIDC Frozen Ground Data Center). There were more than 800 stations in the former Soviet Union where soil temperature from ground surface to 320 cm and soil freezing depth were measured on a daily basis (Chudinova et al., 2006). Since the early 1990s, the number of Russian stations has declined significantly. Similar measurements in Mongolia (40 stations) and China (ca 500 stations) were also carried out using the same methodology (Figure 9.2). China is currently increasing automatic weather stations in remote areas. There were up to 200 stations in the USA (NOAA National Weather Service) where soil temperature were measured. The USDA has established a network monitoring soil temperature and moisture with more than 30 stations since the middle of the 1990s. In Canada similar soil temperature and soil freeze-thaw measurements were carried out in recent decades.

Fig. 9.2. Locations of past and current Northern Hemisphere soil temperature sites.



The Arctic Coastal Dynamics (ACD) program began in 1999. A network of 25 key sites was identified along the coastline of the entire Arctic Basin (Rachold et al., 2005). Rates of erosion are measured on the ground and from remotely sensed imagery. A database has been prepared that includes a classification and properties of over 900 coastal segments. Phase II of ACD is the planning stage.

Unlike ice and snow covers, properties of permafrost terrain are currently not directly detected from remote sensing platforms. However, many surface features of permafrost terrains and periglacial landforms are observable with a variety of sensors ranging from conventional aerial photography to high-resolution satellite imagery in various wavelengths. Zhang et al. (2004) and Duguay et al. (2005) provided a comprehensive overview of satellite remote sensing of permafrost and seasonally frozen ground ranging from optical to passive microwave sensors. Surface indicators of permafrost terrains that are discernable visually and thus by remote sensing include pingos, thaw lakes and basins, retrogressive thaw slumps, thermo-erosional valleys, thermokarst mounds, ice wedge polygons, beaded drainage, palsa fields, slope failures, and rock glaciers. Increasingly, permafrost is detected indirectly by combining various datasets within GIS (remote sensing imagery, DEM, geomorphological parameters, meteorological data, land surface properties) of (e.g. Etzelmülller et al., 2001; Peddle and Franklin, 1993; Peddle and Ferguson, 2002; Grosse et al., 2006). Permafrost can also be detected indirectly through e.g. the observation of permafrost-related changes in hydrology (e.g. Yoshikawa and Hinzman, 2003; Smith et al., 2005), or the relation of the Normalised Difference Vegetation Index (NDVI) to active layer depths (McMichael et al., 1997).

Conventional aerial photography has long been employed to detect and measure changes in permafrost-dominated landscapes, with time series dating back to the 1940s and 1950s being used to monitoring permafrost surface indicators. Until recently, Landsat imagery (MSS, TM, and ETM+) and SPOT imagery were the most frequently used satellite data for interpreting and observing changes in permafrost conditions for non-mountainous regions (e.g. Morrissey et al., 1986; Leverington and Duguay, 1997; Lewkowicz and Duguay, 1999; Grosse et al., 2006). IKONOS and QuickBird satellites and the declassified CORONA spy-satellites are providing new capabilities for observing changes in and inferring the presence of permafrost conditions (e.g. Grosse et al., 2005; Lantuit and Pollard, 2005).

Site-specific investigations of creeping permafrost and slope failures in mountain regions can be made using conventional and satellite imagery and differential SAR interferometry (D-InSAR) to map surface deformation of rock glaciers (Kääb, 2005a) and others. Vegetation and soil moisture can indicate differences in subsurface permafrost conditions. RADARSAT has been used to map zones of wintertime heat loss that indirectly approximate the distribution of permafrost (Granberg, 1994). Scatterometer data have been used to monitor freeze and thaw cycles (Bartsch et al., 2007).

Data from passive microwave sensors, such as SMMR (1978-1987) and SSM/I (1987-present) can be used to detect surface soil freeze or thaw status based upon the spectral sensitivity of brightness temperatures to the state of water (liquid or solid) in the near-surface soil (Zhang and Armstrong, 2001; Zhang et al., 2003; Smith et al., 2004). The Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), launched in 2002, has lower frequency channels and higher resolution, which may be superior for detecting soil freeze/thaw status. These and new satellite-based mapping tools and techniques may yield important advances in the application of remote sensing to spatial and temporal characteristics of near-surface soil freeze/thaw status.

Current measurement accuracies and requirements for permafrost and seasonally frozen ground are given in Appendix B, Table B.8.

9.2. Shortcomings in Current Observations

The GTN-P (thermal state of permafrost and active layer) is built largely on voluntary regional and national networks and programs. Many of these sites are not maintained for long-term monitoring. The existing networks are under-populated and do not represent the full range of climatic and physiographic variability. Many existing sites are only maintained with the support of short-term project funds. The IPA's permafrost initiatives for the International Polar Year are intended to establish a permanent international network of permafrost observatories. While this may establish more permafrost observatories during the IPY, we will still need long-term commitment and resources to maintain the network.

There are significant thematic and regional gaps in the present GTN-P networks, especially in eastern and central Canada, most ice-free areas in Greenland, north-central and northeastern Russia, part of northeast and western China, other mountain regions of Central Asia, the Andes, and many ice free areas in the Antarctic and subantarctic.

Considerable resources are required to maintain and collect data from existing sites, some of which are in remote locations accessible only by aircraft. Use of data loggers reduces the frequency of site visits to recover data. Many sites lack instrumentation for collecting the ancillary data required to analyze the linkages between permafrost and climate.

We also need to access, process and make available the wealth of historical observations extending back in time for 50–100+ years; e.g., the former Soviet Union has daily observations for 800 stations, with some extending back to the 19th century. However, data rescue is labor intensive and can be expensive. In addition, many sites were discontinued in the early 1990s. Furthermore, many of the historical national databases (Russia, China, Mongolia, etc.) lack adequate metadata.

Other systematic networks of observations are needed, as well as ground temperature and depth of seasonal thaw and frost. The Arctic Coastal Dynamics project requires additional sites to monitor the erosion of ice-rich permafrost and its contribution to sediment budgets on the inner continental shelf. The new sites should be near populated areas, to involve local observers. In mountainous regions the presence of permafrost and its deformation and degradation require seasonal measurement of the Bottom Temperature of Snow (BTS) and of the annual movement of ice rich materials (creeping permafrost). Under both seasonally frozen and permafrost conditions, changes in the position of the ground surface relative to a fixed point is another important parameter, characterizing frost heave and subsidence.

Permafrost is currently monitored mainly through ground-based point measurements. Although there is an urgent need and potential to use satellite-based sensors to supplement ground-based measurements and extend the point observations to the broader spatial domain, techniques are neither well developed nor validated. Because remote sensing does not adequately penetrate frozen and unfrozen earth materials, the depths of soil freezing and thawing or properties of permafrost (ground ice volumes and thickness of permafrost) cannot be mapped from space or by aircraft.

We need to develop techniques to observe permafrost indirectly by connecting remotely sensed land surface properties or geophysical parameters (vegetation, hydrology, surface temperature, etc.) with subsurface permafrost properties (active layer depth, active layer temperatures, permafrost temperatures, etc.). For such studies, we need satellite sensors to cover high latitude regions and mid-latitude mountains frequently. High-resolution sensors will permit the monitoring of different permafrost parameters. The strong spatial variability in permafrost-dominated landscapes requires remotely sensed data with high spatial resolution. The same applies to temporal resolution, as many parameters show strong intra-annual variation (e.g., active layer depth, temperatures) so need to be monitored frequently.

Currently, high-resolution spatial datasets with good coverage for permafrost mainly come from aerial surveys (and from some satellite sensors e.g., CORONA) from the 1950-1980s. The high costs of commercial sensors prevent the application of recent high-resolution data from such sources over large areas. High-resolution datasets derived from modern imagery are largely lacking, which hampers the investigation of temporal changes in periglacial landscapes. Recent approaches providing such data for research are on the horizon (e.g., ALOS PRISM). We need to continue and expand long time series of spatially high- and medium- resolution remote sensing data (aerial imagery since about 1930, with resolution of 1 m; CORONA imagery since about 1960, with resolution of 2.5 m; and Landsat imagery since 1972, with resolution of 15-60 m). Spatially very high-resolution (0.2 m to 5 m), multi-spectral sensors operating in the visible and infrared spectrum are desired for the detailed investigation of periglacial tundra landscapes with their complex patterns of permafrost processes and surface features. High-resolution sensors help to quantify coastal retreat on permafrost coasts in the Arctic, thereby helping northern communities to mitigate environmental threats.

Thermal sensors observing land surface temperature are the key to understanding and quantifying energy budgets in tundra-dominated landscapes. Thermal data is a key input parameter for modelling permafrost. More information on the ground thermal regime could be extracted by thermal sensors and by surface energy models. Unfortunately, current thermal sensors are restricted to a medium ground resolution of 60-90 m, and have low temporal resolution (Landsat-7 ETM+, ASTER TIR). Higher resolutions have been used for military purposes (MTI, 20 m) but have not been released for civilian applications. MODIS sensors with their high temporal coverage (2 x daily) have a very low spatial resolution (1 km).

Near-surface soil freeze/thaw status is a critical variable for ecosystem and carbon exchange studies, surface and subsurface hydrology, and surface energy balance, thus weather and climate system. Passive microwave remote sensing sensors, especially low frequency and high-resolution sensors, should be further developed to detect the timing, frequency, duration, and areal extent of near-surface soil freeze/thaw. Combined with products from other sensors, such as surface temperature and snow depth, a comprehensive frozen soil algorithm should be developed to detect and simulate soil thermal regime and freeze/thaw depth at regional and global scales.

Digital elevation models (DEM) are essential for modelling periglacial geomorphology, hydrology, permafrost distribution, and matter fluxes resulting from permafrost degradation. Current DEMs covering circum-Arctic landscapes have inadequate spatial grid-cell resolutions of 1 km. DEMs derived from current satellite systems are not sufficient for the construction of a lowland / low relief DEM (e.g., ASTER DEM with approximately +/- 15 m vertical accuracy). Adequate data could be delivered by sensors with stereo capability (e.g., Cartosat-1, ALOS PRISM), repeat-pass InSAR (TerraSAR-X), or space-based LIDAR sensors. SAR interferometry would help to detect surface changes (i.e., surface settlement or erosion) due to permafrost degradation. Multi-temporal DEM will help to detect volumetric surface changes due to permafrost degradation. ■

Recommendations: Development of Frozen Ground Observations

R9.1 Existing GTN-P borehole and active layer networks must be expanded and the “International Network of Permafrost Observatories (INPO)” must be created. During the IPY period new sites are to be added to the networks; some of them should help to fill gaps in coverage. In addition to refinements in sampling protocols, existing sites require upgrades to include automated data loggers, remote data acquisition and instrumentation for collection of ancillary climate data including snow observations.

R9.2 Further development of the GTN-P requires partnerships to co-locate permafrost monitoring sites with those monitoring other cryospheric components (e.g., snow) and to expand existing networks at reduced cost. Partnerships with industry can help to establish monitoring sites in key resource development areas.

R9.3 Data rescue and sustained management activities must continue. Resources are needed for funding for permafrost data management. The IPY provides an ideal opportunity to recover past permafrost-related and worldwide soil temperature data and to encourage long-term commitments to shared data practices and distributed products. Included is the production and archiving of frozen ground data, information and maps for the production of the third CD Rom Circumpolar Active Layer and Permafrost System (CAPS Version 3.0) by the National Snow and Ice Data Center during the immediate post-IPY period 2009–2010.

R9.4 An international network should be created to monitor seasonally frozen ground in non-permafrost regions. Soil temperature and frost depth measurements should be recommended as standard parameters to all WMO and national cold regions meteorological stations. This new network should develop partnerships to co-locate seasonally frozen ground sites with those monitoring other components such as snow and soil moisture and to standardize protocols.

R9.5 As part of the new network remote sensing algorithms to detect soil freeze/thaw cycles (microwave passive and active sensors) should be developed and validated.

R9.6 New upscaling techniques for research sites and permafrost networks should be developed. A novel area of research is the development, validation and implementation of techniques to extend point source process and permafrost monitoring to a broader spatial domain, to support permafrost distribution modelling and mapping techniques implemented in a GIS framework, and to complement active layer and thermal observing networks with monitoring of active geological processes (e.g. such as slope processes, thermokarst development on land and under lakes, coastal dynamics, and surface terrain stability). High resolution DEMs are required.

R9.7 The application of multi-temporal, basin-scale gravity data for the detection of mass loss from ground ice melting in lowland permafrost regions should be evaluated.

10 Solid Precipitation

Snowfall constitutes a significant part of yearly total precipitation over the cold and polar regions, which makes it an important indicator for climate changes and variations. Snowfall provides a mass flux to winter snowpack, which in turn affects the timing and amount of spring snowmelt runoff, and is critical for the basin- and regional-scale water cycle and water resources. Snowfall affects glacier and ice sheet accumulations, leading to changes in mass balance, and influences the large-scale land-surface radiation and energy budget particularly during the accumulation and melting seasons. Snowfall also impacts ecosystem dynamics, water resource engineering, human societies and activities such as transportation, disaster prevention, agriculture activities, and recreation.

10.1. Status of Observations

Methods of observing solid precipitation include the precipitation gauge network, satellite remote sensing, and ground radar. Precipitation gauge networks and data are long-term and fundamental; they enable us to define global snowfall/climate regimes and changes. Manual and automatic precipitation gauges are used for solid precipitation observations in regional and national networks. Both can measure the water equivalent of snowfall, but not snow particle size. Manual gauges can measure the rate of snowfall at 6-hourly to daily time intervals, and auto gauges can provide hourly (or sub-hourly) snowfall (rate) information. Manual gauges are standard at most national networks. Snow rulers are also used for snowfall observations in national or regional networks. They provide snow depth information only, not the snow water equivalent (SWE). In addition, visibility is also routinely measured during snowfall, mainly at airport locations, and may provide the best proxy for snowfall rate.

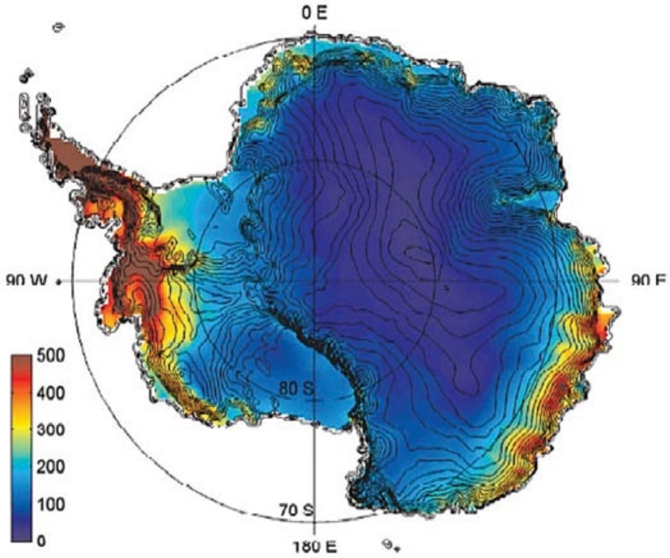
Space-borne precipitation measurements are available from an assortment of experimental and operational platforms. Continuous development and refinements of retrieval algorithms have yielded operational precipitation products based on satellite observations of infrared (IR), passive microwave (MW), and space borne precipitation radar (PR). Figure 10.1 gives an example of a blended snowfall product. Various satellite data have been merged to improve the spatial and temporal coverage of precipitation products (Huffman et al., 1997). For instance, the Global Precipitation Climatology Project (GPCP) blended version 2-monthly data have provided global coverage since 1987. In addition, remote sensing snow cover extent and SWE data from AVHRR and SSM/I products provide information on snowfall and have been widely used for large-scale climate and hydrology analyses. The Dual-frequency Precipitation Radar (DPR) of GPM will observe solid precipitation at 14/35 GHz. Estimation of solid precipitation is a challenge for algorithm development.

Current and forthcoming passive microwave sensors dedicated to precipitation retrievals include the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI), Advanced Microwave Scanning Radiometer (AMSR), Global Precipitation Measurement (GPM) Microwave Imager (GMI), SSM/I as well as SSMI/S on DMSP-16 and beyond. These sensors typically provide high spatial resolution observations in the frequency range 80-90 GHz. The newer instruments SSMI/S and GMI also have channels in the higher frequency window region 150-170 GHz and around the water vapor absorption line at 183.31 GHz. An innovation proposed by the EGPM mission was to use sounding channels (51 and 118GHz) for the retrieval of snowfall and light precipitation at high latitudes. Currently there is little experience in high latitude (snowfall) precipitation retrieval with these sensors.

Although radar provides information about precipitation at high spatial and temporal resolution, it only provides a limited coverage - much less extensive than the gauge networks. The radar network is particularly sparse and expensive to operate at high latitudes. Precipitation and cloud radars can provide information about rain and snowfall rates. Operational radars are in sufficient density for validation of rainfall due to the generally greater vertical extent of rain systems. Snow systems are usually shallower. As a result, the beam tends to overshoot the solid precipitation, which limits the effective range of the radar for solid precipitation. It also tends to overshoot evaporating precipitation from virga (precipitation that evaporates before reaching the ground) and produce false detections. This is a fundamental problem for accurate precipitation measurements.

Current measurement accuracies and requirements for solid precipitation are given in Appendix B, Table B.9.

Fig. 10.1. Antarctic snow accumulation over Antarctica from merged satellite-in situ observations.



Snow accumulation includes redistribution by wind. Satellite observations from AMSR-E and AVHRR instruments are used to guide the interpolation. The effective resolution of the map is approximately 100 km. The estimates of root mean square percentage error apply to regional averages at scales of around 100 km by 100 km. On smaller scales, additional deviations of 30% r.m.s. are likely. Values for locations subject to melt may be unreliable. Units are (kg/m²/a), or (mm/a) water equivalent. (*Courtesy of British Antarctic Survey*)

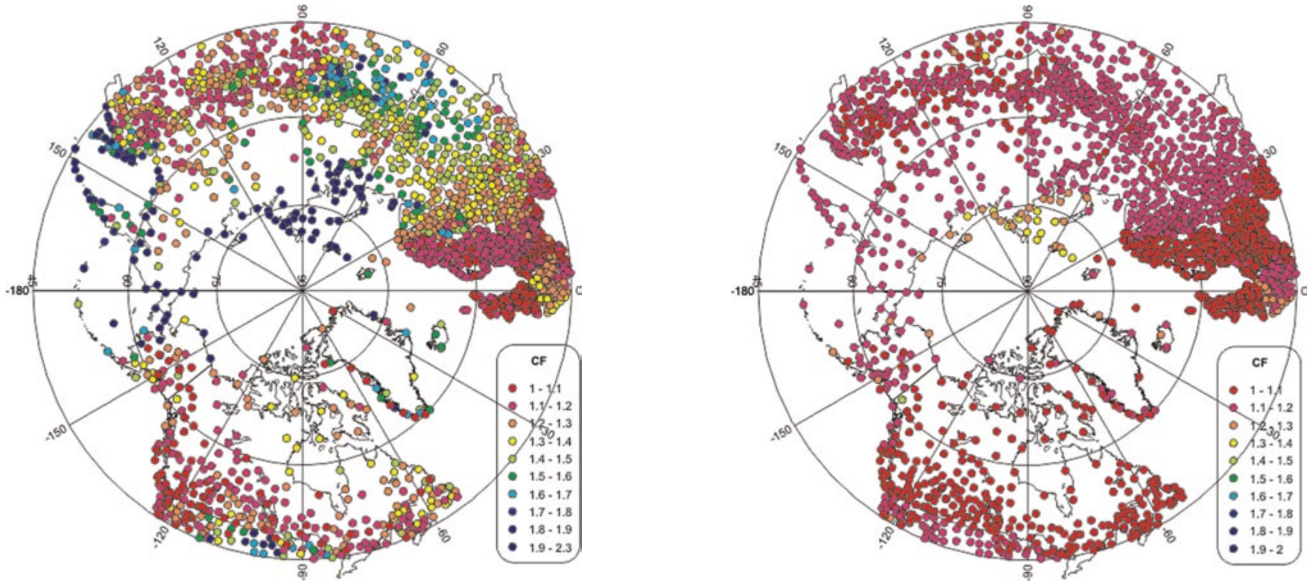
10.2. Shortcomings in Current Observations

Problems in current precipitation gauge networks include: 1) sparseness and decline of the precipitation observation networks in cold regions (i.e. mountains and high latitudes); 2) uneven distribution of measurement sites, i.e. biased toward coastal and the low-elevation areas; 3) spatial and temporal discontinuities of precipitation measurements induced by changes in observation methods (such as automation) and by different observation techniques used across national borders; 4) biases in gauge measurements, such as wind-induced undercatch, wetting and evaporation losses, underestimate of trace and low amount of precipitation, and blowing snow into the gauges at high winds. In addition, data access is also difficult or costly for some regions and countries. There is no operational precipitation network over the oceans. The gauge network is sparse in the Southern Hemisphere. Over the Antarctic solid precipitation is often not measured by gauges due to very high winds and frequent blowing snow in the cold season.

In addition to in situ and satellite data, precipitation from atmospheric reanalyses provides additional information for understanding global precipitation. However, current datasets are far from adequate for monitoring climate change, as evidenced by differences in time series from different products, and from discontinuities in single products. A recent study (Serreze et al., 2005) of various reanalysis and satellite precipitation data shows that reanalysis data from the National Center for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) capture the major spatial features of the observed mean precipitation, and the reanalysis data provide better depictions of monthly precipitation than the GPCP satellite retrievals in the northern regions. Satellite retrievals have also been blended with gauge data (Xie and Arkin, 1997). Examinations of hydrological budgets over several global river basins revealed unrealistically low precipitation in the merged products (Nijssen et al., 2001, Fekete et al., 2004). Over land, the magnitude of these combined products is primarily dominated by gauge observations. The under-estimation of land precipitation in the gauge-based analyses, and thus the merged analyses, is mostly due to the combined effect of a sparse gauge network biased toward low elevations, a lack of consideration of orographic effects, and gauge undercatch of precipitation (Goodison et al., 1998; Legates and Willmott, 1990; Yang, 1999), especially snowfall in cold and windy conditions (Figure 10.2). It is important to identify and correct these inconsistencies, since they will affect the results of large-scale water budget analyses.

Radar networks have very limited spatial coverage over the globe. There are no radars in many countries in the world and they are expensive and can be difficult to operate and calibrate. The radar systems are mainly designed for severe weather detection, with less concern for precipitation and certainly not for snowfall measurements. The major limitation for operational radars is the lack of low-level coverage at moderate (80 km) to long range for precipitation. In complex terrain, mountains often block the radar beam and/or the radar is located to scan over the top of mountains and not in the valleys. A new innovation is the deployment of a network of redundant low cost, low maintenance radars (CASA radars) to scan the low levels of the atmosphere. ■

Fig. 10.2. Precipitation bias correction factors (CF = ratio of corrected vs. measured precipitation) for January and July over the high latitude regions (45°N north) during 1973-2004.



The correction factors are high in January (left) and low in July (right). Winter corrections are particularly high in the coastal regions due to high winds (*Yang et al., 2005*).

Recommendations: Development of Solid Precipitation Observations

R10.1 Solid precipitation observations should be addressed through effective cooperation between GCOS's Atmospheric Observations Panel for Climate (AOPC), the CliC GEWEX projects, and the International Precipitation Working Group (IPWG) of the Coordination Group for Meteorological Satellites (CGMS). Solid precipitation should become a focus for the second phase of the Coordinated Enhanced Observing Period (CEOP).

R10.2 Recommendations for gauge networks and observations include:

- continue conventional point precipitation measurements in existing networks,
- sustain and enhance the gauge network in the cold regions,
- develop guidelines on the minimum station density required for climate research studies on solid precipitation in cold climate regions,
- ensure regular monitoring of the snowfall real-time data quality control and transmission,
- undertake bias analysis and corrections of historical precipitation gauge data at regional to global scale, including the Antarctic,
- examine the impact of automation on precipitation measurement and related QA/QC challenges, including compatibility between national data, and manual vs. auto gauge observations,
- develop digitized metadata for regional and national networks,
- identify and establish intercomparison sites for standardized testing of new technology, such as polarization radar, CASA radar networks, hot plate, pressure, or blowing snow sensors,
- encourage national research agencies to establish programs to provide support for the development of new instruments to measure solid precipitation at high latitudes,
- expand the use of wind shields and direct measurement of winds at emerging auto gauge sites/networks, and
- augment existing AWS networks to include near real-time snow depth measurements in cold regions.

R10.3 Satellite precipitation data and products have greatly advanced our ability to monitor and observe liquid precipitation (rainfall) globally. Similar ability should be developed to measure snowfall from space. The Global Precipitation Mission (GPM) and its European adjunct, EGPM, are critical in this context, as they will cover large regions with a significant portion of snowfall in yearly precipitation.

R10.4 The launch of the GPM should not be delayed further. The EGPM concept was designed to detect and measure snowfall and light precipitation using innovative radiometric techniques combined with a high-sensitivity radar. Future satellite missions adopting the EGPM concept should be strongly encouraged.

R10.5 Improve the blending (combining) of data from different sources (in situ, model, satellite) and develop further intensive field efforts to address scaling issues. Encourage further use of combined active and passive satellite data for snowfall detection/retrieval. Lower the detectability threshold of active space-borne instruments to better than than 5 dBz to detect light rainfall and snowfall. Deploy rain radars with lower detectability threshold. Develop new passive microwave instruments and new channel combinations– particularly at high frequency.

R10.6 Implement the sounding channel technique proposed by the European Global Precipitation Mission (EGPM). Explore use of the new Meteosat Second Generation channels for estimating precipitation. Use aircraft sensors together with extended channel selection studies as a testbed for future satellite instruments. Dedicate high latitude aircraft campaigns for snowfall remote sensing.

R10.7 Expand the network of ground radars to the northern/cold regions to obtain more useful radar observations of snowfall. Deploy the CASA radar concept with high sensitivity for the detection of snow, low level measurements and in complex terrain.

R10.8 Share data and create regional and global radar data sets. Carry out international radar data quality intercomparisons to remove inter-radar biases of precipitation estimates. Make common or open source algorithms available for generating precipitation estimates.

R10.9 Develop and further refine inexpensive ground-based remote sensing instruments for snowfall, including vertically pointing micro radars, such as Precipitation Occurrence Sensing System (POSS) or Micro-Rain-Radar (MRR). Develop dedicated and integrated ground validation programs, for example, within the frameworks of IPWG and NASA's GPM, and Cloudsat (e.g., C3V project), WMO/WWRP (e.g. Helsinki Winter Nowcasting Testbed) or within NHMS' (e.g., Vancouver 2010 Winter Nowcasting in Coastal and Complex Terrain project). Capitalise on emerging technologies and validation opportunities, such as advanced radars or the use of hydrological models, regional or basin water budget analyses, and SWE forecasts.

R10.10 Develop an inventory of all possible technologies for snowfall/parameter retrievals, including other regional assets, such as measurements from power companies, volunteer networks, and web-based data sets. Make data freely available to the international research community. Formalize and coordinate international partnerships for validation of remote sensing precipitation data and products. Coordinate international ground validation programs for snowfall (e.g., GPM, GEWEX, CliC, IPWG) to advance the current state of snowfall retrievals and applications.

11 An Integrated and Coordinated Observing System

The previous chapters assessed the state of observations of cryospheric elements and discussed ways to improve their measurement. This chapter reviews remote sensing and in situ observational needs across all cryospheric elements, and addresses modelling and assimilation, data management, and related observing systems. This approach sets the stage for proposals on system integration.

11.1. Satellite Missions for the Cryosphere

Satellite instruments are essential for delivering sustained, consistent observations of the global cryosphere. No one all-encompassing sensor exists; rather, the combination of data from different yet complementary sensors is required. That realisation underlines the critical importance of yet unachieved synergy. The baseline elements of the optimal satellite remote sensing system are a coordinated combination of visible to thermal infrared wavelength sensors (both high and moderate resolution), passive microwave radiometers, synthetic aperture radars (including systems dedicated to InSAR), laser and radar altimeters, radar scatterometers, and gravity missions. Satellites and sensor packages should be launched in a more coordinated way to avoid duplication, use resources efficiently and create some degree of redundancy. The system should adhere to the ten GCOS principles of satellite climate monitoring.

Synthetic Aperture Radar (SAR)

With its high resolution and all-weather and all-season measurement capability, SAR is in many ways the most powerful element of the cryospheric observation system, with application to ice velocity tracking, mapping ice sheet facies and margins, detecting and tracking icebergs, providing detailed sea-ice information, mapping fast ice, determining floe size distributions, examining wave-ice interactions, and mapping the onset and extent of ice melt and refreeze. SAR also plays a key role in the detection and monitoring of river and lake-ice break-up. Further research is necessary to realize the retrieval of snow-water equivalent (SWE) from SAR data. Continued wide-swath SAR imagery is critical to operational sea-ice analyses and detailed regional ice mapping. Current and planned spaceborne SAR systems provide short-term redundancy of wide-swath coverage, but there is a gap in data continuity beyond 2012, as no spaceborne Earth-observing SAR missions have been approved beyond that date. In order to meet revisit and reliability requirements, two or more wide-swath (500-1000 km) SARs at 100-200 m resolution, or equivalent, would be desirable to provide daily global ice mapping capability.

SAR missions such as Radarsat-2 (planned) and TerraSAR-X (recently launched) could build valuable time series of cryospheric observations. Because they are both commercial satellites, memoranda should be put in place to ensure that parts of their duty cycles are dedicated to cryospheric observation. Furthermore, it is anticipated that Arctic ice services for ship traffic and offshore construction security in particular will benefit from the launch of Radarsat-2, TerraSAR-X and TanDEM-X, due to their high geometrical resolution and multi-polarization capabilities. Detailed work is required to investigate the potential gains in sea-ice classification accuracy by combining X-band with L-band (and/or C-band) SAR data. Improved snow information is expected from TerraSAR-X, leading to improved hydrological modelling in snow-covered and glaciated areas.

We recommend that follow-on Antarctic Mapping Missions (AMMs) be carried out with Radarsat-2, exploiting its ability to routinely switch from a right- to left-looking geometry. The latter is required to enable measurement of the vast area of Antarctica south of 80°S that remained uncovered in the original AMM mission. While the TerraSAR series can look to the left, the inability to downlink data in this mode severely restricts the time available for left-looking data acquisition.

Current and planned SAR systems provide inadequate systematic high-resolution coverage of the Arctic and the Southern Ocean/Antarctica. This situation can be remedied by:

- the continuation of the Alaska Satellite Facility (ASF) Radarsat Geophysical Processing System (RGPS) 3-day sampling strategy to produce a regular weekly "snapshot" of sea ice motion and deformation along with derived properties in the Arctic Basin; and
- the establishment of a similar system in Antarctica.

The latter will require three or four SAR receiving stations on the Antarctic continent to ensure full circum-Antarctic coverage. This number could be reduced by using geostationary data-relay satellites and if SAR missions were equipped with state-of-the-art onboard data recorders with sufficient storage capacity.

Routine output from an Antarctic RGPS (ARGPS) would provide a powerful operational and research tool – especially when used in combination with other satellite data, e.g., passive microwave ice concentrations, visible radiometer measurements of surface albedo, thermal IR temperature products, radar scatterometer ice motion/type products, and radar/LASER altimeter estimates of sea ice thickness. An ARGPS would generate vastly improved time series of ice motion, kinematics, classification and thickness, improved detection of iceberg calving events, tracking of iceberg drift, and monitoring of iceberg groundings.

In addition, we recommend the continued routine acquisition of reduced resolution (1 km) SAR data over the polar regions, along the lines of the Envisat Advanced SAR (ASAR) Global Monitoring Mode. The ground segment to support near-real-time operations has been implemented in several regions, but data accessibility and cost are still perceived as barriers to broader operational use. The current 400-500 km wide-swath capability provides good revisit frequency at high latitudes, but does not allow for daily coverage in the active mid-latitude shipping areas where the revisit frequency is 2-3 days.

Alternating polarization and polarimetric SARs, e.g., Envisat ASAR and Advanced Land Observing Satellite (ALOS) Phased Array type L-band SAR (PALSAR), provide improved seasonal ice and ice/water discrimination capability – the latter under strong wind conditions. Polarimetric SAR and passive microwave (such as WindSat, Coriolis) have the potential for improved ice age classification – this can serve as a proxy measure of ice thickness. Further research and airborne validation are needed to realize the full potential of alternating polarization and polarimetric SAR data.

SAR Interferometry (InSAR)

SAR interferometry (InSAR) is a major missing element in plans for continued cryospheric observation. Continuation of InSAR, and improved coverage with new radar satellites with InSAR capability, can provide direct large-scale estimates of ice discharge and its variability to an unprecedented precision, and to distinguish glacier and ice-sheet thinning caused by changes in ice flow from that caused by accumulation and melt. Future SAR missions should be compatible in terms of frequency and orbital parameters in order to facilitate InSAR coverage and should be supplemented by airborne InSAR surveys.

The limitations inherent to existing InSAR datasets can be largely overcome by launching a series of dedicated InSAR systems optimised for the measurement of ice sheets, ice caps and glaciers while accommodating the critical needs of other user communities, i.e., crustal deformation, hydrology, land cover, and oceanography. This system should operate with short temporal baselines (of a few days for repeat-pass systems) and tight orbit control to maximize the number of usable InSAR pairs, and should have a routine left- and right-looking capability for rapid access and more comprehensive polar coverage, and to enable more detailed coverage of critical regions. This mission would address all ice sheet and glacier objectives related to surface motion.

Spatial resolution, coverage and height accuracy suggest that a swath SAR interferometer might meet the science requirements to measure ice sheet thickness from space. The mission concept is for a P-band (430 MHz) instrument with a 6 MHz bandwidth, comprising two antennae with a 45 m baseline and an off-nadir boresight. This system has the potential to acquire the desired ice-sheet depth measurements for depths of >1 km. Conventional sounding may be sufficient for depths of <1 km and ice-layering studies. Although there are no apparent major technological hurdles to this proposed design, power requirements are high (for deep-ice sensing).

Flying two companion SAR satellites to provide operational, bi-static single-pass interferometry products of a high quality and with tunable interferometric baselines is an exciting technological advance. This enables along-track interferometry and new bi-static applications, e.g., polarimetric SAR interferometry (Pol-InSAR). The German TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) mission is the first step for a planned constellation of radar satellites. The Global Monitoring for Environment and Security (GMES) Sentinel-1 satellite is planned as a C-band SAR mission with a possible two-satellite constellation. The mission requirements are for dual polarization and an interferometric capability. C-band is chosen to ensure continuity of existing ESA data sources, i.e., ERS-1 and –2, and Envisat.

Passive Microwave

The continued routine monitoring of the cryosphere using passive microwave (PMW) sensors has generated a unique climatological dataset that dates back to the 1970s. It should continue without interruption. Key products include global sea ice concentration and extent, ice season length, snow depth on sea ice and ice temperature (since 2002), maps of surface melt onset and refreeze, and terrestrial snow cover areal extent, depth and wet/dry state. Future acquisitions at a high resolution (optimally 1-3 km) are highly desirable. Combining passive microwave with scatterometry may provide further improvements in ice-type discrimination (particularly in the Antarctic), as could the use of polarimetric sensors such as Windsat.

The difficulties that have been experienced in combining SMMR and SSM/I data have underscored the importance of an adequate overlap period for inter-calibration of sensors. An overlap period of one year is recommended. In all cases, operating frequencies should be equivalent to facilitate the creation of seamless time series of key parameters.

The development of a robust spaceborne technique for observing ice-sheet accumulation rate requires the continued collection of PMW data at 6-7 GHz. Improved estimates are likely through the combined acquisition of ice-sheet daily passive and active microwave data, the future acquisition of 6-7 GHz PMW data at a higher spatial resolution, combining them with laser altimeter data, and the merging of satellite data with modelling.

Spaceborne L-band radiometry shows promise as a means of remotely measuring sea ice thickness – a factor that will be tested with the launch of the 1.4 GHz Soil Moisture and Ocean Salinity mission (SMOS) in 2007, albeit at coarse resolution (~50 km). Such sensors also show potential regarding the large-scale measurement of changes in ice sheet near-surface properties. Another emerging technology that shows potential for application to ice-sheet research is Earth-reflected L-band signals from the Global Navigation Satellite System (GNSS). Given the large penetration depth of the L-band signal in dry firn i.e., of the order of ~100 m, the GNSS signals would contain information related to the millennial-scale accumulation rate only. Investigations are needed to assess the capability of L-band radiometry as a means of obtaining information on snow/firn layering at depths of up to 150 m in dry polar firn. A recent setback has been the cancellation of the NASA Hydros mission.

Altimeters

Spaceborne altimeter data continuity is essential for benchmarks of ice-sheet change and the measurement and monitoring of sea ice thickness (and volume when combined with satellite PMW-derived sea ice concentrations and extent). High resolution and more accurate ice sheet digital elevation models (DEMs) can be created by combining satellite radar and laser altimetry data, and by merging ICESat and InSAR data. Improved DEMs are required to examine ice flow and surface roughness in greater detail, the latter being related to sub-glacial topography, which is a major unknown. Follow-on radar and laser altimeter missions need to be launched to ensure uninterrupted coverage and enable monitoring of longer-term change. Ideally, they should fly the same ground track and orbital configuration as ERS-Envisat, to optimize change detection and closely spaced high-latitude coverage.

The extraordinary accuracy displayed by ICESat-1 enables regular repeat laser altimetry coverage of ice sheets on a pentadal or decadal basis. This should be configured to support re-profiling of existing ice cap/glacier traverses, such as those from the NASA PARCA programme in Greenland, and establish new traverses in key areas. The proposed launch of ICESat-2 in 2011 is essential in this respect but will unfortunately follow a gap of 4 years in spaceborne laser altimetry. The continued launch of further laser missions beyond ICESat-2 is a high priority. The GMES Sentinel-3 radar altimeter will operate with a baseline performance of Envisat RA-2 and the high along-track SAR capability of CryoSat-2.

Radar Scatterometers

In addition to providing wind velocity measurements over ice-free oceans, satellite radar scatterometer data are increasingly used in operational and research analyses of sea ice and terrestrial snowcover, large iceberg tracking, and studies of ice sheet near-surface characteristics and surface melt/freeze detection (Long et al., 2001). These low-resolution radars complement SAR with their broader swath and more frequent coverage. Ice volume information can theoretically be inferred from ice type classifications but this is non-trivial. A more robust approach is to combine scatterometer data on areal extent with ICESat or CryoSat-2 altimeter measurements of ice thickness. Scatterometers also aid the large-scale ice edge discrimination on a daily basis. Such discrimination is aided by the combination of scatterometer with SAR, passive microwave and visible/infrared data. Improved sea ice motion products are currently obtainable from the merging of motions from radar scatterometry, passive microwave radiometry, and buoys.

In terrestrial regions, a major challenge in remotely mapping snow cover is the identification of contributions to the measured signal from vegetation, snow, and the underlying soil. This is not possible using a single-frequency scatterometer alone. A scatterometer that operates at multiple frequencies and a dual-frequency radar altimeter, e.g., Envisat, could possibly help in the future with this problem.

Visible to Thermal Infrared

The continuation of high-resolution optical sensor coverage is fundamental for mapping and monitoring cryospheric variability and change. Key sensors are the Landsat series and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), with MODIS as a large-scale alternative. Landsat data extend back to the 1970s, and the launch of the Landsat Data Continuity Mission in the near future is a high priority given the seriousness of a gap caused by the demise of Landsat 7. The GMES Sentinel-2 will carry a Landsat/SPOT-like super-spectral imager at 10-20 m resolution, but is not due to be launched until 2011. The continued large-scale acquisition of Landsat-type imagery over ice sheets is essential to create maps of ice velocity using feature tracking to augment InSAR estimates where the latter are not available or viable.

Landsat and ASTER imagery form a key input to the Global Land Ice Monitoring from Space (GLIMS) consortium.

Future acquisitions are required to measure change against this baseline global inventory. While there is a high demand for continuation of a Landsat-type sensor, a future sensor would strongly benefit from an additional pointing capability to shorten the repeat cycle as well as from a forward and back looking near infrared (NIR) sensor for creation of DEMs. Given the expense of Landsat and SPOT data, there is an urgent need for the community to have unlimited access to archived cryospheric data, and to ensure the continued acquisition of future scenes in key regions.

Large-scale maps of surface skin temperature from AVHRR and MODIS thermal infrared data are a unique resource, with a time series extending back to the late 1970s. The continued production of unified, consistent time series maps of surface temperature, along the lines of the AVHRR Polar Pathfinder product archived at the U.S. National Snow And Ice Data Center (NSIDC), serves as important means of monitoring temperature change and its spatial variability. Such products are in need of validation, e.g., using automated weather station (AWS) data.

More extensive surface albedo datasets are required to capture the progression of large-scale melt-freeze and for surface energy budget evaluations and model validation. There is a strong need to continue global gridded albedo by extending the AVHRR Polar Pathfinder product dataset and further developing the MODIS product. Future airborne and surface-based measurements are essential to evaluate the accuracy of satellite albedo estimates. Multi-angular satellite measurements, e.g., from the Multi-angle Imaging Spectro-Radiometer (MISR) and the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) instruments, are required to better characterize the bi-directional reflectance. Dual-view sensors such as the Advanced Along-Track Scanning Radiometer (AATSR) and a future Sentinel-3 sensor are required for the correction of atmospheric effects.

Satellite Gravity Missions

Analysis of monthly maps of the gravity field by the GRACE project allows determination of time-variations in Earth's gravity with very high precision that correspond to mass changes of the order of one millimetre water equivalent over scales of approximately 500 - 1000 km. This new information enables monitoring of the snow-pack contribution to the redistribution of fluid mass at the earth's surface and complements existing sources, e.g., satellite passive microwave-derived and model output snow products. Continuing GRACE-type satellite gravity missions are essential to provide observations of temporal variations in the distribution of ice and snow mass. Furthermore, new results suggest that these fields can be used to recover mass imbalance and net snow accumulation for the Greenland and Antarctic ice sheets. The combination of time-varying gravity data (CHAMP, GRACE) with a high resolution static field from the Gravity field and steady-state Ocean Circulation Explorer (GOCE), InSAR and GPS adds extraordinary new insight into ice-sheet dynamics and glacial rebound. Such missions are required, however, beyond ESA's GOCE in late 2007 to better understand ice-sheet mass loss, with the resulting impact on global sea-level rise.

Major Gaps in Space-Based Observations

Gaps exist in the coverage of key parameters by planned missions. A number of important future missions have recently been cancelled, and the lack of adequate back-up missions in general means that the failure of a launch could lead to multi-year gaps in key time series. Of particular concern is the delay of AVHRR- and MODIS-type sensors and passive-microwave radiometers onboard the U.S. National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) and the NPOESS series of satellites. If the last satellite from the current NOAA polar series fails during launch or fails in orbit, then there could be a 19-36 month gap in operational polar satellite coverage. These satellites will replace the current Defense Meteorological Satellite Program (DMSP) and NOAA Polar Operational Environmental Satellites (POES). It appears that the NPP mission will be delayed at least 30 months (to 2009), with the first NPOESS satellite (C-1) becoming available in late 2012 or 2013. NOAA plans to launch the last of its POES satellites in 2007 (this satellite has already suffered damage during construction). The DMSP programme expects to be able to make its satellites last well past the 2012 NPOESS launch date, which is particularly important for maintaining the passive microwave record with SSM/I, given that the Conical Microwave Imager/Sounder (CMIS) for NPOESS was cancelled (alternatives are being examined). A radar altimeter is scheduled for launch on NPOESS C-3. The series will contain another key instrument, namely an ARGOS Advanced Data Collection System for relaying data transmitted from ground-based sensors such as ice buoys and automatic weather stations. The imminent delays of NPP and NPOESS will result in serious gaps in the long-term consistent climate data record and have serious ramifications for the operational monitoring of the cryosphere.

The NPOESS Landsat-type sensor has been eliminated from the mission, but will possibly fly on a separate dedicated mission. After the failure of Landsat, glacier monitoring in the optical/infrared spectrum at about 20 m spatial resolution solely relies on data from Landsat 5 (which has been in orbit since 1984!) and on ASTER. As

SPOT data are costly and orthorectification for the 9-times smaller scenes (compared to Landsat) is very time consuming, the launch of a Landsat 7 follow-on mission must be a high priority.

11.2. Ground-Based Observations

An integrated surfase-based observational component of CryOS does not yet exist. The strategy is therefore to use existing resources and infrastructure. At the implementation phase, CryOS will have to establish contact between all operators of manned and automatic stations in polar latitudes and at high altitudes and achieve agreement on a shared program of observations that would include hydrometeorological observations, snow cover, solid precipitation, and temperature of the soil active layer and permafrost. In principle, the system for terrestrial observations should be not specific to the cryosphere, but global and multidisciplinary. This means that CryOS and its partners have to develop a polar and high-altitude subsystem within the multidisciplinary terrestrial observations system needed for the Global Earth Observing System of Systems (GEOSS).

The most important existing ground-based observing system is the surface component of the WMO Integrated Global Observing System. From approximately 11,000 surface meteorological stations in the world, 44 stations operate in Antarctica. In the Antarctic there are currently around 70 automated weather stations (AWSs). They were first installed in the mid-1980s and at present they generate more observations than do manned stations. The Arctic is better covered by stations in its southern continental parts, but only very few island observing stations operate in higher latitudes, so that information on atmospheric pressure at sea level in the inner part of the Artic Ocean comes mostly from buoys of the International Arctic Buoy Program (IABP). AWS are available on the coasts of Russia, Scandinavia, North America and Greenland.

At present, operations at existing stations are not coordinated. The stations could conduct meteorological (including snowfall and rainfall), cryospheric (snow cover, permafrost and frozen soil temperatures) and other types of observations and be connected to the existing data relay systems. The WMO Information System (WIS) is developing the capacity for increased handling of multidisciplinary observations, and serving users both inside and outside of the WMO system. Working Group 7 ("Terrestrial Cryospheric and Hydrologic Processes and Systems") of the International Conference on Arctic Research Planning (ICARP) has proposed to link meteorological, cryospheric and hydrological observations and develop a nested system of up-scaled observations. The observational strategy includes enhanced measurements at the smallest scale to support detailed process studies, contributing modelling and observations within intermediate scale river basins, further link to observations and modelling at the scale of continental river basins, and enhanced long-term observations over the pan-Arctic domain. Such a hierarchical observing strategy has already been established for the GTN-G (which is operated by the WGMS) as part of GCOS/GTOS.

The multi-scale approach and involvement of interdisciplinary networks of research stations may lead to an increase of the observation data flow. It will be feasible only if more use is made of AWS and other autonomous methods of observations. Therefore CryOS recommends further enhancement and maintenance of the AWS networks on the Greenland and Antarctic ice sheets and on remote islands in the Arctic and Southern Ocean, the deployment of AWS in important data and observation gaps, and the fitting of more AWS with snow accumulation measurement devices. Meteorological measurements from AWS networks remain important as key means of estimating net water vapor flux to and from the surface. Sublimation/evaporation is highly sensitive to these fluxes, and represents a yet poorly understood component of ice-sheet mass balance. These are unique datasets that provide data records dating back for decades in some cases and important point measurements in remote locations on vast data-sparse regions. They are also of key importance in the interpretation and validation of satellite retrievals of snow accumulation, ice sheet temperature, albedo, and melt detection. Reliance on autonomous observations, e.g., for solid precipitation and other measurements, can lead to significant errors and biases in data, so systematic calibration, validation, and quality control are a high priority.

Surface "high-bandwidth" radar can resolve near surface layering and give information on accumulation patterns. High-resolution ice-penetrating radar systems are being developed to extend such measurements spatially by detecting and mapping internal ice layers or isochrons in the upper 100-300 m, with individual layers being dated by a few ice core analyses. These systems are at present technologically limited to surface and airborne deployment, although work is underway to develop spaceborne systems.

Ground-based networks of autonomous, mobile robotic units could significantly improve the acquisition of data across Antarctica and Greenland at a range of scales in regions that are often difficult to access. Recent advancements in robotic technology have been demonstrated by the success of Martian rovers. The success of these programs has promoted development of similar systems for terrestrial applications. Several groups are currently developing rover systems for a wide range of cryosphere applications. A large network of ubiquitous, independent, units equipped to measure surface energy and mass flux as well as sub-surface firn properties could greatly improve assessment of ice sheet mass balance and dynamics at spatial and temporal resolutions that are currently under-sampled. Future advancements in cryosphere robotics will be contingent on support to improve structural design, control systems, and advanced artificial intelligence algorithms for enhanced autonomy.

Ground control is an important requirement for many aspects of geophysical mapping by satellite. The maintenance of GPS satellite constellations and GPS networks – the latter to provide the most accurate measure of surface elevation and motion – is crucial. This provides key information with which to calibrate and validate satellite data products, e.g., InSAR estimates of ice velocity, altimeter-derived ice elevation. Year-round GPS measurements are required on outlet glaciers, in support of InSAR missions and to provide detailed information on ice shelf motion due to tidal and inverse barometer effects. Researchers should be encouraged to carry GPS sensors whenever and wherever they are involved in ice sheet field campaigns, and to contribute these data to a central archive.

11.3. Airborne Observations

Aerial sea-ice reconnaissance, which used to be the sole source of real time guidance for navigation in ice-covered waters, is still very important today, especially in the ocean areas and seas that are frequented by icebergs, bergy bits, and growlers. It is an established service and its operation will most likely become even more important as the navigation in the Arctic Ocean intensifies. A less established but very promising approach is remote sensing of sea ice thickness using electromagnetic methods; when it becomes more mature, it may provide valuable support information for calibration and validation of space-based sensing of sea ice thickness.

Sea level rise research requires estimates of ice discharge from fast flowing outlet glaciers that drain the ice sheets through narrow channels in regions of high accumulation. Airborne high-resolution InSAR systems with selectable repeat intervals are ideal for deployment on large unmanned airborne vehicles (UAVs), and plans are afoot to test a new NASA system in Greenland during IPY. It is anticipated that this sensor will, when used in combination with an advanced airborne radar designed to measure ice thickness and internal layers, yield a comprehensive and near-simultaneous baseline assessment of ice discharge through all of Greenland's outlet glaciers. Similar measurements are a high priority in Antarctica, as are repeat missions over both ice sheets to monitor change.

Satellite altimeters are better suited to monitoring large ice masses and operate less well over alpine glaciers, ice fields and smaller ice caps. Other observational methods must be used in these regions, including airborne LiDAR or ALTM (Airborne LASER Terrain Mapper) for providing high resolution DEMs and feature-tracking capabilities. The monitoring of alpine glaciers should be regularly carried out using Airborne Laser Scanning, to derive high-quality DEMs with a sub-meter horizontal accuracy and a vertical accuracy up to ±1 decimeter. It may be possible to use airborne ground-penetrating radar (GPR) at 400-500 MHz to map snow accumulation on alpine glaciers, which is one of the most unknown but also most important parameters for glacier mass balance.

Airborne radio echo sounding provides the capability for mapping and monitoring ice thickness, especially when used in conjunction with laser altimetry. This is important for establishing baseline data for monitoring future changes and understanding glacier dynamics. A global ice thickness mission is required to determine the total volume of ice in glaciers and ice sheets, map the basal topography of Greenland and Antarctica, determine basal boundary conditions from radar reflectivity measurements, and map internal ice structures.

Uncertainties in drainage basin- and ice sheet-wide accumulation rates represent a major error source in current estimates of ice sheet mass balance. A highly coordinated observation strategy is required to use surface traverse and airborne ground-penetrating radar (GPR) and GPS "coffee can" surveys, firn cores, stake networks, satellite remote sensing, numerical simulation and atmospheric modelling, and re-analysis of previous snow accumulation data to derive more accurate continent-wide surface accumulation values.

11.4. Modelling, Data Assimilation, and Reanalysis

Enhanced observations should be used to facilitate further development and updating of a wide range of models with respect to their representation of cryospheric processes. Key areas where improvement in models is needed include:

- surface hydrology and freshwater run-off in regions with snow, ice and permafrost,
- coupling of frozen ground and surface hydrology models with subsequent inclusion of fully interactive

dynamical vegetation schemes,
- fluxes of greenhouse gases in permafrost regions under the influence of a changing climate,
- the atmospheric boundary layer over snow and ice covered surfaces and its influence on large scale atmospheric circulation,
- gas and particle exchange between snow and ice covered surfaces and the atmosphere, taking into account different types of vegetation and their growth phases,
- surface energy budget, including surface albedo in regions with cryosphere,
- improved multi-layer models of snow cover including snow on various types of vegetation, frozen ground and permafrost,
- models of individual glaciers, their growth, decay and movement,
- modelling of regional glacier systems and equilibrium-line changes under a changing climate,
- processes at the ice sheet grounding line,
- ice shelf models including iceberg calving processes,
- development of comprehensive ice sheet models that take mechanical degradation as well as melting into account, and their inclusion in long-term climate simulations and in studies of the ocean thermohaline circulation and sea-level change,
- sea-ice rheology, dynamics, and thermodynamics including meltponds and polynyas,
- modelling of ice ridging, hummocking, fast ice,
- the effect of all types of ice formation and melt on ocean circulation processes, water mass production, gas and particle exchange with atmosphere (including carbon cycle).

The WCRP and Earth System Science Partnership (ESSP) model inter-comparison projects (MIPs) provide not only a mechanism for quantitative evaluation of models or model components, but also an opportunity for enhanced collaboration within the international community. The legacy of MIPs is a benchmark against which subsequent model developments can be assessed. Implementation of CryOS will facilitate the provision of cryospheric data for relevant MIPs, and is essential to fully exploit the potential of objective analysis, data assimilation and reanalysis.

Reanalysis activities provide unprecedented opportunities for diagnostic studies of the atmosphere. A new challenge in this area of research is to initiate and sustain new, more sophisticated reanalysis systems capable of resolving not only variables pertinent for numerical weather prediction (NWP) but also variables characterising the full climate system and interaction between its parts. An ocean reanalysis project is underway, and an atmospheric chemistry reanalysis is being considered. A necessary prerequisite for all such types of activities should be comprehensive and systematic assembling of low level satellite data and its massive reprocessing using the most updated, calibrated and validated algorithms, with production, where possible, of continuous data series obtained with a series of similar sensors.

Meteorological reanalyses, including completed pioneering projects at the NCEP/NCAR and ECMWF (ERA-15 and ERA-40), have been used to evaluate large-scale patterns of snow cover, Antarctic precipitation, atmospheric moisture transport and vapour flux convergence in the Arctic. Two projects relevant for cold climate regions are the Arctic System Reanalysis (ASR) that is developing as a component of the U.S. SEARCH program, and the North America Regional Reanalysis (NARR) underway at NCEP. The ASR will include the best possible polar physics and seeks to take full advantage of remote sensing data including the TIROS Operational Vertical Sounder (TOVS) and Vertical Temperature Profile Radiometer (VTPR) for retrievals of temperature and humidity profiles, GPS for precipitable water and SSM/I for precipitable water and sea ice concentration. The domain covers much of the Arctic, including Greenland. Initial results for test years indicate that the NARR provides significant improvement in precipitation, temperatures and winds relative to the global NCEP model. A key issue relevant to the ASR is the optimal use of TOVS in cloudy conditions typical of the Arctic. This will require coordination with the polar remote sensing community. The ASR will also benefit from efforts to improve the available assimilation database through the rescue and quality control of previously unused or underused conventional data, including Canadian rawinsonde reports prior to the 1950s, and upper-air data from the Russian North Pole programme.

Data assimilation schemes for cryospheric variables are in general underdeveloped. Sea ice extent and concentration data assimilation schemes are in operation in several real-time modelling and service providing centres, but ice thickness and motion data are not. Sea ice dynamic/thermodynamic models have the potential to estimate quantities not directly observable, such as age and ridged ice volume fraction. CryOS has to steer the further development of sea-ice data analysis, assimilation, and reanalysis at several meaningful spatial scales, and to contribute to the ongoing efforts of developing an ocean reanalysis. It is important to produce reanalysis data sets for the Arctic and Southern Ocean sea ice concentration and thickness, and snow on ice, to encompass years of the Scientific Ice Experiment (SCICEX), and with error estimates for these variables. Reprocessing of cryospheric data products should be organized and promoted as part of the overall reprocessing activity being developed by the WCRP.

It is also necessary to improve the use of cryospheric products in short-term prediction systems. As in the reanalysis systems, short-term forecast models use very little information about the cryosphere. Only sea ice extent, snow cover, and snow water equivalent are currently used in operational forecast models, and they are not used broadly. Sea ice motion, concentration, and ice surface temperature are only used experimentally. To ensure that observations proposed by CryOS are usable in assimilation and eventual reanalysis of cryospheric variables, efforts should be made to understand their error structure, and study, as fully as possible, the statistical description of errors in observations by various methods.

11.5. Data and Information Management

CryOS envisions an **integrative approach** to processing and managing cryospheric data, where data from multiple sources are routinely combined to create higher-level products that can be easily used for integrated analyses. The strategy should ensure both the *preservation* of data and broad, interdisciplinary, and non-expert access and use of data. These aims are not exclusive to CryOS, and any data management system needs to consider other data networks. The data and information management component must facilitate the flow of data and information in cryospheric research, long-term scientific monitoring, and operational monitoring. It must go beyond the traditional service of archiving and serving data, by encouraging the development of flexible *integration engines* to combine a variety of data types ranging from model fields to socioeconomic data to point data from diverse and distributed data centers.

A model of the data integration engine for CryOS is the WCRP Coordinated Enhanced Observing Period (CEOP) activity. CEOP has been accepted as the main water and energy cycle data processing engine for GEOSS. It produces water and energy cycle data sets using a four-dimensional data assimilation of satellite and in situ observations supplemented by calibration and validation on the base of high quality measurements at a set of reference stations. It is an example of how to combine different *data types* from a *variety of sources*, with a *known quality*. Model output for the area around reference

Recommendations: Data Assimilation and Reanalysis

R11.1 Promote detailed validation of reanalysis projects for cold climates and cryosphere-related elements.

R11.2 Promote the use of reanalysis as a monitoring tool.

R11.3 Evaluate the maturity of new data products that can be assimilated by models or used for model verification.

R11.4 Promote the further development of data assimilation schemes and objective analyses for cryospheric variables, together with a thorough treatment of error covariances.

R11.5 Establish appropriate dynamical downscaling techniques of reanalysis data to facilitate their use in cryospheric impact models that operate in high-mountain terrain at about 10 to 100 m spatial resolution.

R11.6 Consider opportunities for an Antarctic reanalysis.

R11.7 Facilitate the development of a climate system reanalysis with inclusion of cryospheric components.

R11.8 Improve the utilization of satellite data in automated analyses and incorporate fractional ice cover and ice dynamics in global circulation models.

R11.9 Investigate indirect methods of combining multiple remote-sensing products and physically-based models to infer ice thickness.

R11.10 Improve algorithms for estimating global sea ice concentrations from passive microwave sensors by using data assimilation techniques, and compare results with those from sensors with a higher spatial resolution.

stations is merged with local observations and integrated with high-level satellite products. This integration scheme leverages the strengths of different groups in different locations: GCM data products come from the World Data Center for Climate based at the Max-Planck Institute for Meteorology of Germany, data Integration and Archiving is done at the University of Tokyo and JAXA of Japan, in situ station observations are supplied by numerous local and national organizations. CEOP has demonstrated state of the art capabilities by merging satellite data, surface-based observations, and model output, to produce useful hydrological cycle data products. CEOP should therefore be used as a prototype system that will be able to significantly improve CryOS products.

A very different example of an integration engine is the recent emergence of visual globes. These tools allow easy visualization and overlay of quite broad geographically based data. Visual globes are relatively easy to learn and use, and allow quick visualization of an extremely broad range of data types from distributed data sources. However, they do not often provide a means of quantitative analysis or data quality control. A longer-term vision is to achieve interoperability between products from these diverse engines, for example by merging hydrological data from CEOP with population or health statistics to produce both a visual and quantitative product. Such a unified data system will require

- the support and involvement of communities associated with all elements of the cryosphere,
- joint work with the International Global Water Cycle Observation programme (IGWCO) and CEOP,
- coordination of data acquisition from satellites in orbit,
- somewhat increased support to existing in situ networks,
- involvement of additional stations capable of making required observations,
- dedicated data management scheme capable of operating proactively,
- an acknowledged governance mechanism with sufficient authority,
- development and acceptance of standards for error reporting, and quality checks on merged data sets,
- official acceptance of this initiative as a project at an intergovernmental level,
- an implementation plan.

With increasingly sophisticated data analysis, upgrades to products, and the development of new algorithms comes the obligation to document and properly reference contributions from individuals and institutions to the final data product. Accepted standards of how to properly reference data products, previous versions of an upgraded product, and other contributors need to be established.

Archiving of Data and Exchange

The foundation of the data and information management component of CryOS lies in the efficient and timely flow of data and information in cryospheric research, long-term scientific monitoring, and operational monitoring. Key to this is the accessibility of data. The sharing or release of all data relevant to climate and cryospheric science in a timely fashion will be encouraged, so that optimum use can be made of any one dataset.

For long term research or monitoring, secure and methodical data preservation is essential. Initiatives for data stewardship based on acknowledged standards and best practice for data processing, archival, quality control, and documentation will be encouraged. Using identifiable and well-established facilities such as the World Data Centres, archives of the space agencies, or national data centres with lasting mandates will ensure that data are preserved for future use and reanalysis. While individual projects (such as CEOP) may temporarily store data for ease of processing or access, they should not be viewed as permanent archives, and may need to find archival facilities for their products in the long term. The IPY Data and Information System (DIS) is conducting a survey of all data collected during IPY. It is expected that this survey will reveal that some types of data are not associated with established data repositories. CryOS will work with DIS, to help address these issues.

With the increasing volume of data, a challenge for users is to understand what products are available. To overcome this, CryOS will work with the data providers and national and international data centers to promote central metadata portals. Most of the major data centers have a metadata portal, but many of the smaller polar research institutes or universities do not have comprehensive portals to allow easy access to databases. Many of the existing portals are not linked, forcing users to search in many locations. A key metadata and information service will be the Data and Information Service for CliC (DISC). The core of this service will be one or more web-based search engines that will provide a comprehensive overview of cryospheric data, based on discovery-level metadata. This system will work to ensure that data and data products from all sources are known, available and accessible to the users from a single location. DISC and other similar portals such as the Global Change Master Directory (GCMD) and the Antarctic Master Directory will work together to provide metadata that allow a user to judge the availability and usefulness of data for their particular application, with links to the data supplier. CryOS will promote comprehensive documentation of data, including information on the origins, quality and accessibility of data, and efficient linkages between all data and metadata centres. A consolidated and unified approach to cryospheric data will also help identify data gaps. DIS and other projects during IPY are expected to discover data gaps. CryOS will work with these groups.

CryOS will be proactive in seeking and collecting metadata for relevant data sets. All metadata will conform to the ISO 19115 standard for geographic metadata, to the WMO Core Metadata Profile, to the CEOS-IDN guidelines, and to the GEOSS interoperability specifications. To maintain interoperability between data and metadata centres, adherence to the ISO 19115 and ISO 19139 standards is essential. This will make the search engines easier to use and more powerful, allowing metadata to be easily updated from all data centres or data services that use this standard.

Activities

Flexibility is required to ensure that the data system remains relevant as technology and needs evolve. This will require a number of ongoing activities including:

- working with the CEOP project to further develop tools for integrating diverse and geographically distributed remote sensing and in situ data,
- following the developments in data management and dissemination closely throughout the IPY,
- working with IPY DIS to find suitable permanent archives for IPY data,
- collaborating with data centres and research projects in the application of standards and techniques for data and information management,
- leading and/or contributing to data policy and service development where necessary,
- identifying gaps in climate and cryospheric data requirements and seeking opportunities to address these gaps (it is expected the DIS will identify several of these gaps),
- encouraging and initiating data collection and recovery projects,
- encouraging the reprocessing of data sets for climate studies,
- encouraging discussion on how to provide appropriate references for use of improved data products,
- identifying data archives that are not open for easy access, and promoting the use of standards to improve access, and
- advising individual, collaborating projects on data and information management issues.

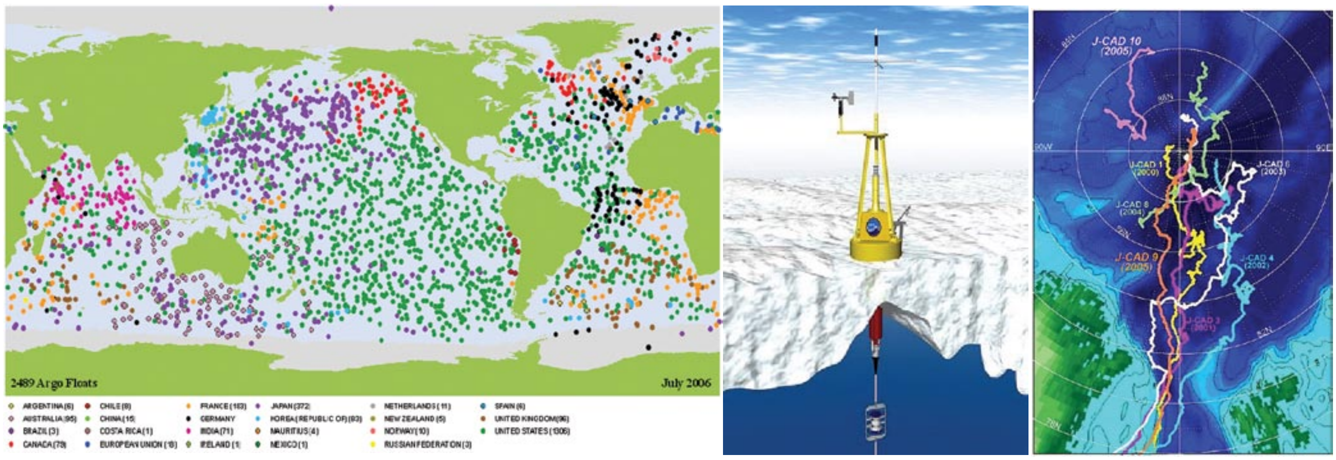
11.6. Related Observing Networks and Activities

Several observing systems relevant to CryOS have recently begun to be developed. This includes two polar observing systems: the Sustained Arctic Observing Network (SAON) and the Pan Antarctic Observing System (PAntOS). Within each of these, polar ocean observing systems are also being discussed, including an Arctic GOOS and a Southern Ocean Observing System (SOOS). It is expected that CryOS will form the cryosphere portion within each of these observing networks. Components of observing systems relevant to these and other networks are discussed below.

Arctic and Southern Ocean Observing Systems

The use of Argo buoys has revolutionized observations of the ocean by providing subsurface temperature and salinity data from a network of 3000 (target) buoys capable of reaching a depth of 2000 m and resurfacing every 10

Fig. 11.1. Locations of Argo and similar buoys, the J-CAD buoy design and deployment, and tracks of 10 J-CAD buoys.

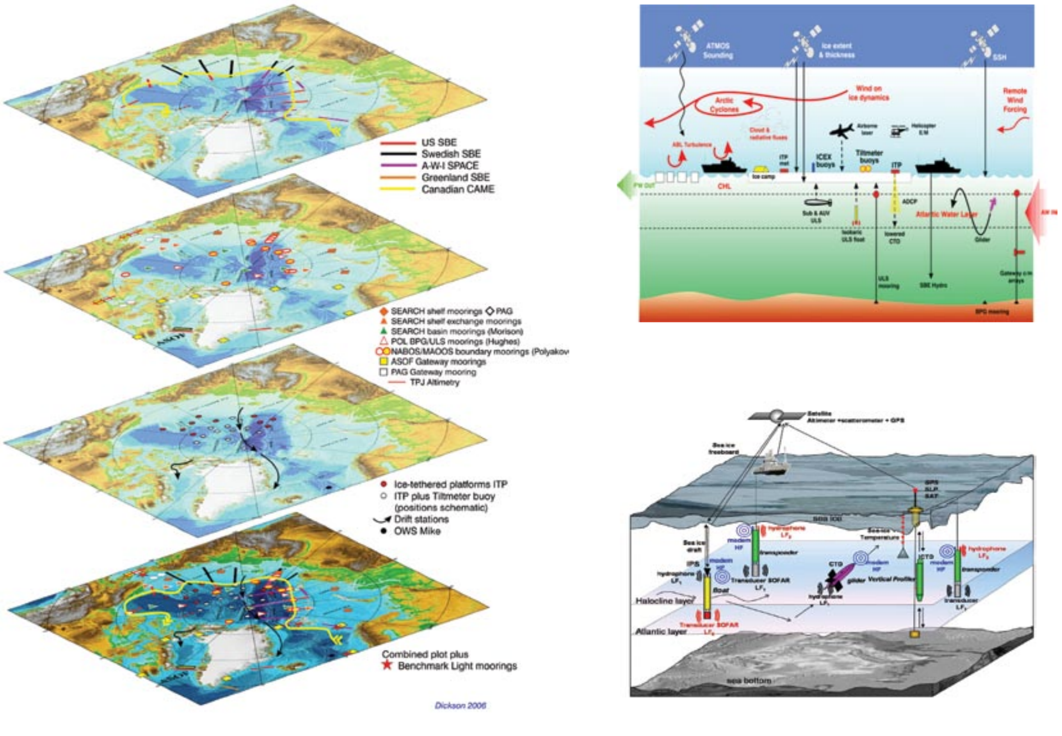


days to transmit the data via satellite. At present, the polar oceans with sea ice cover remain almost completely void of observations. In Figure 11.1 a single dot at the North Pole represents the only J-CAD buoy in the area. Since the year 2000, ten such buoys have been deployed on sea ice and reported meteorological air temperature, barometric pressure, wind speed and direction, water temperature and conductivity at predefined depths up to 250 m, and the ocean current speed every 10 m up to the depth of 260 m. The JCAD buoy and positions of ten deployed buoys are shown in Figure 11.1. The cost of a J-CAD buoy is a limiting factor for its operational use.

Economical observations from sea ice-based buoys have been in place in the Arctic since the 1970s and Antarctic since the 1980s. They are coordinated by the International Arctic Buoy Program (IABP, 1979-present) and the WCRP/SCAR International Programme for Antarctic Buoys (IPAB, 1995-present). The buoys are equipped with basic meteorological sensors and mostly report their position and atmospheric pressure at sea level to WMO in real-time for improving meteorological forecasts in extremely data-sparse regions of the sea-ice zone. The IABP attempts to maintain an observing network with buoys no more than 250 km apart, which requires an array of at least 60 buoys at any given time. These need to be replenished on a regular basis due to the harsh Arctic conditions. The IABP also envisions enhanced data integration and management of observations taken from the sea ice. CryOS strongly supports the efforts of both programmes to maintain drifting buoy networks at an optimal level. This is a challenge in the Southern Ocean in particular.

Discussions on the development of a comprehensive and sustained Arctic Observing System have recently been held, of which the ocean is a key component. The possibility of using sea ice as a base for carrying a tether with profiling instruments is being seriously considered. There have been several reviews on the way forward in this area. DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies) is funded by the EU 6th Framework Program. The Arctic Ocean Sciences Board (AOSB) initiated an outline of a joint AOSB-CliC IPY Project entitled “integrated Arctic Ocean Observing System” (iAOOS), which is based on observations from ice-tethered buoys, already existing programs like IABP, satellites, and oceanographic cruises. CryOS should contribute to the observations of iAOOS (Figure 11.2). A similar program entitled the “Climate of Antarctica and the Southern Ocean” (CASO) is the lead project in the IPY Antarctic Ocean Circulation cluster (Figure 11.3). CASO goals are to obtain a synoptic circumpolar snapshot of the physical environment of the Southern Ocean, and in collaboration with other IPY activities will extend the snapshot to include

Fig. 11.2. Thematic transects and stack of iAOOS observations from satellites to seabed.



biogeochemistry, ecology, and biodiversity, to enhance understanding of the role of the Southern Ocean in past, present and future climate. CryOS strongly supports iAOOS and CASO development, as well as the efforts of SCAR and SCOR (Scientific Committee on Oceanic Research) to jointly develop plans for a Southern Ocean Observing System (SOOS).

Currently, there are a few moored upward-looking sonar (ULS) systems collecting time series records of ice draft at selected Arctic and Antarctic locations. ULS data are an important means of validating satellite estimates of sea ice thickness. Long-term ULS mooring programs should be deployed and maintained in key locations, e.g., in the Fram Strait for monitoring the outflow of ice from the Arctic Ocean, and in the Canadian Archipelago. A ULS on the forthcoming ice-tethered observing platforms is recommended. ULS data will provide essential validation of ice thickness retrievals from current and future altimetry missions, which when combined with improved sea ice concentration retrievals will produce more accurate estimates of regional ice volume and mass balance. Sea ice volume is a key climate parameter and an important component of high-latitude heat and freshwater budgets.

Related Hydrological Studies of Cold Climate Regions: Arctic - HYCOS

The temperature, salinity, sea ice, and circulation of the Arctic Ocean strongly depend on the inflow of fresh water. Therefore, CryOS considers it relevant and important to promote the development of corresponding hydrological observations. The WCRP Arctic Climate System Study (ACSYS) and CliC projects, in collaboration with the Arctic Monitoring and Assessment Programme (AMAP), proposed the development of an Arctic component of the World Hydrological Cycle Observing System (WHYCOS). Arctic HYCOS should be developed within the wider and more science oriented Arctic-Hydra IPY activity that addresses the Arctic hydrological cycle and examines linkages between atmospheric forcing and continental discharge to the ocean. Arctic HYCOS will be based on the existing national databases and observation systems in the Arctic countries that have historical long-term observation series on the large rivers discharging to the Arctic Ocean, as well as stations on tributaries and smaller rivers. The project envisages the development of a trial system on four rivers flowing into the Arctic Ocean. After the trials, the project should be extended to the entire Arctic Ocean basin (Figure 11.4).

11.7. Historical Data and Paleo Research Observations

Historical and paleoclimatic records are required to establish baselines and the context for interpretation of variability and trends. Continuing ice core analysis is required to gain information on temperature, global and regional climate change forcing (greenhouse gases, dust, cloud condensation nuclei, etc.), and potential changes in

Fig. 11.3. Locations of CASO process studies.

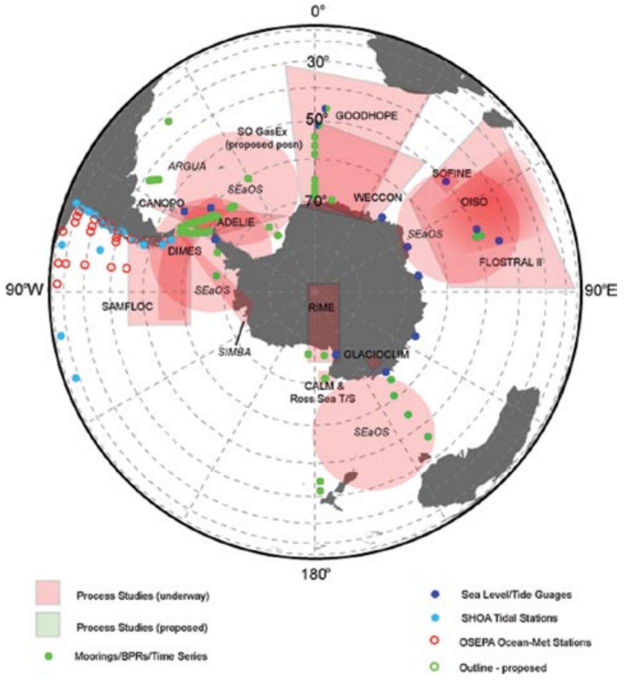
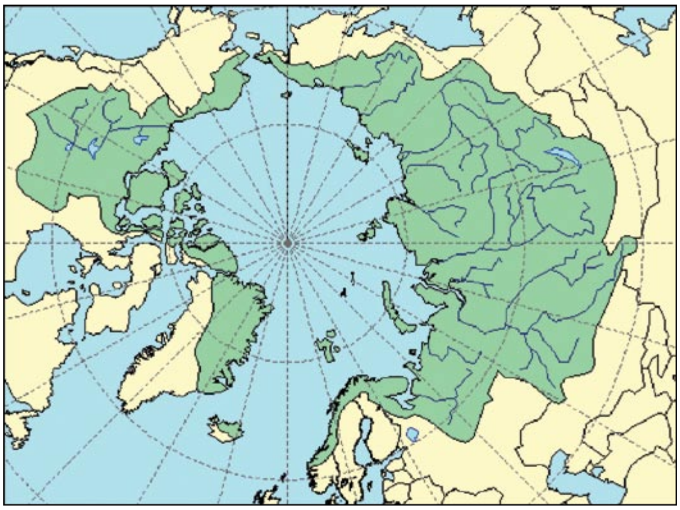


Fig. 11.4. Planned coverage of the Arctic HYCOS program.



ice sheet surface elevation. This information quantifies climate sensitivity in ice-covered regions and provides benchmarks against which theories and models of polar climate, mass balance and sea-level changes, past and future, can be tested. Common markers in Greenland and Antarctica allow bipolar studies of the north-south phasing of change. Research should continue into retrieving high-resolution proxy records of Antarctic sea ice extent in the pre-satellite era from firn/ice cores, and longer-term (millennial) proxy records from analysis of paleo-phytoplankton assemblages in ocean-sediment cores. In particular, the wider regional applicability of using methanesulphonic acid (MSA) concentrations in shallow cores as an indicator of regional sea ice extent in the pre-satellite era needs to be tested.

Changes in the cryosphere have been monitored in a globally coordinated way by direct observations since 1894. Data on glacier length change measurements at an annual resolution form the backbone for validation of numerous cryospheric models and the assessment of past and future climate change effects on glaciers. In many parts of the world, the maximum extent of glaciers in the Little Ice Age (LIA) between 1750-1850 has been mapped for thousands of glaciers from fieldwork, historic maps, or other documented evidence. This data has still to be transformed from the analog map format to a digital form. Multispectral high to mid-resolution (i.e., 15 m) satellite images have a still uncovered potential for determining the LIA extent from trim lines and well preserved moraines for many remote areas of the world (e.g., the Arctic) with sparse in situ data. Since 1963 glacier mass balance observations from more than 50 glaciers are available for model validation and sea level rise estimation. The potential for extending them in combination with satellite data and numerical models has not yet been fully exploited.

The collation, digitization and analysis of the long term ice record contained in historic regional ice charts produced by various Northern Hemisphere countries is needed to document historic variability and trends in the sea-ice state and the climate over the past 1000 years. The historic record of sea ice extent in the Antarctic does not extend back in time as far, nor is the record as comprehensive, as in the Arctic. Further evaluation of the whaling record as a proxy indicator of sea ice extent in the pre-satellite era is important.

The historical record of cryospheric observations using spaceborne sensors documents how the cryosphere has changed on regional and global scales. The record compiled from data available to the science community is usually taken to begin in the 1970s with the advent of programs such as Landsat and Seasat. However, earlier satellite missions were obtaining invaluable data as early as 1962 with the launch of the Corona, Argon and Lanyard photographic reconnaissance satellites. Until recently, data from these early sensors were not available to the science community, and the photos could have languished in data vaults at the risk of losing essential metadata and engineering information. Fortunately, actions were taken in the mid-1990s by the U.S. government to preserve, document, and distribute these unique observations. Given the scientific importance of these types of early observations, CryOS recommends that countries with space-faring capabilities critically examine their data holdings so as to stabilize early data sets, and develop policies on how historical and recent data not usually distributed to the science community can eventually be made available. ■

12 Implementation

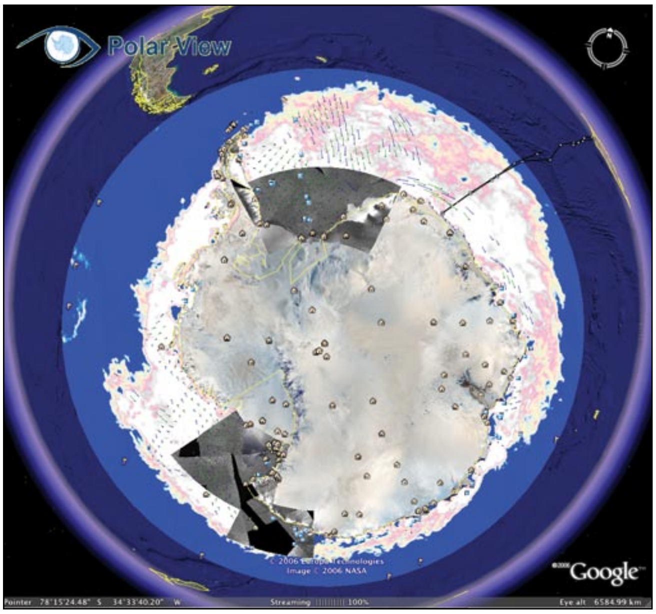
The previous chapters detailed current measurement capabilities, measurement requirements, and shortcomings of existing systems. Specific recommendations were made on how to fill the gaps. This chapter provides implementation considerations and timelines, serves as an action plan, and discusses governance and coordination.

12.1. Synergy in a More Comprehensive Observing System

The development of a more complete observing system for the cryosphere is both timely and essential, particularly given the dramatic changes occurring within the cryosphere and their broad ranging implications for society. Despite the fact that the cryosphere is known to be an important component of the climate system, and that the economic importance of adaptation to climate change is becoming indisputable, surface networks for individual cryospheric elements are generally declining and there are serious problems with satellite data continuity and acquisition. Actions are required to develop and maintain the observing systems. GEO is expected to address such issues.

Operators of cryospheric networks and related communities have not been as efficient as required. Cryospheric surface networks and satellite sensors, as a rule, operate individually, focusing entirely on the element that they are supposed to monitor. Their observations do not support, as much as they could, the generation of integrated cryospheric products. Is there a way to make these surface networks and satellites work synergistically, producing a more comprehensive picture of the cryosphere, and contributing to other components of environmental monitoring? The answer to this question is apparently “yes”, but lies beyond the domain of CryOS. Our overarching recommendation is that it is necessary to effect significant changes in how multi-disciplinary environmental observations are conducted in principle, so as to make them more effective.

Fig. 12.1 Google Earth visualization of Polar View data over Antarctica, including AMSR-E ice cover, ice drift from ENVISAT ASAR, drift buoys, ASAR 3-day mosaic, and meteorological stations.



With regard of the surface-based network, IGOS should propose the initiation of an inventory of all observing stations belonging to IGOS partners, research networks, academies of sciences, and engineering communities, with a view to augmenting their observational programs with additional observations. With respect to the cryospheric elements, CryOS would like to see observations as outlined in this report made at a larger number of surface meteorological stations, research observatories, and engineering observing networks. For example, permafrost boreholes should be supplemented with relatively inexpensive AWS and precipitation gauges, which will significantly increase the usefulness of permafrost observations. CryOS would like to invite IGOS partners and other IGOS Themes to start an inventory of existing observing platforms and to evaluate the potential for such platforms to make more multidisciplinary observations. Reporting procedures for these observations should also be considered, noting the capabilities of the modern data relay systems, such as the WMO Information System. Data transmission, acquisition, archival, and adherence to reporting standards need to be reviewed. WMO and the Group on Earth Observations (GEO) should initiate the process. Assembling a data set of multidisciplinary surface-based and airborne observations during the IPY period would be a good starting point, and would provide an understanding of the necessary capabilities of such a system for the polar regions.

For the space-based system, the recommendation of CryOS is to proceed as quickly as possible with inter-agency coordination of research and operational missions, so that as complete as possible a data series from multiple sensors is available for users. The Global Interagency IPY Polar Snapshot (GIIPSY) IPY Project will be the first attempt to achieve a quantum leap in this direction during the IPY period.

Interoperability of various observing systems is one of the main concerns of GEO. CryOS recommends the systematic development of standardized distributed environmental data processing, such as the GRID approach for processing satellite data and running models, together with the development of commonly accepted standards for data visualization and quality control and assessment. The use of GIS, e.g., the visual globes approach like that provided by Google Earth (Figure 12.1), will make it possible to overlay different types of data and to identify gaps. However, not only is visualization required, but also an increased ability to support quantitative applications. For the cryosphere, such techniques would enable the use of data from various sensors for such applications as snow monitoring, sea ice thickness analysis accounting for snow on ice, thermal monitoring of permafrost with reference to the terrain type, and many others.

12.2. Coordination and Governance

To the extent possible, the Theme recommendations represent a consensus between what the cryospheric community would require from observations and what observing system operators would be able to deliver. Discussion of the progress and implementation of the report recommendations will require close coordination with many organizations having expertise, authority, and resources. CryOS therefore links to many existing programs.

Links within IGOS

Given that the cryosphere is the frozen part of the global water cycle, the Cryosphere Theme is conceptually a subset of the **Integrated Global Water Cycle Observations** (IGWCO) Theme. Methodologically, it has to build on mechanisms used by IGWCO, such as the WCRP Coordinated Enhanced Observing Period (CEOP). IGWCO and the Cryosphere Theme must be coherent, and mutual reviews of recommendations and implementation solutions should be ensured. IGWCO is implemented through a focal point at the World Meteorological Organization (WMO) Secretariat.

The Cryosphere Theme links to the **Ocean Theme** in that both have a direct interest in sea ice, and in that the melting of ice on land will contribute directly to a rise in sea level. The focus of the Cryosphere Theme lies in how to observe sea ice as one element in the cryosphere, whereas the focus of the Ocean Theme lies more in determining the role of sea ice in the coupled ocean-atmosphere-ice system and hence in climate prediction. The Cryosphere Theme also links to the **Coastal Theme**, in which the emphasis is on observations to improve the capacity to assess the state of coastal and marine ecosystems and to provide timely predictions of likely future states. Thus while the emphasis in the Cryosphere Theme is on the physical characteristics of sea ice, the emphasis in the Coastal Theme is more on the role of sea ice and coastal land ice in ecology, and on transfers at the boundary between land and sea, including coastal erosion and near-shore sedimentation. Maps of ice volume and ice cover and the thickness of pack ice are called for under the Coastal Theme.

Coverage of the land surface by ice, snow, permafrost and seasonally frozen ground is an issue relevant for the Land Theme. Similarly, permafrost and seasonally frozen ground observations need to be linked to the **Land Theme**. For the **Global Carbon Theme**, the cryosphere plays an important role in modulating fluxes over land and ocean surfaces, and in storing potentially massive quantities of carbon in permafrost regions. Glacier-related floods and mudslides, avalanches, and loss of construction stability are examples of possible issues for the **Geohazards Theme**. Advances in geodetic observations and hence joint work with the **Dynamic Earth Theme** are required to effectively monitor mass balance of glaciers and ice sheets.

Coordination will be needed across the IGOS Themes to avoid duplication and to take advantage of what has already been achieved. The first step is the development and application of a common inventory of observing systems and the use of joint data handling and visualization tools. This will enable the quality of observing systems to be assessed and their usefulness for multidisciplinary applications to be improved.

Links with International Programs

CryOS was initiated by WCRP through its Climate and Cryosphere (CliC) project and ICSU through its Scientific Committee on Antarctic Research (SCAR). CliC is also co-sponsored by SCAR. CryOS is designed to implement key elements of the CliC science and coordination plan and implementation strategy in the observational domain.

The three main stakeholders for the Cryosphere Theme are the World Meteorological Organization (WMO), the International Council for Science (ICSU), and the Intergovernmental Oceanographic Commission (IOC) of UNESCO, all being IGOS Partners. They are also sponsors of WCRP, another IGOS Partner. The WCRP strategic framework for the years 2005 - 2015 is aimed at coordinated observation and prediction of the Earth System, and CryOS will contribute to its goals.

The WMO Integrated Global Observing System, including the World Weather Watch Global Observing System, World Hydrological Cycle Observing System, WMO Space Programme, and the WMO Information System, all have a strong bearing on the Cryosphere Theme and should be involved in its implementation. SCAR's co-sponsorship of the Theme will ensure an appropriate linkage with its research programmes. The Theme recommendations will also be submitted to the International Arctic Science Committee (IASC), which has been working with the wider

Arctic community through the International Conference on Arctic Research Planning (ICARP) and the Arctic Council to develop a suite of plans for cryospheric observations (http://www.iasc.se/icarp.htm) and Arctic Observing Networks. It is envisaged that IASC will be engaged to some degree in implementing CryOS. Interest is also expected from the regional political bodies, the Arctic Council, and the Parties to the Antarctic Treaty. CEOS and its member satellite agencies are main customers and implementers of IGOS themes and, in particular, of CryOS. The many national agencies making in situ measurements in polar regions, and whose efforts are coordinated through IASC and SCAR, will also be major customers and implementers of CryOS.

In the future, it is expected that many of the Earth observations made for global monitoring of the environment will be integrated under GEOSS, which will provide integrated global Earth observations to meet the decision-making needs of a wide ranging user community. GEOSS will build on current components of the IGOS partners, while encouraging the development of new ones, as part of an integrated global observing strategy. The 10-year implementation plan for GEOSS states explicitly that it will support the implementation of actions called for in the GCOS Implementation Plan and the relevant IGOS Theme Reports, and calls on space agencies to commit to the suite of implementation measures called for in IGOS Theme reports.

Programmes like GCOS, GOOS and GTOS (the Global Climate, Ocean, and Terrestrial Observing Systems) will contribute to GEOSS, as will the ocean and sea-ice observations made under the aegis of the Joint WMO/IOC Technical Commission on Oceanography and Marine Meteorology (JCOMM), which includes an Expert Team on Sea Ice. JCOMM is the implementation arm for GOOS, and receives strategic advice from GOOS on what measurements need to be made. At present little of that advice concerns sea ice. The main source of advice to GOOS on ocean measurements, including sea ice, comes from the Ocean Observations Panel for Climate (OOPC), which is co-sponsored by GOOS, GCOS and the WCRP. The OOPC also provides advice to GCOS. GOOS and GCOS overlap in that the ocean component of GCOS is the climate component of GOOS – the overlap being represented by the OOPC, which advises both bodies.

Advice on sea-ice measurements needed in polar regions has been published by GCOS in its 2nd report for the UN Framework Convention on Climate Change (UNFCCC) on the adequacy of the observing systems for climate, in its GCOS Implementation Plan (GIP), and in its supplement to the GIP. The recommendations made in the Cryosphere Theme report can be considered as updates to, and refinements of, the GCOS recommendations in that they take into account the requirements set forth in those reports. CryOS will seek reviews, approval and involvement of the CEOS Strategic Implementation Team and work with the GCOS Secretariat, GCOS Panels and implementing bodies.

The Ocean Theme is jointly managed for the IGOS Partners by GOOS, so a close connection between the Cryosphere and Ocean Themes will encompass the interests of GOOS, JCOMM, OOPC and the ocean part of GCOS, as well as of the IOC. For instance, the WMO-IOC JCOMM Observations Programme Area (OPA) is seen as an important mechanism for implementation, via the GOOS and the Data Buoy Cooperation Panel (DBCP) in connection with the existing WCRP/SCAR International Programme for Antarctic Buoys and International Arctic Buoy Program. Through such cooperation, the Theme team hopes to propose a solution that would, for instance, extend Argo-type observations to waters covered by sea ice. In the JCOMM Services Programme Area the activities of CryOS are the most relevant for the operational sea-ice services, and are important for the programmes such as the Safety of Life at Sea (SOLAS), the Global Maritime Distress and Safety System (GMDSS), the Marine Pollution Emergency Response Support System (MPERSS), and even for the prediction of wind waves and storm surges. Additional advice on sea-ice measurements and polar ocean observing systems will come from regional organizations such as the Arctic Ocean Science Board (AOSB), EuroGOOS, and the newly established Arctic GOOS Regional Alliance, and professional consortia like the International Ice Charting Working Group.

The Global Terrestrial Observing System (GTOS) is a major partner for the Cryosphere Theme. It is responsible for such crucial networks as the Global Terrestrial Networks (GTNs) for permafrost, glaciers, hydrology, run-off, and lakes (GTN-P, GTN-G, GTN-H, GTN-R, GTN-L). The Cryosphere Theme should work in close cooperation with the GTOS's Terrestrial Observations Panel for Climate. The UN Food and Agricultural Organization (FAO) hosts and sponsors the GTOS Secretariat. It must be kept informed of the Theme recommendations and implementation considerations. It is expected that these interests will be considered within the context of the IGOS Partners by the Land Theme.

The Cryosphere Theme has also had the privilege to receive input from the Commission of Cryospheric Sciences (UCCS) of the International Union of Geodesy and Geophysics (IUGG), the International Permafrost Association (IPA), the World Glacier Monitoring Service (WGMS), and the Global Land-Ice Monitoring from Space (GLIMS) programme. Research projects with observational orientation and international scope, such as the U.S. National Science Foundation Center for Remote Sensing of Ice Sheets, create a basis for future observing systems, and, in many cases, remain the only supporters of certain types of observations.

Within SCAR, CryOS implementation will be supported by programmes such as Ice Sheet Mass Balance and Sea Level (ISMASS), Antarctic Sea Ice Processes and Climate (ASPeCt), Antarctica in the Global Climate System (AGCS), International Trans-Antarctic Scientific Expedition (ITASE), and the Expert Group on Permafrost and Periglacial Environments (EGPPE).

Links with National and Regional Programs

While international bodies and programmes can trigger activities and coordinate them, it is the national agencies that build such systems. Therefore, CryOS should build on existing and planned national, regional, bi- and multilateral activities. The implementation of CryOS largely depends on the involvement of such major satellite operators like CSA, ESA, Eumetsat, JAXA, NASA, and NOAA. National academies of sciences, agencies, and university research projects and consortiums such as the Canadian CRYSYS project, NEESPI, PolarView, SEARCH, and others are capable of providing additional expertise and resources. Establishment and development of regional CliC groups, such as Asia CliC, will contribute to CryOS implementation.

Schedule

The implementation of CryOS, the IGOS Cryospheric Observing System, should be phased to take place over three time intervals:

- Phase 1: 2007-2009
- Phase 2: 2010-2015
- Phase 3: beyond 2015

The initial two-year near-term phase 2007-2009 corresponds to the IPY period. The Theme team has proposed an overarching activity for IPY, which is entitled “State and Fate of the Cryosphere”. That proposal has been accepted as a core IPY programme. The CryOS recommendations will be made widely known to the IPY project community through the IPY ICSU/WMO Joint Committee and the IPY Subcommittees on Observations, Data, Education and Outreach. The IPY community will be requested to follow the recommendations to the extent possible. Some of the approved IPY projects, like GIIPSY, Polar CEOP, CASO, iAOOS, and Arctic-HYDRA, will start implementing the recommendations directly. This period should allow testing of the infrastructure elements contributing specifically to observations of the high latitude polar regions. It will facilitate reviews of progress, identification of observational gaps, and plans for the deployment of appropriate infrastructure.

The development of the IPY DIS fully includes the considerations on interoperability presented in this report. IPY activities may be instrumental not only in creating a snapshot of the polar regions but also in setting a precedent for a more interoperable system for the rest of the globe. Likewise, CryOS will provide an example of the future multidisciplinary observing system required for GEO.

During Phase 1, more specific plans aimed at implementation of CryOS recommendations will be prepared by appropriate IPY committees, representatives of the Cryosphere Theme team, and participants in relevant IPY projects. These plans should be presented to GEO and included in GEO implementation plans as the basis for requesting support from nations participating in the building of GEOSS.

Phase 2 will focus on activities required to preserve the legacy of the IPY observing, data and information management system, to address the weaknesses detected in the high-latitude observing system, to expand the system to the global cryosphere, and to realize plans or concepts for space observing systems for the cryosphere. This intermediate phase corresponds in time to the life of large-scale funding instruments such as the European Union’s 7th Framework Programme, and defines the interval over which scientific activities will be focused. Most of the satellite missions during this period are already known, and CryOS will focus on ensuring better coordination of the missions and their outcomes.

During Phase 3, beyond 2015, we would expect plans to be developed and realized for the operationalization of CryOS. It is hoped that during Phases 1 and 2, space agencies will have developed mission plans that can be implemented in Phase 3 to fill key observational gaps, and along with plans for routine operational observations of such essential parameters as solid precipitation and/or snow water equivalent.

Governance

Internationally, implementation of the Cryosphere Theme will be led by WCRP through CliC (B. Goodison) and by ICSU through SCAR (C. Summerhayes). WCRP and ICSU recognize that the global observing systems should acknowledge the cryosphere as a critically undersampled component within the Earth System. Oversight and reporting will take place through bodies such as CliC, SCAR, and the International Arctic Science Committee (IASC). Overall, CliC and the Cryosphere Theme Team leaders are responsible for reporting on progress to the

Opportunities Provided by the International Polar Year 2007-2008

From 1 March 2007 to 1 March 2009, ICSU and WMO will preside over the International Polar Year 2007-2008, which will spawn a wide range of observations of the cryosphere at both poles. The IPY will serve as a test bed for some cryospheric observations. It is a stated aim of the IPY to leave behind a legacy of observing networks that represent a quantum advance in what we have at present. This is a unique opportunity to bridge in situ, airborne and satellite observations, and to combine this data set with the latest models of polar variability. To this end the CliC IPY project titled "The State and Fate of the Polar Cryosphere" will incorporate the interests of the Cryosphere Theme during the IPY period, and ensure cooperation with other IPY projects. The CryOS team should ensure that it makes a significant contribution to the development of the IPY and of observing systems to follow the IPY.

Cooperation between the IGOS Cryosphere Theme team and the IPY Subcommittee on Observations (SCOBS) is essential to achieve these goals. SCOBS has established a Space Task Group to plan, together with the Global Interagency IPY Polar Snapshot (GIIPSY) Project, a continuous, gap-free IPY legacy dataset comprising a full seasonal cycle of microwave and visible/IR data of the entire polar cryosphere. Since SCOBS is only tasked until 2009, it is critical that the Space Task Group establish mid-term plans for an appropriate transition to a long-term, coordinated inter-agency cryospheric observation strategy.

A GEO IPY Implementation Action was specifically developed in order to "Prepare and agree on a plan of GEOSS activities aimed at implementation of the recommendations on the development of cryospheric observations contained in the IGOS-P Report on Cryosphere including initial set of activities to be implemented as part of the International Polar Year 2007-2008 program." Specific activities that may be anticipated in this GEOSS Implementation Action include maintaining existing systems to monitor the cryosphere, making a global snapshot of the cryosphere during the IPY, establishing "supersites" that include cryospheric observations, extending the WCRP Coordinated Enhanced Observing Period (CEOP) activities over the polar regions and including of cryospheric variables, establishing the initial elements of the Arctic Ocean Observing System, and beginning the implementation of the Arctic HYCOS project. It is hoped that GEOSS will be able to facilitate provision of resources sufficient to maintain the existing networks and start implementing some new cryospheric components of the of the global observing system.

IGOS Partners and GEO. On a regional level, SCAR will be responsible for reporting on Antarctic activities through its various cryospheric groups; CliC will be responsible for reporting on progress in the Arctic. We also hope to engage the interest of IASC's cryospheric research groups in monitoring implementation as part of their ongoing Arctic climate assessment activities.

During Phase 1 (IPY), implementation will be coordinated by a group that will include representatives of the CryOS team and IPY governing bodies, with invitations to relevant partners (e.g., other IGOS Themes). Support by GEO for this initiative will be critical to its success. Toward the conclusion of the IPY field period and with the closure of the IPY International Planning Office, a permanent position or an office to monitor and coordinate the implementation of CryOS should be established, and resources for its operations identified. It is proposed that CryOS implementation be led by an oversight committee accompanied by a Scientific Steering Group with expertise in the various cryosphere domains, as well as expertise in satellite and in situ systems.

Within the first two phases of CryOS, some of the non-routine, scientific observations currently obtained by ad-hoc scientific satellite missions will become routine and operationalized. This implies that CryOS must increasingly interface with GEOSS and the operational organizations delivering cryosphere-relevant services for routine, operational cryospheric data products also of relevance to climate research, such as the GMES and the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF).

Resources and Commitments

The development of the IGOS Cryosphere Theme has been supported by the following organizations with staff effort and travel funds over the last three years:

- **Space agencies:**
  CSA, ESA, JAXA, NASA, NOAA/NESDIS
- **International bodies:**
  ICSU/SCAR, WCRP/CliC
- **Research institutes:**
  JAMSTEC

The core theme team has taken action toward the implementation of CryOS in 2007 and beyond. The recommendations in this report will be reviewed by national agencies responsible for space (NESDIS, ESA, CSA, JAXA, NASA) and in situ measurements (e.g., the U.S. National Science Foundation, the British Antarctic Survey, the Institut Paul Emile Victor (French Polar Institute), and the Alfred Wegener Institute). Commitments from these agencies and institutes will be sought in 2007 and beyond. The re-launch of the CryoSat mission (CryoSat-2) by ESA already indicates a commitment to cryospheric observations. Similarly, funded IPY projects constitute commitments by agencies for in situ and satellite (e.g., GIIPSY) measurements. The IGOS Cryosphere Theme is, in fact, the plan for the observing system legacy sought by the IPY organisers for the cryposphere. In May 2007, the Fifteenth WMO Congress approved a proposal from CliC that will make WMO the founder of a Global Cryosphere Watch that lays the foundation for the legacy of IPY. Along the same lines, GEO is committed to the IPY through its CL-06-05 task on IPY, in which CryOS plays a leading role.

Resources from the IGOS Partners will be sought under the recognition that the cryosphere is an essential element of many of the existing observing programmes, and cuts across many of the existing approved Themes. Resources for implementation are expected to originate from the primary partners, each taking responsibility for deployment of appropriate observing system infrastructure. Once the framework for CryOS implementation actions is established, other funding initiatives by the EC Framework programme or national funding agencies will be explored to allow for active cryospheric research community participation in the establishment of the anticipated global integrated observing system.

Capacity building and implementation might be undertaken in the following way:

- The IGOS Partners agree on the lead institution.
- The IGOS Partners, and/or GEO, form a CryOS implementation group consisting of representatives from the major partners and stakeholders.
- The CEOS Stategic Implementation Team (SIT) and WMO review the CryOS recommendations and indicate ways in which space and other agencies contribute to satellite and in situ observations of the cryosphere.
- The lead institution and stakeholders work with national and international funding agencies to incorporate the Theme recommendations into existing programs or to develop new programs.
- The CryOS implementation team works with the other IGOS Themes and relevant partners (GCOS, GTOS, etc.) to avoid duplication of effort.

The CryOS implementation group should hold a workshop as soon as possible to tie implementation action to specific agencies, institutions, and individuals that are capable of ensuring their completion. The workshop would result in an implemenation plan.

Assessment and Feedback

Indicators of success in the near-term include the development of an IPY Polar Snapshot, an augmentation of existing CEOP sites or GTN sites, the initial development of an integrated approach for cryospheric data products, the expansion of research to improve snow water equivalent and solid precipitation estimates from space, the development of Arctic and Antarctic observing systems such as Arctic-HYCOS, and the establishment of an IPY data management structure. In the mid- and long-term, success can be measured by improvements in the assimilation and use of cryospheric data in weather and climate models, the development of a SAR virtual satellite constellation, the augmentation of selected supersites, the recovery of archived data for fundamental climate data records, the digitization and analysis of historic ice charts, a reprocessing of all cryospheric variables with better calibrated satellite data and improved algorithms, the implementation of the P-band microwave concept for ice sheet sounding and permafrost applications, and an expansion of the cryospheric reference network.

Arrangements for a regular assessment of CryOS implementation progress and performance should be made and suggestions sought for amendments to the implementation actions. Extensive reviews should be held at approximately three-to-five year intervals, with the first in 2010. As with the initial development workshops, the review meetings should be held on different continents to ensure geographic diversity. Key users and stakeholder groups should be represented. The first Theme update should be initiated after the first review in 2010.

Implementation of the recommendations, capacity building, and the development of the research resource base should go hand in hand with the formation of a cryosphere “community of practice”. Such a community will informally unite data users and providers at several levels. For instance, the European Global Monitoring for Environment and Security (GMES) initiative and the establishment of several communities of practice under the auspices of GEO produce a web of relations between members of the community, create a demand for products, and stimulate the adaptation of products to specific user needs. A community of practice creates market mechanisms for self-development and bottom-up growth.

12 Implementation

Implementation Actions

Table 12.1 summarizes primary actions aimed at implementation of the Theme recommendations. They form the initial elements of the CryOS Implementation Plan. These actions are provided for each of the implementation phases. Table 12.2 lists broad implementation actions across the phases. It is essentially a summary of Table 12.1, but also ties the actions to specific recommendations from the cryosphere domain chapters. ■

Table 12.1. Implementation actions in three timeframes.

Observing System Type	**Near Term IPY: 2007-2008**	**Mid Term Post-IPY: 2009-2015**	**Long Term**
Space Infrastructure	Ensure coordinated interagency planning of the IPY Polar Snapshot (plan for SAR/InSAR; high-resolution Vis/IR; and optimization of coverage in respect to ICESat laser cycles) and continuity in higher-level polar data products for an IPY legacy dataset. Forge inter-agency relationships for the development of a virtual multi-frequency, multi-polarisation SAR constellation for meeting requirements for: routine and frequent cryospheric mapping; InSAR for topographic change and ice dynamics; and snow mapping. Continue to develop and improve methods for estimating the spectral properties of snow and ice from satellites. Plan the continuity of Landsat class optical mapping capability for world glacier monitoring.	Implement a virtual SAR constellation for polar applications – based on uniform, standard, routine data acquisition. Develop integrated data processing capabilities for cryospheric products from SAR virtual constellation, and investigate GRID-based processing. Develop integrated, operational analysis products based on cryospheric data assimilation, models, satellite, and in situ data, and develop operational cryospheric forecasting capability. Implement a mission concept for routine DEMs of glacierised surfaces. Implement a mission to guarantee continuity in satellite sensors with Landsat capability for glacier monitoring.	Establish an operational, international SAR satellite constellation for all-weather cryospheric remote sensing, retaining essential modes for large-scale mapping and charting, InSAR terrain mapping, and sea-ice dynamics. Implement cooperative, global, operational World Glacier Inventory monitoring service. Ensure continuity in multi-frequency, high-resolution (<12 km) passive microwave radiometry – including C-band channel for all-weather SST. Operationalise satellite SWE and time-variable gravity measurements. Implement P-band concept for ice-sheet sounding, taiga biomass, and potential permafrost applications.

Observing System Type	Near Term IPY: 2007-2008	Mid Term Post-IPY: 2009-2015	Long Term
Space Infrastructure	Develop and establish satellite concepts for measurements of SWE and solid precipitation and assess retrieval uncertainties. Develop a laser altimeter successor to ICESat.	Implement a dual-, high-frequency radar mission for SWE and extension to GPM for solid precipitation. Launch a high latitude radar altimeter successor to CryoSat. Assure adequate temporal overlap of satellite sensors for inter-calibration and consistent time series.	Ensure that high spectral resolution optical sensors are planned for future satellites.
Near Surface: AUV/UAVs	Coordinate near-surface, high-resolution remote sensing activities from aircraft, UAV and AUVs with satellite and in situ experiments during IPY.	Develop 'smart', autonomous, in situ sensors for ice and polar ocean sampling with satellite data relay mechanisms.	Established a balanced plan comprising satellite and new (AUV/UAV) autonomous observing system elements.
In Situ Infrastructure	Supplement sparse, sporadic, and declining basic in situ observation networks with precipitation, SWE, snow depth, lake and river ice, permafrost borehole temperatures, ice-sheet/glacier core properties, met/ocean/ ice mass balance tracked buoys, glacier mass balance. Plan selection of at least 15 reference CryoNet "Supersites" with comprehensive suites of relevant measurements (e.g., by augmentation of existing CEOP and/or GTN sites). Ensure that in situ moorings in oceans with ice cover contain Upward Looking Sonar ice draft measurement capability. Review and develop as needed appropriate best practices via the establishment of 'observer' protocols and standard suites of instrumentation for in situ sampling and coordinate amongst respective communities (e.g., ASPeCt and CEOP standards). Create a global 2D glacier inventory (polygon outlines) as a reference for glacier change assessment within the framework of GTN-G.	Sustain/Convert essential short-term/temporary post-IPY network into long-term CryoNet sites. Augment selected supersites, and extend essential geographic networks to obtain appropriate measurement density and siting, for representative data. Implement recommendations of the International Conference on Arctic Research Planning Working Group on Terrestrial Cryospheric and Hydrologic Processes and Systems. Guarantee continuity in essential historical time-series (e.g. reference glacier sites). Employ, in so far as possible, station autonomy and NRT telemetry to facilitate data assimilation and data exploitation for satellite cal/val. Adopt GCOS climate monitoring principles (GCMP) for all operational satellites and in situ sites.	Implement an integrated in situ network (CryoNet)– across range of different cryo environments. Evaluate an in situ cryospheric reference network (CryoNet) and supplement with new sites, and retire others, as needed. Ensure that CryoNet is an acknowledged and supported component of the WMO Integrated Global Observing System. A large network of autonomous robots, equipped to measure surface energy and mass flux, should be developed.

Observing System Type	Near Term IPY: 2007-2008	Mid Term Post-IPY: 2009-2015	Long Term
In Situ Infrastructure	Strengthen the support of already established monitoring networks like GTN-G or GTN-P. Develop observer networks in Native communities and involve schools.	Capacity building measures: regional training of local community observers and recruitment of schools, particularly for river-, lake-ice, and snow networks.	
Data and Data Management	Establish IPY Data Management Structure (or Data Information System) and standardize metadata principles (e.g. unique meta-tagging of all IPY legacy data for archive retrieval). Coordinate the unification and quality control of historical datasets (e.g. GLIMS & WGMS). Identify and initiate data rescue and reprocessing of historical benchmark datasets (e.g. glacier terminus locations and previously classified imagery). Develop tools for integrating diverse and geographically distributed remote sensing and in situ data. Establish public/educational interface/visualisation of IPY data using Google or Virtual Earth forums.	Implement an Antarctic Geophysical Processing System for routine SAR sea-ice drift dynamics data products. Develop integrated, operational analysis products based on data assimilation, and develop operational cryospheric forecasting capability. Recover and reprocess long-time-series archived data for cryospheric fundamental climate data records (FCDRs). Undertake reprocessing of all cryospheric variables based on IPY legacy dataset and better calibrated and validated retrieval algorithms. Initiate an Antarctic reanalysis project. Initiate colocation, digitization and analysis of the long-term ice record contained in historic regional ice charts produced by various countries needed to document variability and trends over the past 1000 years. Facilitate the development of processing of distributed data based on GRID technology. Implement standard data formats for distributed web and data visualization services.	Ensure long-term validation, quality control, reprocessing, and media updates of essential cryospheric data sets. Develop seamless integration and distribution of cryospheric data products, including data fusion products (e.g. mass balance of sea ice, land ice, terrestrial snow cover). Assimilate cryospheric products in next-generation Earth-system GCMs, operational weather forecast models, and climate models covering short-range to seasonal forecasts.

Observing System Type	Near Term IPY: 2007-2008	Mid Term Post-IPY: 2009-2015	Long Term
Integrative Actions	Develop long-term plan and begin to augment CEOP supersites with essential CryoNet capabilities. Encourage efficient data collection and NRT (GTS) transmission or transfer to IPY data system. Run process studies during IPY to determine error covariance characteristics for data assimilation. Develop a plan for repatriation and reprocessing of essential cryospheric datasets for reanalysis projects. Promote data integration efforts including development of techniques to merge in situ and satellite measurements. Promote a unified data policy for satellite and in situ data access across international and national agencies, and data providers. Promote development of operational methods for sea ice thickness determination, particularly in Antarctica by enhancing the Antarctic ice thickness monitoring project. Educate the public on where and how to access CryOS and IPY data. Assist WMO and ICSU in establishing a Global Cryosphere Watch. Identify a Community of Practice for GEO/GEOSS.	Establish network of stations for all cryospheric applications (CryoNet) and satellite calibration and validation and data assimilation. Establish near real-time data transfer capability for all CryoNet data. Develop process-oriented science to facilitate assimilation of all cryospheric data into NWP and climate models. Reprocessing to be planned and financed as part of fundamental activities for satellite Agencies and IPY Data repositories. Federate independent providers of cryospheric data products and services, on national and international level (e.g. EuroClim, PolarView)	Reprocessing of climate records must be planned and financed as part of fundamental activities for satellite agencies and cryosphere data repositories Develop seasonal-interannual forecasting capability for ice-sheet and glacier, dynamics, mass-balance changes, melt runoff, and sea-level rise rate estimates. Establish governance of sustained integrated Cryo Observing System in partnership with GEO, with appropriate mechanisms for long-term sustained financing. Develop a plan for funding for sustained in conjunction with GEO

Table 12.2. Implementation actions across timeframes. Links to specific recommendations from the cryosphere domain chapters are given in parentheses after the action, e.g., R3.2.

Short Name	Action
IPY	Promote coordinated inter-agency planning of the IPY Polar Snapshot including new integrated data management concepts and future data acquisition and management planning for IPY legacy via GIIPSY and SCOBS collaboration. Undertake extensive reprocessing of all cryospheric variables based on IPY legacy dataset and better calibrated and validated retrieval algorithms. (Relevant to all cryospheric domains)
SAR	Implement a virtual multi-frequency multi-polarisation SAR constellation that should be optimized to satisfy all key cryospheric requirements, including InSAR capability. (R3.2-3, R4.4-5, R4.13-14, R5.8, R6.1, R6.5, R7.4)
Optical/PMW	Provide continuous and improved data acquisition from Landsat optical class and multi-frequency high-resolution passive microwave radiometry. (R3.2, R3.4, R.4.1, R4.13, R5.7, R6.3, R6.5, R7.3, R8.1, R8.4, R8.6, R8.7)
Altimeter	Provide continuous, coordinated, and improved altimetry measurements. (R4.6, R4.14, R6.2)
Gravity	Operationalize gravity measurements for cryospheric applications. (R6.7)
P-band	Develop and implement a P-band concept for ice sheet sounding, taiga biomass and potential permafrost applications. (R6.4, R9.4)
AUV/UAV	Coordinate efforts to develop and implement near-surface remote sensing methods from aircraft, UAV and AUVs, which should complement satellite and in situ measurements, especially during IPY. (R4.7, R4.9, R6.4, R6.6, R10.6)
CryoNet	Coordinate international planning and establishment of operational in situ observation networks. The coordination should be made with existing CEOP and GTN networks. Ensure a data stream optimized for future cryospheric data assimilation systems. WCRP, WMO WWW, and GEO should provide the vision to facilitate integrating cryosphere network to already existing meteo/hydrological networks. (R3.1, R3.4, R5.2, R5.4-5, R6.9, R8.2, R9.2-3, R10.1, R10.7)
SWE	Develop, implement, and operationalize a satellite mission for SWE and solid precipitation retrieval. (R3.2, R3.4, R4.13, R10.3-4, R10.9)
DEM	Construct a high-resolution DEM covering both polar regions. (R6.2, R7.4, R9.5)
Data Management	Collocate, recover, provide quality control for, digitize, and reprocess historical, archived, and present datasets to construct cryospheric fundamental climate data records (FCDR). (R4.2, R4.10, R5.1, R5.6, R7.1, R7.5, R9.6)
Data Transfer	Establish an appropriate data transmission and communication system for cryospheric observations that would satisfy WMO Information System requirements and retransmission capability. (R4.9)
Data Assimilation	Develop comprehensive cryospheric data assimilation systems based on in situ and remotely sensed observations that can eventually provide cryosphere-ocean-atmosphere prediction and reanalysis capabilities. Error covariances should be obtained intially from IPY activities. (R3.5, R4.11, R4.14, R5.11, R7.1, R10.5)
Community of Practice	Define user-led community of stakeholders, from providers to the final beneficiaries, i.e., a “Community of Practice”. Verify their precise needs and modes of work.
Outreach and education	Develop capacity building measures for regional observer networks involved with schools including IPY activities. River-, lake-ice, and snow measurements are of particular interest.

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The literature referenced in this report is not intended to be exhaustive.

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B Observational Capabilities and Requirements

The following tables provide current measurement capabilities and observational requirements for each cryosphere domain (snow, sea ice, etc.). In some cases observational requirements are listed separately for satellite and in situ observations because of different applications. Codes are as follows: C = Current Capability, T = Threshold Requirement (Minimum necessary), O= Objective Requirement (Target), L = Low end of measurement range, U = Unit, H = High end of measurement range, V = Value, cl = climate, op = operational.

Table B.1. Summary of current/planned capabilities and requirements for terrestrial snow parameters.

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Snow Cover	C	20	100	%	15-20	%	1	km		day	e.g. MODIS
	T	0	100	%	10	%	0.5	km	1	day	Hydromet
	O	0	100	%	5	%	0.1	km	12	hr	
Snow Water Equivalent, satellite (Shallow)	C	0	0.2	m	2-10	cm	25	km	1	day	e.g. AMSR-E
	T	0	0.3	m	3	cm	0.5	km	6	day	Hydromet
	O	0	0.3	m	2	cm	0.1	km	12	hr	
Snow Water Equivalent, satellite (Deep)	C	none	---	---	---	---	---	---	---	---	Need HF SAR
	T	0.3	3	m	10	%	0.5	km	6	day	Hydromet
	O	0.3	3	m	7	%	0.1	km	12	hr	
Snow Water Equivalent, in situ (Shallow)	C	0	3	m	1	cm	1	m	30	day	Hydromet
	T	0	3	m	1	cm	1	m	7	day	Hydromet
	O	0	3	m	1	cm	1	m	1	day	
Snow Depth, satellite (Shallow)	C	0	~0.7	m	6-35	cm	25	km	1	day	e.g. AMSR-E
	T	0	1	m	10	cm	0.5	km	6	day	Hydromet
	O	0	1	m	6	cm	0.1	km	1	hr	Transportation
Snow Depth, satellite (Deep)	C	none	---	---	---	---	---	---	---	---	Need HF SAR
	T	1	10	m	10	%	0.5	km	6	day	Hydromet
	O	1	10	m	6	%	0.1	km	1	hr	Transportation
Snow Depth, in situ	C	0	10	m	1	cm	1	m	1	day	Hydromet
	T	0	10	m	1	cm	1	m	6	hr	Hydromet
	O	0	10	m	1	cm	1	m	1	hr	

Table B.2. Summary of current/planned capabilities and requirements for sea ice parameters.

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Extent/Edge	Ccl Cop	NA	NA	km	15 0.1	km	15 0.1	km	1 3	day	AMSR VIR, SAR, AUV
	T	NA	NA	km	10	km	10	km	1	day	CMIS
	Ocl Oop	NA	NA	km	5 0.1	km	1-5 0.1	km	1 1	day	CMIS, SAR, AUV
Concentration	Ccl Cop	15 0	100	%	5-20	%	15	km	1	day	AMSR, VIR, SAR, AUV
	T	0	100	%	<10	%	15	km	1	day	
	O	0	100	%	<5	%	10	km	1	day	CMIS, SAR, AUV
Leads/polynyas	Ccl Cop	0 0	100 in-det.	% km^2	5-20 0.1	% km^2	15 0.5	km	1 1	day wk	AMSR, SAR, AUV
	T										
	Ocl Oop	0 0	100 indet.	% km^2	5 0.1	% km^2	10 0.1	km	1 1	day	MODIS, PM, AUV
Stage of Development (Ice Age)	Ccl Cop	0	100	%	5-20	%	15	km	1	day	SSMI, VIR, Scat, SAR
	T	0	100	%	<10	%	15	km	1	day	SAR
	Ocl Oop	0	100	%	<5	%	10	km	1	day	SAR
Motion[1]	Ccl Cop	0	100	km day^{-1}	5 0.5	km day^{-1}	25 1	km	1 3	day	AMSR[2] SAR[2], buoys
	T	0	100	km day^{-1}	3	km day^{-1}	25	km	1	day	SAR
	Ocl Oop	0	100	km day^{-1}	1 0.5	km day^{-1}	1 0.1	km	1 1	day	More freq. SAR, improved MIZ performance
Thickness	Ccl Cop	0	10	m	0.5 10	m %	0.5 0.5	km	0.5 1	yr wk	ICESat op ice charts, mass balance buoys, AUV
	T	0	10	m							
	Ocl Oop	0	10	m	0.1 10	m %	25 0.5	km	1 1	mo day	sat. altimeter, mass balance buoys, AUV
Ridge Height, Concentration	Ccl Cop	0	10	m	-	m					SAR
	T	0	10	m	2	m					SAR
	Ocl Oop	0	10	m	1	m					SAR

Snow Depth on Ice	Ccl	0	100	cm	10-20	cm	15	km	1	day	AMSR
	T	0	100	cm	5	cm	10	km	1	day	CMIS
	Ocl	0	100	cm	2	cm	5	km	1	day	CMIS
Melt Onset, Duration of Melt	Ccl	1	365	doy	4	day	15	km	1	day	AMSR, Scat
	T	1	365	doy	2	day	15	km	1	day	
	Ocl	1	365	doy	1	day	10	km	1	day	
Surface Characteristics (albedo, meltpond, dust, snow properties, temperature)[3]	Ccl	0	100	%	10	%	1	km	1	day	MODIS, but not currently produced, AUV
	T	0	100	%	10	%	1	km	1	day	
	Ocl	0	100	%	1-5	%	0.5	km	1	day	
Volume/Mass Flux	Ccl										Derived from motion, thickness, concentration
	T										
	Ocl	0	indet.	km^3 day^{-1}	1	km^3 day^{-1}	25	km	1	day	

[1] Velocity measurement, range and errors are for each orthogonal component.
[2] Antarctic measurements are less robust than for the Arctic primarily due to the influence of weather.
[3] Range and errors for albedo and meltpond concentration. Other parameters listed not yet regularly observed. There is overlap of these products with products in snow chapter and albedo/temperature chapter.

Table B.3. Summary of current/planned capabilities and requirements for lake and river ice parameters.

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Concentration	C			%		%	100-1	m-km	1	wk	Radarsat, AVHRR, OLS
	T	0	100	%	10	%	100	m	1	day	AMSR-E, SAR, optical
	O	0	100	%	5	%	30	m	1	day	SAR, optical
Ice areal extent (and open water area)[1]	C			km^2		%	250-500	m	1	day	MODIS
	T			km^2	10	%	100	m	1	day	SAR, optical
	O			km^2	5	%	30	m	1	day	SAR, optical
Freeze-up and break-up date /ice cover duration[2]	C			days	1	d	point			yr	In situ obs.
	T			days	2	d	100	m	1	yr	SAR, optical,
	O			days	1	d	30	m	1	yr	
Thickness	C	0	5	m	2	cm	point		1-2	wk	In situ obs.
	T	0	3	m	5	cm	100	m	1	wk	SAR, passive mw
	O	0	5	m	2	cm	10	m	1	day	
Snow depth on ice	C	0	1	m	2	cm	point		1-2	wk	In situ obs.
	T	0	.8	m	5	cm	100	m	1	wk	SAR, passive mw
	O	0	1	m	2	cm	10	m	1	day	
Areal extent of floating and grounded ice[1]	C			km^2		%	10	m	1	wk	SAR
	T			km^2	10	%	5	m	1	wk	SAR
	O			km^2	5	%	3	m	1	wk	
River ice jams and dams[1]	C			km^2		%	0.5	m	1	hr	Aerial survey
	T			km^2	10	%	10	m	1	day	SAR, optical
	O			km^2	5	%	3	m	1	day	
Flooding extent caused by jams and dams[1]	C			km^2		%	10	m	1	wk	Radarsat
	T			km^2	10	%	5	m	1	day	SAR, optical
	O			km^2	5	%	3	m	1	day	
River icings (aufeis)[1]	C			km^2		%	15-30	m	2	mo	Landsat, ASTER, SAR
	T			km^2	10	%	10	m	1	wk	SAR, optical
	O			km^2	5	%	3	m	1	wk	

[1] The measurement range is not specified because the size (km^2) of the parameter can be very variable.
[2] Freeze and break-up dates are expressed in Julian Days while ice duration is in days. The measurement range is not specified because the dates and number of days can be highly variable and some lakes at higher latitudes can have a perennial ice cover.

Table B.4. Summary of current/planned capabilities and requirements for ice sheet parameters.

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Ice margin	C	0	1000	km	2	km	2	km	5	yr	AVHRR
	T	0	1000	km	2	Km	2	Km	5	yr	Hi-res optical and SAR
	O	0	1000	km	25	m	25	m	1	yr	
Grounding Line	C	0	1000	km	1	km	1	km	5	yr	
	T	0	1000	km	1	Km	1	Km	5	yr	Hi-res optical/ InSAR
	O	0	1000	km	100	m	1	km	1	yr	
Surface Accumulation	C	0	50	cm water eq/yr	1	cm water eq/yr	25	km	1	yr	Passive microwave, P/E/ models and in situ
	T	0	50	cm water eq/yr	1	cm water eq/yr	25	km	1	yr	Active/ passive microwave
	O	0	50	cm water eq/yr	1	cm water eq/yr	1	km	6	mo	
Basal Melt Magnitude	C	0	20	m/yr	100	cm/yr	10	km	1	yr	Inferred
	T	0	20	m/yr	100	cm/yr	10	km	1	yr	
	O	0	20	m/yr	10	cm/yr	1	km	6	mo	
Basal Melt Distribution	C	0	10^4	km^2	1	km	50	km	1	yr	
	T	0	10^4	km^2	1	km	50	km	1	yr	UHF/VHF radar
	O	0	10^4	km^2	1	km	10	km	1	yr	
Surface Elevation	C	0	4	km	50	cm	1	km	1	yr	
	T	0	4	km	50	cm	1	km	1	yr	Radar and laser altimeter
	O	0	4	km	50	cm	1	km	1	yr	
Surface Elevation Change	C	0	5	m/yr	10	cm/yr	5	km	1	yr	
	T	0	5	m/yr	10	cm/yr	5	km	1	yr	Radar and laser
	O	0	5	m/yr	10	cm/yr	1	km	6	mo	
Snow/Firn Density	C	0	910	kg/m^3	50	kg/m^3	100	km	5	yr	
	T	0	910	kg/m^3	50	kg/m^3	100	km	5	yr	In situ obs
	O	0	910	kg/m^3	10	kg/m^3	100	km	5	yr	
Snow Grain Size and Shape	C	0.1	3	mm	0.25	mm	100	km	5	yr	Optical and in situ
	T	0.1	3	mm	0.25	mm	100	km	5	yr	
	O	0.1	3	mm	0.25	mm	100	km	5	yr	
Surface Temperature	C	173	278	°K	1	°K	10	km	1	yr	In Situ
	T	173	278	°K	1	°K	10	km	1	yr	Annual average THIR
	O	173	278	°K	1	°K	10	km	1	mo	

Internal Temperature	C	173	273	°K	0.1	°K	500	km	5	yr	
	T	173	273	°K	0.1	°K	500	km	5	yr	Borehole temp.
	O	173	273	°K	0.1	°K	500	km	5	yr	
Gravity Field	C				2	mgal	1	km	1	yr	
	T				2	mgal	1	km	1	yr	Airborne Gravity
	O				0.5	mgal	1	km	1	yr	
Surface Velocity Field	C	0	15	km/ yr	10	m/yr	1	km	6	mo	
	T	0	15	km/ yr	10	m/yr	1	km	6	mo	GPS and InSAR
	O	0	15	km/ yr	10	m/yr	1	km	6	mo	
Vertical Velocity Variation	C	0	1	m/yr	10	cm/yr	100	km	5	yr	
	T	0	1	m/yr	10	cm/yr	100	km	5	yr	Vertical strain gauges
	O	0	1	m/yr	10	cm/yr	100	km	5	yr	
Ice thickness	C	.010	4	km	20	m	50	km	10	yr	Ice sheet wide
	T	.010	4	km	20	m	50	km	10	yr	VHF and UHF Radar
	O	.010	4	km	20	m	1	km	10	yr	
Internal Layer Depth	C	.010	4	km	20	m	50	km	10	yr	
	T	.010	4	km	20	m	50	km	10	yr	VHF and UHF radar
	O	.010	4	km	20	m	1	km	10	yr	
Iceberg calving rate	C	0	30	km/ yr	1	km/yr	1	km	1	yr	Inferred
	T	0	30	km/ yr	1	km/yr	1	km	1	yr	
	O	0	30	km/ yr	1	km/yr	1	km	6	mo	
Changes in ice sheet morphology (crevasses, shear margins)	C	0	100	m	100	m	1	km	1	yr	
	T	0	100	m	100	m	1	km	1	yr	Hi Res optical and InSAR
	O	0	100	m	100	m	1	km	1	yr	
Surface melt extent	C	0	20	10^6sq km	2500	km^2	25	km	1	day	
	T	0	20	10^6sq km	2500	km^2	25	km	1	day	Passive and active microwave
	O	0	20	10^6sq km	400	km^2	10	km	1	day	
Surface melt duration	C	0	100	Melt days	1	Melt day	25	km	1	day	
	T	0	100	Melt days	1	Melt day	25	km	1	day	Passive and active microwave
	O	0	100	Melt days	1	Melt day	1	km	1	day	

Ice Sheet Mass Change	C	0	200	km^3/yr	50	km^3/yr	500	km	1	yr	Flux approach not included in this category
	T	0	200	km^3/yr	50	km^3/yr	500	km	1	yr	Satellite Gravity
	O	0	200	km^3/yr	10	km^3/yr	500	km	1	yr	
Geothermal Heat Flux	C	0	1	w/m^2	1	w/m^2	1000	km	10	yr	
	T	0	1	w/m^2	1	w/m^2	1000	km	10	yr	TBD approach
	O	0	1	w/m^2	1	w/m^2	100	km	10	yr	

Table B.5. Summary of current/planned capabilities and requirements for iceberg parameters.

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Limit of iceberg area	C	NA	NA	km	10	km	10	km	1	day	SAR, SLAR airborne reconnaissance
	T	NA	NA	km	10	km	10	km	2	hr	same
	O	NA	NA	km	10	km	10	km	2	hr	same
Concentration of icebergs	C	0	100	%	10	%	1	deg	1	day	same
	T	0	100	%	<10	%	1	deg	1	day	same
	O	0	100	%	<5	%	1	deg	1	day	same
Iceberg position	C	NA	NA		10	%	1	km	1	day	same
	T	NA	NA		<10	%	1	km	1	day	same
	O	NA	NA		<5	%	1	km	2	hr	same
Iceberg Size	C	0.01	100	km	30	%	.01	km	1	day	same
	T	.001	100	km	30	%	.01	km	1	day	same
	O	.001	100	km	30	%	.001	km	1	hr	same
Iceberg Draft	C	1	1000	m	30	%	10	m	1	day	shipborne, modelling
	T	1	1000	m	30	%	1	m	1	day	altimeter (for large bergs)
	O	1	1000	m	30	%	1	m	2	hr	altimeter
Iceberg Mass	C	0	NA	kg	30	%	15	km	1	day	shipborne, modelling
	T	0	NA	kg	30	%	15	km	1	day	altimeter (for large bergs)
	O	0	NA	kg	30	%	10	km	2	hr	altimeter
Iceberg Velocity	C	0	30	km day^{-1}	10	%	1	km day^{-1}	1	day	SAR, SLAR, scatterometer visible/IR
	T	0	30	km day^{-1}	10	%	1	km day^{-1}	1	day	SAR, SLAR, scatterometer visible/IR
	O	0	30	km day^{-1}	10	%	0.5	km day^{-1}	2	hr	SAR, SLAR, scatterometervisible/IR

Table B.6. Summary of current/planned capabilities and requirements for glaciers and ice caps.

Parameter	C O T	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Area	C				1	%	5	m	30	yr	airborne
	O				3	%	30	m	5	yr	Landsat etc.
	T	0.01		km^2	3	%	50	m	5	yr	Hi-res optical
	O	0.01		km^2	1	%	15	m	1	yr	
Topography	O										Airborne
	C	0	8500	m sl.	5	m	100	m	5	yr	For models
	T	0	8500	m sl.	0.1	m	30	m	1	yr	Mass balance
Velocity	O				1	%	point		1	yr	In situ
	C	0	10	km/ yr	5	%	10	m	1	yr	InSAR, hi-res optical, etc.
	T	0	10	km/ yr	1	%	20	m	1	mo	
Glacier dammed lakes	O				1	%	1	m	1	yr	airborne
	C	0.05	10	km^2	3	%	50	m	1	mo	SAR, hi-res optical
	T	0.01	10	km^2	1	%	15	m	5	day	
Facies, snowline	C						point				In situ
	T			class	200	m	100	m	1	mo	Position of boundary
	O			class	30	m	30	m	10	day	
Accumulation	C				5	%	point				In situ
	T	0.05	8	m	10	%	500	m	1	yr	Ku-, X-SAR
	O	0.10	5	m	5	%	100	m	1	mo	
Mass balance	C				0.10	m	point				In situ
	T	0	±5	m	0.20	m	500	m	1	mo	process model & SAR
	O	0	±5	m	0.05	m	100	m	1	yr	
Ice thickness	C	0	200	m	2-5	m	100	m	30	yr	In situ, airborne

Table B.7. Summary of current/planned capabilities and requirements for snow/ice temperature and albedo.

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Snow/ice Albedo (broadband)	C	30	100	%	7	%	1	km	1	day	e.g. MODIS
	T	0	100	%	1	%	8	km	1	hr	Hydromet
	O	0	100	%	0.5	%	5	km	30	min	
Snow/ice Surface Temperature	C	190	290	K	2-3	K	1	Km	100	min	
	T	200	275	K	1	K	1	km	1	hr	Hydromet
	O	200	275	K	0.1	K	0.1	km	30	min	

Table B.8. Summary of current/planned capabilities and requirements for terrestrial permafrost and seasonally frozen ground parameters.

Parameter	C T O	Measurement Range			Accuracy		Resolution				Comment or Principal Driver
		L	H	U	V	U	Spatial		Temporal		
							V	U	V	U	
Permafrost[1]											
Permafrost thermal state	C	-20	0	^{0}C	0.05	K	Vertical profile		1	yr	Key parameter of the GTN-P; in situ measurements; (annual upper 20-100 m; deeper 5 a)
	T	-20	0	^{0}C	0.01	K			1	yr	
	O	-20	0	^{0}C	0.01	K			1	yr	
Permafrost thickness	C	0	1600	m	1	m	Point		10-100	yr	Measured or interpolated from temperature profiles; inferred from geophysical logs or surface surveys; modeled parameter
	T	0	1600	m	0.5	m			10	yr	
	O	0	1600	m	0.5	m			10	yr	
Permafrost distribution (continental)	C	0	100	%		%	10	km	10	yr	inferred from ground temperatures, photo terrain interpretation, geophysics
	T	0	100	%	2	%	1	km	10	yr	
	O	0	100	%	1	%	1	km	1	yr	
Permafrost distribution (mountain)	C	0	100	%		%	25	m	1	yr	Distributed models, based on DEM, calibrated with BTS; distribution based on elevation (m)
	T	0	100	%	2	%	25	m	1	yr	
	O	0	100	%	1	%	25	m	1	yr	
Downslope velocity of creeping permafrost	C	0.01	15	m / yr	1	cm	Point		1	yr	Survey transects, repeat high-resolution imagery, radar, InSAR
	T	0.01	15	m / yr	1	cm	10	m	1	yr	Same; InSAR
	O	0.01	15	m / yr	1	cm	10	m	1	yr	Same; InSAR
Annual surface elevation change	C	0	1	m	1	cm	Point		1	yr	In situ survey transects, LIDAR maps, InSAR
	T	0	1	m	1	cm	10	m	1	yr	
	O	0	1	m	1	cm	1	m	1	yr	
Ground ice volume	C	0	100	Vol %	5-10	Vol %	Point		One time		In situ measurements (sampling during borehole drilling)
	T	0	100	Vol %	5	Vol %	1	m			Geophysical investigations
	O	0	100	Vol %	5	Vol %	0.1	m			
Active Layer[1]											**Areas underlain by permafrost**
Active layer depth	C	0	5	m	1	cm	Point		1	yr	In situ measurements (maximum value at end of summer, key GTN-P parameter)
	T	0	5	m	1	cm			7	day	
	O	0	5	m	1	cm			7	day	
Soil temperature[2]	C	-60	35	^{0}C	0.1	K	Vertical profile		1	day	10 cm interval to 1.2m on data recorder; GTOS TEM parameter
	T	-60	35	^{0}C	0.05	K			6	hr	
	O	-60	35	^{0}C	0.05	K			6	hr	

Surface temperature	C	-70	45	^{0}C	1	K	1	km	1	day	MODIS
	T	-70	45	^{0}C	1	K	100	m	1	day	
	O	-70	45	^{0}C	1	K	10	m	0.5	day	
Soil moisture[2]	C	0		Vol %	1-5	Vol %	Point		1	day	Monitored continuously at some locations, or based on sampling during drilling or soil pits; GTOS TEM parameter
	T	0		Vol %	1-5	Vol %	1	m			Same; SAR
	O	0		Vol %	1-5	Vol %	0.1	m			Same; SAR
Duration of thaw	C	0	365	days	14	d	Point		1	day	Computed from weather records and inferred or measured from
	T	0	365	days	7	d	1	km			
	O	0	365	days	7	d	100	m			
Seasonal frost heave / thaw subsidence	C	0	100	cm	1	cm	Point		0.5	yr	In situ survey transects, LIDAR maps, InSAR
	T	0	100	cm	1	cm	10	cm			
	O	0	100	cm	1	cm	1	cm			
Seasonally Frozen Ground[1]											**Areas not underlain by permafrost and beyond limits of permafrost**
Onset of seasonal freezing	C	0	365	days	14	d	Point		14	day	Determined from interpolation of soil temperature profiles or frost tubes; passive microwave
	T	0	365	days	7	d	1	km	7	day	
	O	0	365	days	7	d	100	m	7	day	
Depth of seasonal freezing	C	0	4	m	1	cm	Point		1	yr	Determined from interpolation of soil temperature profiles or frost tubes; passive microwave
	T	0	4	m	1	cm			7	day	
	O	0	4	m	1	cm			7	day	
Duration of freeze	C	0	365	days	14	d	Point		1	day	Computed from weather records and inferred or measured from
	T	0	365	days	7	d	1	km			
	O	0	365	days	7	d	100	m			
Distribution of seasonal freezing	C	0	100	%		%	25	km	5	day	Microwave (passive and active) sensors at regional scale; sequential
	T	0	100	%		%	10	km			
	O	0	100	%		%	1	km			
Coastal Dynamics											
Coastal retreat	C	0	30	m / yr	0.5	m / yr	Point		1	yr	Ground surveys, DGPS, aerial photos, high-resolution satellite
	T	0	30	m / yr	0.25	m / yr	0.25	m			
	O	0	30	m / yr	0.25	m / yr	0.25	m			
Isostatic vertical motion	C	0	15	cm / yr	1	mm	Point		1	yr	DGPS
	T	0	15	cm / yr	1	mm	1	km			DGPS, LIDAR, Laser Altimetry,
	O	0	15	cm / yr	1	mm	1	km			
Wind speed and direction	C	0		m / s	0.1	m / s	Point		1	min	Anemometer
	T	0		m / s	0.1	m / s					
	O	0		m / s	0.1	m / s					

Storm surge	C	NA	NA	NA	NA	NA	NA		NA		NA
	T						25	m	1	day	Time-lapse camera, tide gauge, Opportunistic SAR
	O						25	m	1	hr	
Sediment transport	C	NA	NA	NA	NA	NA	NA		NA		NA
	T						250	m	7	day	MODIS
	O						250	m	1	day	
Sea ice extent	see Sea Ice table										
Ice scouring depth	C			cm	10	cm		m			Multi-beam sonar
	T				10	cm		m			
	O				10	cm		m			
Ice scouring area	C	0	100	%	20	%	10	m			Multi-beam sonar
	T	0	100	%	10	%	1	m			
	O	0	100	%	10	%	1	m			
Subsea permafrost distribution	C	0	100	%		%	10	km	10	yr	Boreholes, multibeam sonar, shallow seismic
	T	0	100	%		%	1	km	10	yr	
	O	0	100	%		%	1	km	1	yr	
Subsea permafrost thickness	C	0	500	m	1	m	Point		10-100	yr	Boreholes, multibeam sonar, shallow seismic
	T	0	500	m	1	m			10	yr	
	O	0	500	m	1	m			10	yr	

[1] includes all aspects of snow cover.

[2] applies also to seasonally frozen ground

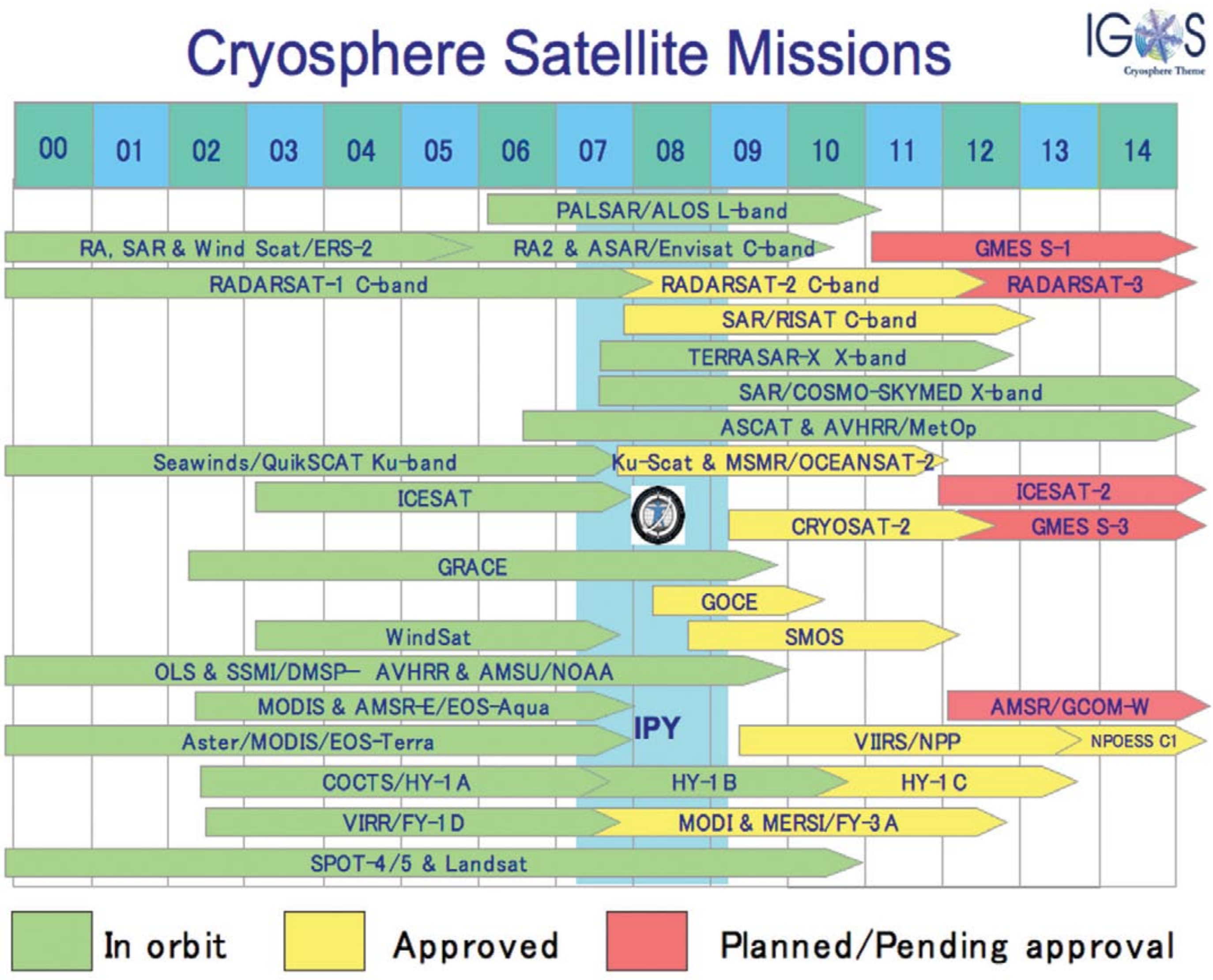
Table B.9. Summary of current/planned capabilities and requirements for snowfall parameters. (Adopted from http://www.nosa.noaa.gov/requirements.html)

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment or Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Snowfall amount	C	0	100	mm	1	mm	1	km	1	day	MODIS/ SSMI
	T	0	100	mm	1	mm	0.5	km	1	day	Hydromet
	O	0	100	mm	1	mm	0.1	km	12	hr	
Precipitation/ Snowfall rate	C	0	100	mm/ hr	2-10	cm	25	km	1	day	AMSR-E/ TRMM
	T	0	100	mm/ hr	3	cm	0.5	km	1	day	Hydromet Transportation
	O	0	100	mm/ hr	2	cm	0.1	km	12	hr	
Precipitation type	C	NA	---	---	---	---	---	---	---	---	Need HF SAR
	T	0.3	3		10	%	0.5	km	1	day	Hydromet
	O	0.3	3		7	%	0.1	km	12	hr	
Snow particle size	C	0	~0.7		6-35		25	km	1	day	e.g. AMSR-E
	T	0	1		10		0.5	km	1	day	Hydromet
	O	0	1		6		0.1	km	1	hr	

C Satellite Missions in Support of the Cryosphere Theme

Figure C.1 gives a timeline for current and future satellite sensors that can be used to estimate properties of the cryosphere. Table C.1 lists sensors and satellites for key cryospheric variables.

Fig. C.1. Timeline of current and future satellites.



C Satellite Missions in Support of the Cryosphere Theme

Table C.1. Current and future satellites and sensors for key cryospheric variables and quantities.

Sensor types	Laser altimeter	Radar altimeter	High-res Radar (SAR)	Low-res radar (Scat)	High-res vis/IR	Mid-res vis/IR	Passive Microwave	Gravity
Satellites and Sensors	ICESat	ERS-2, Envisat, CryoSat-2, GMES-Sentinel-3	ERS-2 SAR, Envisat ASAR, Radarsat1-2, ALOS-PALSAR, TERRASAR-X, COSMO-SKYMED, RISAT, GMES-Sentinel-1	ERS2-Wind Scat, QuikScat, MetOp-ASCAT, OCEANSAT-2, HY-2A Scat	SPOT 1-5, Landsat, ASTER, GMES Sentinel-2	AVHRR, Landsat-TM/ETM+, DMSP-OLS, MODIS, VIIRS, HY-1,	SSMI, AMSR-E, Windsat, SMOS, HY-2A	GRACE, GOCE
Ice Sheets	Elevation/ Thickness change	Elevation/ Thickness	Motion, Extent	Extent, Snow/Ice Facies		Extent	Melt/Freeze onset	Mass change
Glaciers and Ice Caps	Surface topography and change	Surface topography and change	Velocity, topography, facies, lakes	Facies	Extent, velocity, snowline	Extent		Mass change
Sea Ice	Freeboard/ Thickness	Freeboard/ Thickness	Motion, Extent, Floe Size Distribution	Extent, Melt/Freeze Onset, Motion	Floe Size Distribution, Meltponds	Extent	Extent, Concentration, Snow thickness	Geoid
Snow	Accumulation	Accumulation	Accumulation	Accumulation		Extent	Extent, Thickness	Mass Loading
Solid Precipitation and SWE								Mass Loading
Temperature					*	*	*	
Albedo					*	*		
Lake and river ice	Thickness		Motion, Extent	Extent, Melt/Freeze Onset	Floe Size Distribution, Meltponds	Extent	Extent, Snow thickness	
Permafrost and frozen ground			Motion, slope failures, surface deformation, thermokarst subsidence	Freeze-thaw status of the active layer	Coastal erosion, Thermokarst, mapping of permafrost surface indicators	Land cover mapping, land cover change, near surface temperatures, thermokarst mapping	Freeze-thaw status of the active layer	Mass change due to ground ice melting

D Acronyms

AAO	Antarctic Oscillation
ACCO-Net	Arctic Circum-Polar Coastal Observatory Network
ACD	Arctic Coastal Dynamics
ACIA	Arctic Climate Impact Assessment
ACSYS	WCRP Arctic Climate System Study
ADEOS	Advanced Earth Observing Satellite
AIDJEX	Arctic Ice Dynamic Experiment
AIRS	Atmospheric InfraRed Sounder
ALISON	Alaska Lake Ice and Snow Observatory Network
ALOS	Advanced Land Observing Satellite
ALTM	Airborne LASER Terrain Mapper
AMAP	Arctic Monitoring and Assessment Programme
AMM	Antarctic Mapping Mission
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AO	Arctic Oscillation
AOPC	Atmospheric Observation Panel of GCOS
AOSB	Arctic Ocean Sciences Board
Arctic HYCOS	Arctic (component) of WHYCOS
ARGPS	Antarctic RGPS
ARM	Atmospheric Radiation Measurement Program
ASAR	Advanced SAR
ASOS	Automated Surface Observing System
ASF	Alaska Satellite Facility
ASR	Arctic System Reanalysis
ASPeCt	Antarctic Sea Ice Processes and Climate
AVHRR	Advanced Very High Resolution Radiometer
AUV	Autonomous Underwater Vehicle
AWS	Automatic Weather Station
BOREAS	Boreal Ecosystem-Atmosphere Study
BTS	Basal temperature of snow
BU	Break-up (date)
CALM	Circumpolar Active Layer Monitoring
CAPP	Carbon Pools in Permafrost Regions Project
CASA	Collaborative Adaptive Sensing of the Atmosphere
CASO	Climate of Antarctica and Southern Ocean
CCC	Canadian Centre for Climate
CEOP	Coordinated Enhanced Observing Period
CEOS	Committee on Earth Observing Satellites
CERES	Clouds & The Earths Radiant Energy System
CDR	Climate Data Record
CFO	Complete freeze-over
CGMS	Coordination Group for Meteorological Satellites
CHAMP	CHAllenging Mini-satellite Payload
CID	Canadian Ice Database
CIMO	WMO Commission for Instruments and Methods of Observation
CIS	Canadian Ice Service
CliC	WCRP Climate and Cryosphere project
CMC	Canadian Meteorological Centre
CMIS	Conical Scanning Microwave Imager/ Sounder
CNES	Centre National des Etudes Spatiales, France
COSPAR	Committee on Space Research (member of ICSU)
COPES	Coordinated Observation and Prediction of the Earth System
CryoNet	Cryospheric Network
CryOS	Cryosphere Observing System
CreSIS	Center for Remote Sensing of Ice Sheets
CSA	Canadian Space Agency
CSIRO	Commonwealth Scientific and Industrial Research Organization, Australia
DARMS	Drifting Automatic Radio-Meteorological Station
DAAC	Distributed Active Archive Centers
DAMOCLES	Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies
DEM	Digital Elevation Model
DInSAR	Differential InSAR
DIS	(IPY) Data and Information Service
DISC	Data and Information Service for CliC
DMSP	Defense Meteorological Satellite Program
DOE-ARM	U.S. Department of Energy’s Atmospheric Radiation Measurement
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EGPM	European Global Precipitation Mission
EM	Electro-magnetic
ENSO	El Nino and the Southern Oscillation
ENVISAT	Environmental Satellite
EOS	NASA Earth Observing System
ERS	European Remote Sensing
ESA	European Space Agency
ESSP	Earth System Science Partnership
ETM+	Enhanced Thematic Mapper

D Acronyms

EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FLAR	Forward Looking Airborne Radar
FOV	Field-of-view
FU	Freeze-up (date)
GCM	General Circulation Model
GCMD	Global Change Master Directory
GCMP	GCOS Climate Monitoring Principles
GCOS	Global Climate Observing System
GCW	WMO Global Cryosphere Watch
GEMS	Global Environment Monitoring Program
GEO	Geostationary satellites
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GEWEX	WCRP Global Energy and Water Cycle Experiment
GHOST	Global Hierarchical Observing Strategy
GIIPSY	Global Inter-Agency IPY Polar Snapshot Year
GIP	GCOS Implementation Plan
GIS	Geographic Information System
GLIMS	Global Land-Ice Measurement from Space
GLOF	Glacial Lake Outburst Flood
GLOSS	Global Sea-Level Observing System
GLRID	Global Lake and River Ice Phenology Database
GMDSS	Global Maritime Distress and Safety System
GMES	Global Monitoring for Environment and Security
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GOES	Geostationary Operational Environmental Satellites
GOOS	Global Ocean Observing System
GOS	Global Observing System
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Mission
GPR	Ground-penetrating radar
GPS	Global Positioning System
GRA	GOOS Regional Alliance
GrADS	Grid Analysis and Display System
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
GSWP	Global Soil Wetness Project
GTN-G	Global Terrestrial Network for Glaciers
GTN-H	Global Terrestrial Network for Hydrology
GTN-L	Global Terrestrial Network for Lakes
GTN-P	Global Terrestrial Network for Permafrost
GTOS	Global Terrestrial Observing System
GTS	Global Telecommunicatons System of WMO
GWSP	Global Water System Project
HELP	Hydrology for Environment, Life and Policy
HIRS	High resolution Infrared Radiation Sounder
HYDROS	Hydrosphere State mission
IABP	International Arctic Buoy Program
IAHS	International Association of Hydrologic Sciences
iAOOS	Integrated Arctic Ocean Observing System
ICARP	International Conference on Arctic Research Planning
ICESat	Ice, Cloud, and land Elevation Satellite
ICSU	International Council of Scientific Unions
IDN	International Directory Network
IFOV	Instantaneous field of view
IGOS	Integrated Global Observing Strategy
IGOSP	Integrated Global Observing Strategy Partnership
IGWCO	International Global Water Cycle Observation
INPO	International Network of Permafrost Observatories
InSAR	Interferometric SAR
IOC	Intergovernmental Oceanographic Commission of UNESCO
IPA	International Permafrost Association
IPAB	WCRP/SCAR International Programme for Antarctic Buoys
IPCC	Intergovernmental Panel on Climate Change
IPS	Ice Profiling Sonar
IPY	International Polar Year 2007-2008
IPWG	International Precipitation Working Group
IR	Infra-red
ISCCP	International Satellite Cloud Climatology Project
ISO	International Organization for Standardization
IHDP	International Human Dimensions Programme
ITU	International Telecommunication Union
IUGG	International Union of Geodesy and Geophysics
JAMSTEC	Japan Agency for Marine-Earth Science and Technology

JAXA	Japan Aerospace Exploration Agency
J-CAD	JAMSTEC Compact Arctic Drifter
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
JERS	Japanese Earth Resources Satellite
JRA	Japanese Reanalysis
LASER	Light amplification by stimulated emission of radiation
LEO	Low earth orbit
LIA	Little Ice Age
LIDAR	Light Detection and Ranging
LTER	Long-term Ecological Research
MASTER	MODIS/ASTER
MW	Micro-wave
MIP	Model Intercomparison Project
MISR	Multi-angle Imaging SpectroRadiometer
MIZ	Marginal Ice Zone
MetOp	Meteorological Operational (satellite)
MODIS	Moderate Resolution Imaging Spectroradiometer
MRR	Micro-Rain-Radar
MSA	Methanesulphonic Acid
MSU	Microwave Sounding Unit
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
NARR	North American Regional Reanalysis
NASA	National Aeronautic and Space Administration (USA)
NASDA	National Space Development Agency (Japan), now called JAXA
NCEP	National Centers for Environmental Prediction (USA)
NEESPI	North Eurasian Earth Science Partnership Initiative
NESDIS	National Environmental Satellite Data and Information Service (USA)
MHMS	National Hydrological and Meteorological Service
NOAA	National Oceanic and Atmospheric Administration (USA)
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRT	Near real time
NSCAT	NASA Scatterometer
NSIDC	National Snow and Ice Data Center (USA)
NSF	National Science Foundation
NWP	Numerical Weather Prediction
NWS	National Weather Service, U.S.
OLS	Optical Line Scanner
OOPC	Ocean Observation Panel for Climate
OPA	Open Program Area
PACE	Permafrost and Climate in Europe
PALSAR	Phased Array type L-band SAR
PARCA	Program for Arctic Regional Climate Assessment
PMW	Passive Microwave
POES	Polar-orbiting Operational Environmental Satellites
POSS	Precipitation Occurrence Sensing System
QPE	Quantitative precipitation estimation
RGPS	Radarsat Geophysical Processing System
SAM	Southern Annular Mode
SAR	Synthetic Aperture Radar
SBA	Societal Benefit Areas of GEOSS
SCAR	Scientific Committee on Antarctic Research
SCICEX	Scientific Ice Expedition
SCOBS	Subcommittee on Observations
SeaBASS	SeaWiFS Bio-optical Archive and Storage System
SEARCH	US Study of Environmental Arctic Change
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SHEBA	Surface Heat Budget of the Arctic Ocean
SLAR	Side-Looking Airborne Radar
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Surface Moisture – Ocean Salinity
SNOTEL	Snow Telemetry
SPOT	Satellite Earth Observation System by Centre National d'Etudes Spatiales
SRTM	Shuttle Radar Topography Mission
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
STG	Space Task Group
SWE	Snow Water-Equivalent
TARR	Third Assessment Report (of IPCC)
TEMS	Terrestrial Ecosystem Monitoring Sites
THIR	Temperature Humidity Infrared Radiometer
TIR	Thermal Infrared Sensor
TM	Thematic Mapper
TOVS	TIROS Operational Vertical Sounder
TSP	Thermal State of Permafrost
TRMM	Tropical Rainfall Measuring Mission
UAV	Unmanned Aerial Vehicle
ULS	Upward Looking Sonar
UCCS	IUGG Commission for Cryospheric Sciences
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme

UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	US Department for Agriculture
USGS	US Geological Survey
VIIRS	Visible Infrared Imager Radiometer Suite (NPOESS)
Vis	Visible
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modelling (CLIVAR)
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service
WGNE	Working Group on Numerical Experimentation (WCRP)
WHYCOS	World Hydrological Cycle Observing System
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
WMO WWW	WMO World Weather Watch
WOAP	WCRP Observation and Assimilation Panel
WWRP	World Weather Research Programme
XML	Extensible Markup Language

E Contributors

The core team consists of:

Jeff Key, Chair
National Oceanic and Atmospheric Administration
Madison, Wisconsin USA

Mark Drinkwater, Vice-chair
European Space Agency
Noordwijk, The Netherlands

Jinro Ukita, Vice-chair
Chiba University
Chiba, Japan

Vladimir Ryabinin
Joint Planning Staff of the WCRP
Geneva, Switzerland

Marzena Kaczmarska
SCAR, Scott Polar Research Institute
Cambridge, UK

Barry Goodison
Meteorological Service of Canada
Ottawa, Canada

Victoria Lytle
CliC International Project Office
Tromsø, Norway

Colin Summerhayes
SCAR, Scott Polar Research Institute
Cambridge, UK

Don Hinsman (liaison to IGOS)
WMO Secretariat
Geneva, Switzerland

The main authors are:

Jerry Brown
International Permafrost Association, USA

Don Cline
National Oceanic and Atmospheric Administration, USA

Josefino Comiso
National Aeronautics and Space Administration, USA

Claude Duguay
University of Waterloo, Canada

Guido Grosse
University of Alaska-Fairbanks, USA

Ken Jezek
Ohio State University, USA

Paul Joe
Meteorological Service of Canada, Canada

Boele Kuipers
Norwegian Polar Institute, Norway

Rob Massom
Australian Government Antarctic Div.; Antarctic Clim.
Ecosys. Coop. Res. Centre, Australia

Walt Meier
National Snow and Ice Data Center, USA

Frank Paul
University of Zurich, Switzerland

Helmut Rott
Universitaet Innsbruck, Austria

Sharon Smith
Geological Survey of Canada, Canada

Stein Tronstad
Norwegian Polar Institute, Norway

Daqing Yang
University of Alaska-Fairbanks, USA

Tingjun Zhang
National Snow and Ice Data Center, USA

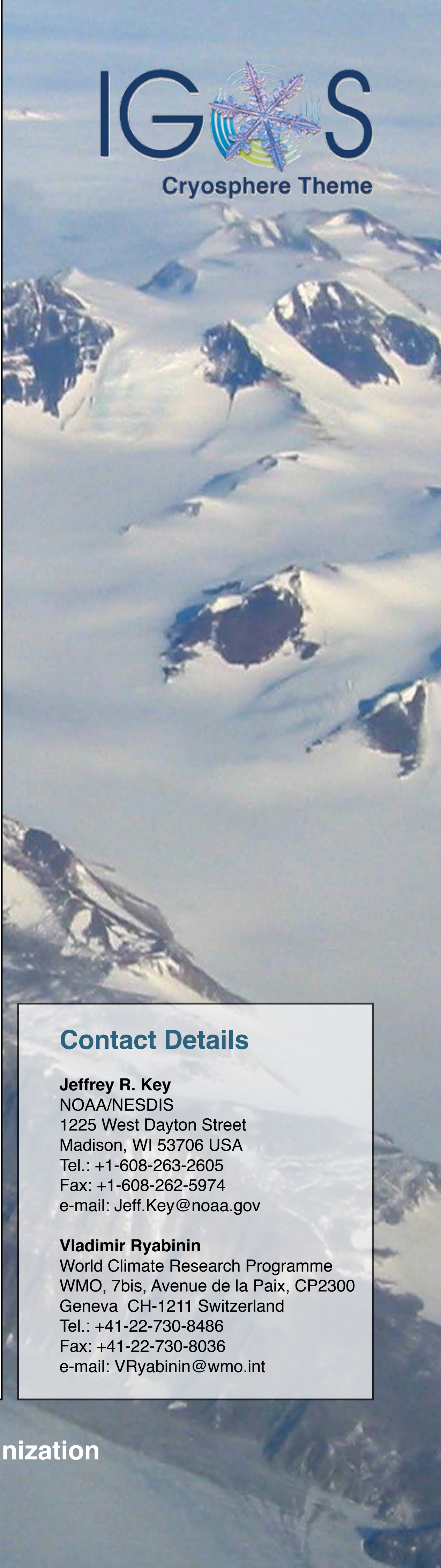
Editorial Assistance provided by:

Angélique Prick
CliC International Project Office, Norway

Jennifer O'Leary
University of Wisconsin-Madison, USA

Other contributors and reviewers are listed at http://igos-cryosphere.org.

IGOS
Cryosphere Theme



The IGOS Partners

CEOS
Committee on Earth Observation Satellites
http://www.ceos.org

FAO
Food and Agriculture Organization of the United Nations
http://www.fao.org

GCOS
Global Climate Observing System
http:// www.wmo.ch/web/gcos

GGOS
Global Geodetic Observing System
http://www.ggos.org

GOOS
Global Ocean Observing System
http://www.ioc-goos.org

GAW
WMO Global Atmospheric Watch
http://www.wmo.ch/web/arep/gaw/gaw_home.html

GTOS
Global Terrestrial Observing System
http://www.fao.org/gtos

ICSU
International Council for Science
http://www.icsu.org

IGFA
International Group of Funding Agencies for Global Change Research
http://www.igfagcr.org

IOC of UNESCO
Intergovernmental Oceanographic Commission of UNESCO
http://ioc.unesco.org

UNEP
United Nations Environment Programme
http://www.unep.org

UNESCO
United Nations Educational, Scientific and Cultural Organization
http://www.unesco.org

WCRP
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http://wcrp.wmo.int

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Contact Details

Jeffrey R. Key
NOAA/NESDIS
1225 West Dayton Street
Madison, WI 53706 USA
Tel.: +1-608-263-2605
Fax: +1-608-262-5974
e-mail: Jeff.Key@noaa.gov

Vladimir Ryabinin
World Climate Research Programme
WMO, 7bis, Avenue de la Paix, CP2300
Geneva CH-1211 Switzerland
Tel.: +41-22-730-8486
Fax: +41-22-730-8036
e-mail: VRyabinin@wmo.int

Printed by the
World Meteorological Organization