State and fate of the polar cryosphere, including variability of the Arctic hydrological cycle

by B. Goodison[1], J. Brown[2], K. Jezek[3], J. Key[4], T. Prowse[5], A. Snorrason[6] and T. Worby[7]

Introduction

The cryosphere collectively describes elements of the Earth system which contain water in its frozen state and include sea, 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. The cryosphere is inseparable from the polar freshwater system on land, on ice and on the sea.

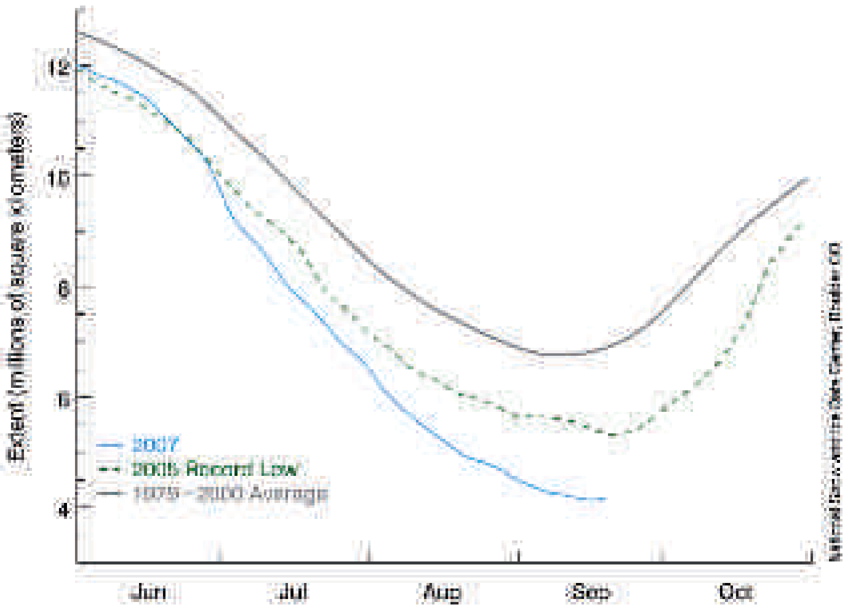


Figure 1 — Arctic sea ice extent in the summer melt season (area of ocean with at least 15 per cent sea ice)

The cryosphere, its changes and its impacts receive not only increased scientific scrutiny but now constant coverage by the media, creating an unparallelled demand for data and information on past, present and future changes of our snow and ice resources. The rate of reduction of many snow and ice masses over the past decade continues to increase (Lemke et al., 2007). Loss of the ice cover is expected to affect the Arctic's freshwater system and surface energy budget and could be manifested in middle latitudes as altered patterns of atmospheric circulation and precipitation (Serreze *et al.*, 2007). Most recently, the 2007 Arctic sea-ice decline set a new record absolute minimum already in August 2007 with extent continuing to decline until mid-September 2007 (Figure 1), capturing the attention of policy-makers as the prospects for new trans-Arctic sea routes loom ever closer. Adequate knowledge of the cryosphere is essential for polar and global science applications, including weather and climate prediction, assessment and prediction of sea-level rise, availability of freshwater resources, navigation, transportation,

1 Chair, WCRP/CliC SSG and Science Manager IPY, Environment Canada, Ottawa Canada. barry.goodison@ec.gc.ca
2 President, International Permafrost Association, P.O. Box 7, Woods Hole MA 02543 USA. jerrybrown@igc.org
3 Polar Research Center, School of Earth Sciences, Ohio State University, Columbus, Ohio, USA. jezek.1@osu.edu
4 NOAA/NESDIS, 1225 West Dayton St., Madison, WI 53706 USA. jkey@ssec.wisc.edu
5 Research Scientist, Environment Canada & University of Victoria, Victoria Canada.terry.prowse@ec.gc.ca
6 Hydrological Service, National Energy Authority, Grensasvegur 9, IS-108 Reykjavik, Iceland. asn@os.is
7 Senior Research Scientist, Australian Antarctic Division, Hobart, Australia. A.Worby@utas.edu.au

fishing, mineral resource exploration and exploitation and construction in cold climate regions. Yet the cryosphere is arguably the most undersampled domain in the climate system. The timing of IPY 2007-2008 for observing and increasing our knowledge about the rapid change in our polar regions could not have been more appropriate. IPY cryosphere projects are now being implemented. A selection of plans and review of progress of some of the IPY initiatives to better understand the cryosphere and related hydrological components follows.

State and fate of the cryosphere

The State and Fate of the Cryosphere (IPY 105) provides a framework to understand the state of the cryosphere and its associated past, present and future variability and change in time and space. The aim is to document not only changes to the global cryosphere but also to highlight the diverse impacts of these changes on understanding the polar environment in terms of its physical and biogeochemical interactions with the ocean, atmosphere and terrestrial systems and the impacts on, and interactions with, social, cultural and economic systems. It will:

- Assess the current state of cryospheric parameters in high-latitude regions, providing a snapshot of the cryosphere and an evaluation of its current (IPY) state in the context of past states and projections of the future;

- Formulate the observational requirements of cryospheric variables for weather, climate and hydrological monitoring and prediction and for other environmental assessments (Integrated Global Observing Strategy Theme on Cryosphere (IGOS-Cryo));

- Strengthen international cooperation in the development of cryospheric observing systems.

A global, quantitative assessment of the current state of cryospheric and related hydrological parameters draws on results from many IPY and ongoing scientific studies. IPY-funded Arctic and bipolar projects related to climate, including those involving cryosphere and hydrology, can be found at http://clic.npolar.no/reports/archive/ipy_fnd_proj_cipo_22May07.xls.

The cryosphere observing system: legacy of IPY 2007-2008

International Polar Year 2007-2008 provides a unique opportunity to develop polar observing systems and, by doing so, close one of the most critical gaps in global observations. A key goal of the State and Fate of the Cryosphere Project has achieved significant success—the Integrated Global Observing Strategy Theme on Cryosphere (IGOS-Cryo). One of the near-term goals of the World Climate Research Programme (WCRP) Climate and Cryosphere (CliC) Project is to help ensure that IPY is not just a "blip", but that there is a legacy of infrastructure, observational systems and data management which remains after IPY.

CliC and several partners, including the co-sponsor, the Scientific Committee on Antarctic Research (SCAR), are developing the conceptual framework for CryOS (Figure 2)—a sustained, robust observing system for the cryosphere and a crucial element of the future multidisciplinary observing system. Current observational capabilities, requirements for observations and higher-level products and recommendations for actions needed to further develop CryOS are documented in the recently approved IGOS-Cryosphere Theme Report (http://igos-cryosphere.org).

The initial phase of CryOS development coincides with IPY. The approach is to engage relevant IPY projects and increase coordination between them with the objective of producing legacy datasets and the capability to extend them continuously after the end of IPY. 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. 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 for the near-, mid- and long-term. There are many near-term recommendations for during the IPY, two examples being to:

- Ensure coordinated interagency planning of the IPY polar snapshot and achieve better continuity in higher-level polar data products from existing satellites, for the IPY legacy dataset;

- Supplement sparse and sporadic basic *in situ* observation networks for precipitation, snow water equivalent, permafrost borehole temperatures, ice sheet core properties, met/ocean/ice mass balance tracked buoys, and mountain glaciers; and plan the selection and augmentation of at least 15 reference "supersites" of integrated monitoring with suites of relevant cryospheric measurements (e.g. by augmenting existing Coordinated Enhanced Observing Period sites and/or Global Terrestrial Network (GTN) sites).

Adopting the recommendations will ensure that IPY legacy datasets are available as benchmarks for gauging future climate variability and change, that important *in situ* observational networks are reinvigorated, that plans are made for follow-on programmes for key spaceborne sensors (e.g.

NASA/Goddard Space Flight Center Scientific Visualization Studio

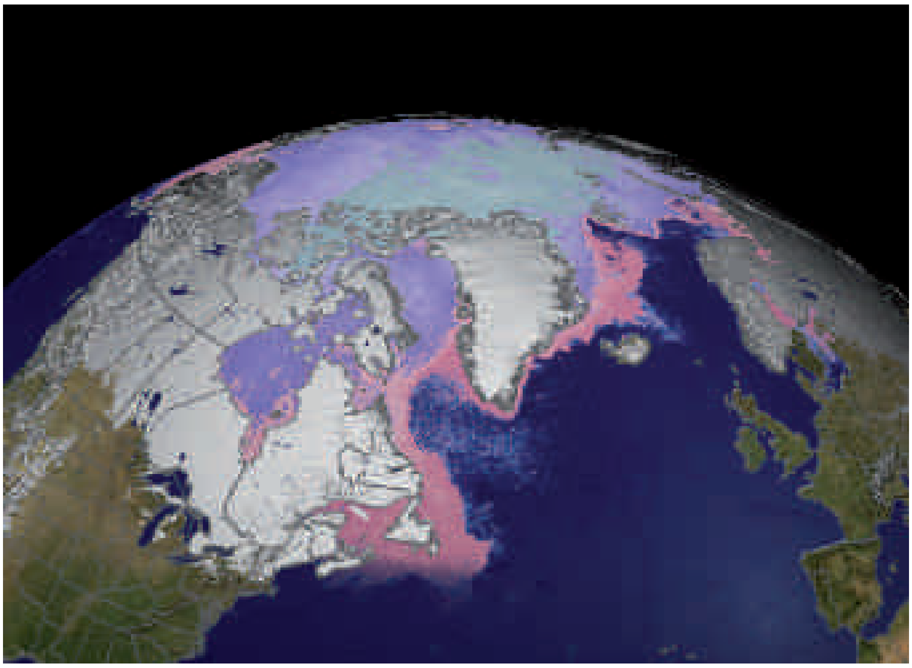


Figure 2 — The CryOS vision offers the potential to realize a complete picture of cryosphere components within the next 10-15 years. This satellite picture (moderate-resolution imaging spectroradiometer) of snow cover, sea-ice temperature, glaciers and ice sheets across the Arctic illustrates the diversity of the cryosphere .

passive microwave imaging systems) and that innovative data-management systems deliver data and geographic information system services to the science community, policy-makers, and the public. National Meteorological and Hydrological Services and space agencies have a leading role to play for these recommendations to be turned into practice.

Global Interagency IPY Polar Snapshot Year (GIIPSY)

Satellite data are critical in the derivation of new high-latitude cryosphere products, as *in situ* data are sparse or non-existent in these remote regions. The first achievements of CryOS are in the area of coordination of satellite observations of the cryosphere. A project entitled "Global Interagency IPY Polar Snapshot Year (GIIPSY)" (IPY 91) aims to obtain high-resolution, broad spectral snapshots of the polar regions during 2007-2008.

The primary purpose is to use these snapshots as gauges for comparing past and future environmental changes in the polar ice, ocean and land. In the spirit of the International Geophysical Year (IGY), the goal is to secure these datasets as our legacy to the next generation of polar scientists. The programmatic goal is to identify ways in which the resources of all space-faring countries can be used in such a way as to achieve our science objectives without putting a burden on any single organization. A general description of the GIIPSY programme, including observational objectives, is at http://www-bprc.mps.ohio-state.edu/rsl/GIIPSY/. Those systems available for cryospheric studies are shown in Figure 3. GIIPSY will generate a number of unprecedented datasets contributing to studies of sea-level rise and hemispheric climate, ocean circulation and polar air-sea interactions, regional climate, polar precipitation and hydrology, permafrost and Arctic aquatic ecosystems, transportation and hazards. CryOS is certainly considered as "an early success" of IPY.

Arctic Hydra—a new integrated study of the Arctic hydrological cycle

The cryospheric system is inseparable from the freshwater system. The temperature, salinity, sea ice and circulation of the Arctic Ocean strongly depend on the inflow of fresh water. In assessing the agreement in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) climate models, Waliser (2007) noted that good model agreement occurs where there is a robust observational basis and the quantities are physically unambiguous. Components involving frozen water typically exhibit the worst agreement and fluxes generally exhibit better agreement than reservoirs. Storage and flux estimates for the pan-Arctic water cycle, synthesizing existing literature-based estimates and modeling results, have been recently reported (Serreze *et al.*,2006). Through its integrated monitoring systems, including integrated hydrographic stations, IPY Arctic-HYDRA will help to provide a new level of consistency not previously available in the baseline information from which these syntheses can be drawn.

Arctic-HYDRA (IPY 104) is a consortium-based international study to provide a quantitative picture of the state of the pan-Arctic hydrological system (Figure 4) during the IPY campaign. The main goals of the project are to:

- Characterize variability in the Arctic Hydrological Cycle (AHC) and to examine linkages between atmospheric forcing and continental discharge to the ocean;
- Assess the historical response of the Arctic Ocean to variations in freshwater input from rivers and net precipitation over the ocean;

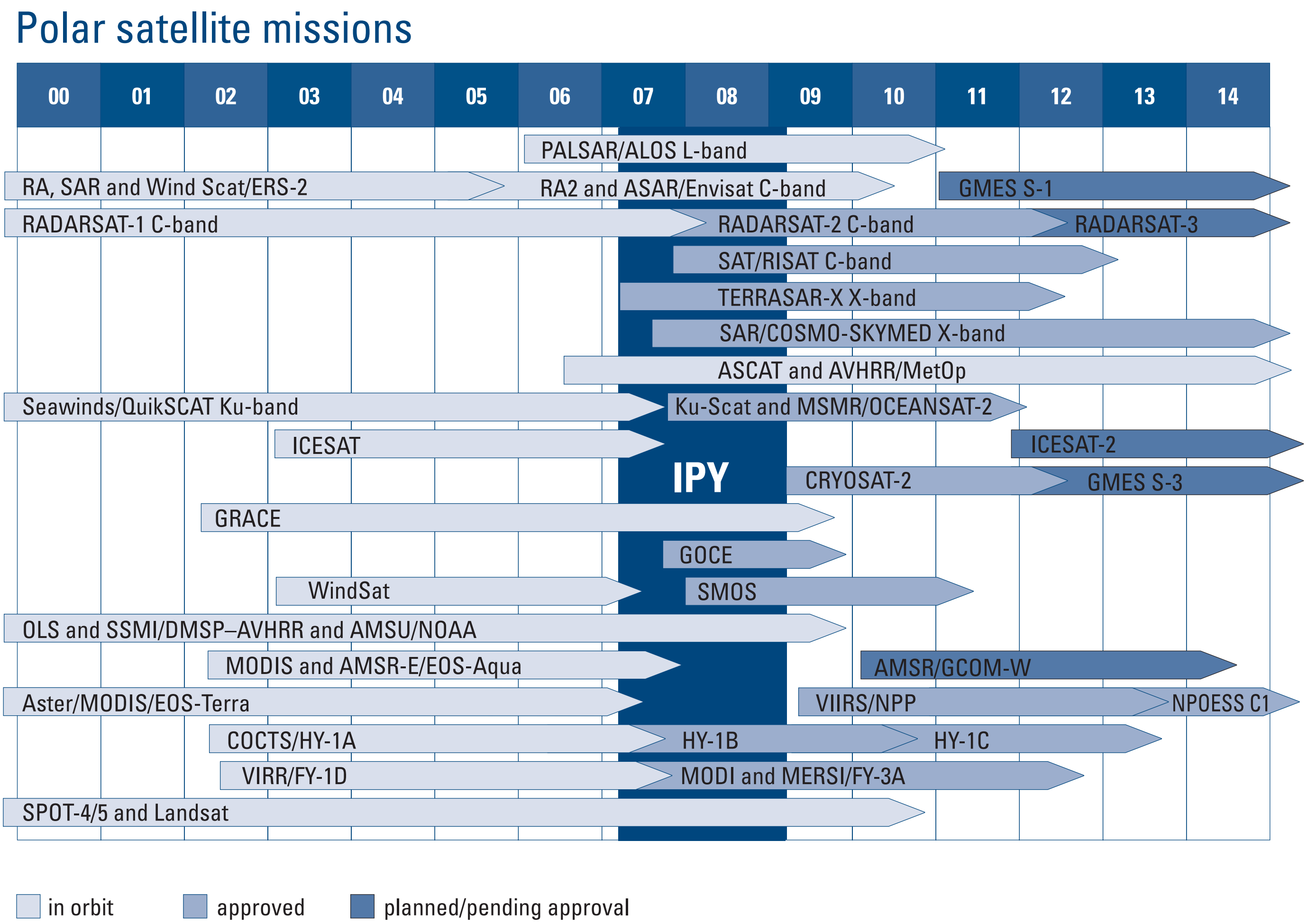


Figure 3 — Timeline of the cryosphere satellite missions

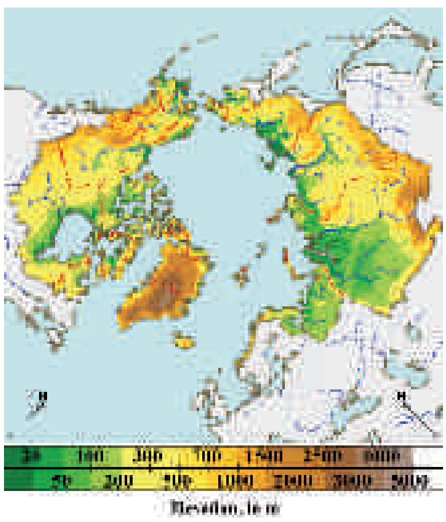
- Attribute to specific elements of the AHC or to external forcing the sources of observed spatial-temporal variability in the land-ocean-ice-atmosphere system;

- Detect emerging changes in the contemporary state of the AHC in near-real-time and to place such changes into a broader historical context.

Given the scope of these goals and the relatively short time-frame of the IPY, Arctic-HYDRA also forms part of the parallel longer term (10- to 15-year) objectives of the International Conference on Arctic Research Planning (ICARP) Working Group 7 project— Terrestrial Cryospheric and Hydrologic Processes and Systems.

Canada has an IPY activity that will make a major contribution to Arctic-HYDRA. A key component is freshwater flux research and prediction, which aims to quantify key hydrological/cold region processes/parameters affecting freshwater flux to the Arctic Ocean, validate and improve coupling of hydrological/land-surface models to predict freshwater flow/flux to the Arctic Ocean and provide an improved assessment of the hydro-climatology of the Canadian Arctic. This component is, in turn, linked to aquatic ecosystems, through nutrient flux research and prediction initiatives, to aquatic ecosystem hydro-ecology and ecological integrity and to community-based monitoring, hence providing an integrated view of the northern freshwater aquatic systems.

To optimize synergies between the hydrological and ecosystem components and to build on existing research programme infrastructure, the Mackenzie region was selected as the "supersite" location for the more intensive process-based experimental field work and data collection. In addition, there will be data from nine new Arctic stations made available through Water Survey of Canada. These studies will contribute to improved climate modelling at the regional scale and within numerical weather prediction systems. Such



Arctic-RIMS, http://rims.unh.edu/

Figure 4 — Arctic-HYDRA will promote a fully pan-Arctic perspective for its IPY water studies.

results will extend beyond the scope of the IPY, and will provide a basis for future studies in these northern regions.

The planning and implementation of Arctic-HYDRA, and many IPY studies involving fieldwork and modelling studies, require input from such regional studies and will benefit from experience gained in similar projects conducted during the pre-IPY period, such as the Nordic study on Climate and Energy (http://www.os.is/ce/).

National/regional terrestrial cryospheric contributions

The Variability and Change in the Canadian Cryosphere builds on the Canadian CRYSYS project, on Canadian strengths in remote-sensing, climate analysis and modelling and operational activities. It was designed to make a signicant contribution to WCRP/CliC's State and Fate of the Cryosphere project. It extends an earlier study on Canadian Cryospheric response during the extremely warm summer of 1998 (Atkinson *et al.*, 2006). This project will:

- Provide information on the current state of the Canadian cryosphere during IPY as a contribution to the IPY snapshot and its legacy datasets;
- Place current cryospheric conditions in the context of the historical record to document the magnitude of changes over the 50 years since International Geophysical Year (IGY 1957-1958);
- Characterize and explain the observed variability and changes in the context of the coupled climate-cryosphere system; and
- Improve the representation of the cryosphere in Canadian land-surface and global and regional climate models to provide current and future climate simulations of the cryosphere for climate impact and adaptation studies.

Key components are the further development of the Canadian data portal to the IPY Distributed Information System and development of outreach activities to incorporate traditional knowledge with remotely sensed information and engagement of northern communities in cryospheric monitoring. It will provide northern Canadians with new information on how fast snow and ice are melting, what causes conditions to vary from one year to the next and what the ice will look like to the next generation in 30 years' time.

Snow cover and its properties, over land, sea ice and ice masses will receive considerable attention during IPY. The Russian Academy of Sciences has planned several initiatives, including measurement of variations in snow-depth and snow-water equivalent over the Eurasian region and investigation of the influence of changes in snow-cover thickness in the pre-winter period on frozen ground regimes. For Canada, a key deliverable is snow-cover and snow-water equivalent information for mountainous and high Arctic regions. Integrated data products using satellite, *in situ* and modelled data are desired, but validation of any product for remote regions is essential.

A unique IPY contribution, already completed during April 2007, was a coordinated series of snow measurements made across the Northwest Territories and Nunavut, Canada, as part of SnowSTAR-2007 (M. Sturm, USA CRREL Fairbanks, leader), a 4 000-km barren lands traverse (http://www.barrenlands.org/MainPage.html) from Fairbanks, Alaska, USA, to Baker Lake, Nunavut. The measurements of snowpack physical and chemical properties collected along the traverse represent the first ever systematic acquisition of snow data across this region. These data will be used to refine satellite snow-water equivalent retrieval algorithms, assess the performance of distributed snow models, and determine regional gradients in snowpack mercury and soot. In addition to the scientific objectives of the traverse, more than 50 schools in Canada and the USA participated in the journey by tracking the progress of the expedition via a Website updated with daily text, audio and photographic dispatches from the field. Informal outreach activities were held in all the communities visited. This is one excellent example of outreach to students and northerners to build scientific capacity: a goal of IPY.

One cannot consider snow cover and its change without considering changes in precipitation, particularly solid precipitation. As a contribution to IPY, the WMO Commission for Instruments and Methods of Observation (CIMO), in consultation with the Executive Council Panel of Experts on Antarctic Meteorology, the World Climate Programme, the Commissions for Basic Systems, Climatology, Hydrology and Agricultural Meteorology, WCRP-CliC and the Global Climate Observing System, is to assess the methods of measurement and observation of solid precipitation, snowfall and snow depth at automatic unattended stations used in cold climates (polar and alpine) (http://www.wmo.ch/pages/prog/www/IMOP/reports/2003-2007/CIMO-MG-4_2006_Final-Report.doc#Item_Annex_2, page 3). The support of National Meteorological and Hydrological Services for this activity is an excellent example of WMO Members' contributions to IPY and its legacy.

Changes in river and lake ice are important hydrological and cryospheric components of the high-latitude terrestrial system, affecting aquatic ecosystems, controlling spring runoff, impacting transportation over ice and economic development. Canada will update its

HENRY HUNTINGTON

Figure 5 — SnowSTAR 2007 traverses the Canadian tundra: challenges of deriving an areal snow-water equivalent estimate (a collaborative effort of US and Canadian scientists, led by Matthew Sturm, US Cold Regions Research and Engineering Laboratory).

freshwater ice archive and conduct a national assessment of changes in land ice throughout Canada since IGY. Research on pan-Arctic lake-ice cover will provide a better understanding of the impacts of the large-scale atmospheric and oceanic oscillations on past lake-ice conditions and, together with modelled projections of future climate, will offer insight into future regional changes to lake-ice characteristics and resulting hydrological and ecological impacts in various regions of the Arctic.

Environment Canada and the Russian State Hydrological Institute are beginning the processing of freeze-up/break-up data for a collaborative circumpolar analysis of temporal trends in freshwater ice regimes. The Russian Federation also plans to investigate the variability of thermal and ice regimes of rivers in the north of the European part of the Russian Federation and to estimate the influence of river runoff on heat and salt balance and the ice regime of the Arctic Ocean basin. The bases for prediction of catastrophic situations, related to the ice events in the river mouth areas, are to be developed, using data from observations and numerical models.

Many institutes will contribute to improving their modelling capabilities for the terrestrial cryospheric and hydrological components based on the new observations and improved model parametizations achieved during IPY. This includes evaluation of simulations of the cryosphere in operational and developmental versions of global and regional climate models and numerical weather prediction models. Several countries will lay special emphasis on snow-cover parameterization (snow/vegetation effects, snowpack structure) to improve understanding of cryosphere response/feedbacks within the global climate system and sensitivity and robustness of climate-change projections in high latitudes.

State and fate of permafrost

One of the major contributions to understanding the changing cryosphere and hydrosphere will be provided through the project entitled "Thermal State of Permafrost (TSP)" (IPY 50) coordinated by the International Permafrost Association (IPA). The permafrost temperature regime (at depths of 10-200 m) is a sensitive indicator of the decade-to-century climatic variability and long-term changes in the surface energy balance. TSP will measure temperatures in existing and new boreholes over a fixed time period to provide a "snapshot" of permafrost temperatures in both time and space. Approximately 500 existing boreholes have been identified in the northern hemisphere and a limited number of boreholes are also available in the Antarctic. TSP includes the Circumpolar Active Layer Monitoring project with its approximate 150 sites (www.gtnp.org) (see Figure 6).

Several "regional transects" across the major permafrost zones in North America, Europe (Permafrost and Climate in Europe (PACE) Project) and Eurasia have been identified to assess changes in south-north permafrost boundaries. The IPA/TSP network will provide the locations for long-term measurements. No global database currently exists that defines the thermal state of permafrost within a specific time period. Reported or unpublished temperature measurements were obtained at various depths and

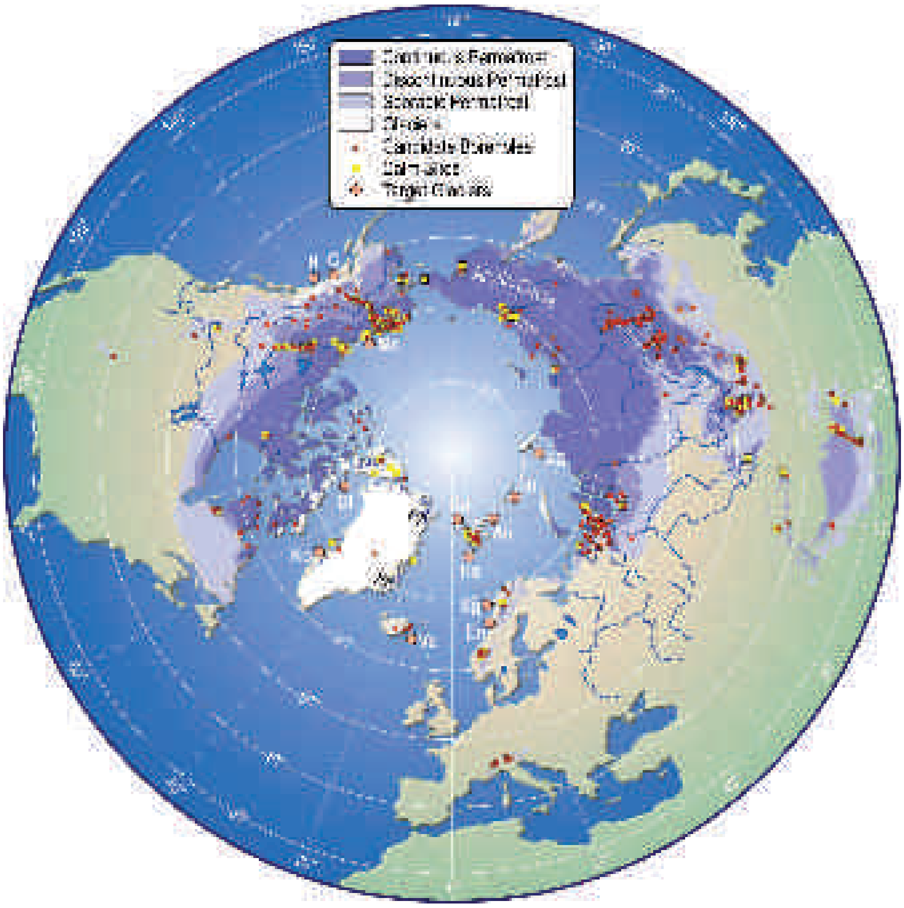


Figure 6 — Location of permafrost candidate boreholes, active-layer monitoring sites (after International Permafrost Association) and GLACIODYN target glaciers.

periods over the past five decades, yet we know these temperatures have changed and at different rates for different regions.

The TSP temperature and active layer datasets will serve as future baselines for the assessment of the rate of change of near-surface permafrost temperatures, to assess changes in permafrost boundaries and to validate models, climatic scenarios and temperature reanalysis approaches. Each of the 18 countries involved in TSP is responsible for its own measurements. Data are incorporated into the WMO/FAO/IPA Global Terrestrial Network for Permafrost (GTNP). Related IPY-IPA projects include the monitoring of coastal erosion at key sites under the Arctic Coastal Dynamics project (IPY 90) and the assessment of carbon stocks in permafrost regions under the project entitled "Carbon Pools in Permafrost Regions" (IPY 373).

Marine cryosphere

In our understanding of sea ice and its changes, knowledge of ice thickness and snow depth on the ice are essential, in addition to extent, in order to assess freshwater flux to the ocean, local climate, changes in marine ecosystems or trafficability.

Sea-ice cover, especially in the Arctic (see Figure 1), is undergoing significant climate-induced changes, including a reduction in extent and a net thinning. During IPY, researchers from many nations will be studying the properties and processes that govern this sea-ice cover and exploring its role as an indicator and amplifier of climate change, as part of their coordinated ocean traverses. Improved representation of sea-ice in climate models for both the Arctic and Antarctic, based on IPCC AR4 assessments, is needed as no—or very few—individual model simulations shows trends comparable to observations, depending on the time window for analysis (Stroeve, 2007).

Numerous techniques will be brought to bear on this task, including expeditions, satellite remote-sensing, autonomous rovers, buoys, ocean moorings and numerical models. Autonomous systems allow studies of the sea-ice climate interactions in regions not always readily accessible. For example, project IPY 95 studies the seasonal ice zone (SIZONET), autonomously measuring sea-ice mass balance and examining solar radiation in the atmosphere-ice-ocean system (http://www.crrel.usace.army.mil/sid/IMB/). Again for the IPY 2007-2008, the Russian Federation deployed North Pole drifting station NP-35 the first station, NP-1, having been deployed in 1937. They will investigate the upper ocean, sea ice and snow cover, and collect meteorological and atmospheric measurements to identify key processes in the atmosphere and alterations of sea-ice cover to examine atmosphere-sea-ice coupling.

Observing the sea ice itself forms the principal component of several IPY oceanographic projects within the framework of the Integrated Arctic Ocean Observing System (iAOOS) proposed by the Arctic Ocean Sciences Board and WCRP/CliC (see article by Summerhayes, Dickson *et al.*, in this issue, 271-284). One interesting component of iAOOS was the International Sea-Ice Summer School, held in Svalbard in July 2007 to reflect recent progress in our understanding of sea ice and its interaction with the ocean and atmosphere. It is part of the outreach programme of IPY.

The ongoing operation of the International Arctic Buoy Programme by WMO Members is essential for our understanding of the climate and cryosphere of the changing polar regions. In the Arctic in 2007, more than 120 buoys were deployed for national operational and research purposes. Similarly, current and historical products being produced by Members through their national ice services will provide valuable information to establish the baseline for sea ice for the IPY period and beyond.

In the Antarctic, the major field experiments are now in progress. The WCRP/SCAR International Programme for Antarctic Buoys plans to achieve a significant increase in the buoy development. The "Antarctic Sea Ice in IPY" project (IPY 141) has two major research activities in September-October 2007. As in the Arctic Ocean, observations of the sea ice in the Southern Ocean will be coordinated with oceanographic observations in the framework of the WCRP project Climate of Antarctica and the Southern Ocean (IPY 132) and become an intrinsic part of the developing Southern Ocean Observing System (see article by Summerhayes, Dickson *et al*., in this issue, 271-284).

One is the Sea Ice Mass Balance in Antarctica (SIMBA) programme on the *Nathaniel B. Palmer* (Steve Ackley, Chief Scientist) in the Bellingshausen Sea, while the other is the Sea Ice Physics and Ecosystem Experiment (SIPEX) aboard the *Aurora Australis* (Tony Worby, Chief Scientist) in the area 120-130°E of the eastern Antarctic. Both programmes will focus on improving our understanding of the physical characteristics of the sea ice, sea-ice drift/dynamics, ice/snow thickness distributions and the relationship between ice physics, sea-ice algae and ecosystem dynamics. The GLAS instrument aboard ICESat will be activated on 1 October 2007 to coincide with these field programmes and every effort will be made to coordinate field activities in the regions covered by ICESat data.

The objective is to provide valuable ground-truthing data for satellite instrument calibration/validation. Related initiatives include the establishment of a new snow and ice classification working group and establishment of a sea-ice data portal at the Australian Antarctic Data Centre.

Ice sheets, ice masses

The world's ice sheets, ice shelves, ice caps and glaciers store most of the world's freshwater. Their response to climate variability and change are now being documented through enhanced *in situ* and satellite observation and monitoring and weather, climate and process modelling. The stability of these ice masses, their changing surface characteristics and runoff patterns and their ultimate contribution to sea-level rise is a particular focus of IPY.

The GIIPSY project noted above will make an essential contribution through new and continuing satellite acquisitions over the ice masses of the polar regions. For example, for the first time, there will be: one summer and one winter Synthetic Aperture Radar (SAR) snapshot of the polar ice sheets, glaciers and ice caps for documenting ice-surface physical parameters; pole-to-coast multi-frequency for Interferometric Synthetic Aperture Radar (InSAR) measurements of ice-surface velocity and repeated X-band InSAR topography for detecting local changes in ice-sheet elevation associated with motion of subglacial water.

Continuing studies will offer new knowledge of volume change, melt extent and mass balance. An example of the latter is the project on ice and snow mass change of Arctic and Antarctic polar regions using satellite gravimetry from the Gravity Recovery and Climate Experiment (GRACE). The project will map for the first time the time variations of loss/gain of ice mass observed by GRACE, in response to climate change. This will provide monthly time series and geographical maps of the integrated variations of mass over large remote regions such as the Antarctic and Greenland, which can then be further expressed in terms of sea-level contribution.

There are many projects in and around Greenland and the Antarctic that will contribute to a better understanding of the current and past climate system of the polar regions and the Earth. The Antarctic Surface Accumulation and Ice Discharge project makes use of the unique focus of IPY cooperation to synthesize, collect, analyse and produce comprehensive datasets on the spatial and temporal patterns of accumulation of snow and the perimeter discharge of ice from the Antarctic ice sheet. It will build on past efforts and stimulate new ones:

- To be able to represent the spatial and temporal variability of Antarctic accumulation at an unprecedented level of detail;
- To compare new surface velocity data with the previous large-scale mapping of ice speed, and isolated older measurements, to provide useful indications of the temporal variation of ice discharge and grounding line position along large portions of the Antarctic's grounded perimeter; and
- To determine ice thickness at the grounding line to complete the calculation of ice discharge: what is happening at the edge of the ice sheets is critical to understanding stability and sea-level change.

One of the fastest warming areas in the polar regions is the Antarctic Peninsula. Studies using the Larsen B and C ice shelves as laboratories will be initiated during IPY. With the loss of ice shelves such as these, outlet glaciers that nourished them with land ice accelerated rapidly, losing a disproportionate amount of ice to the ocean. A new initiative on Larsen C, using coupled existing and new field measurements, will determine the state of its health and stability in response to climate change. Existing data and new field measurements (e.g. Global Positioning System, automatic weather stations and ground penetrating radar), coupled with an analysis of remote-sensing data, ice-shelf numerical models and control methods, aim to provide a more comprehensive analysis of the ice-shelf evolution in a changing climate.

Similarly, for Greenland, there is an effort to determine its stability, history, and evolution. Understanding how Greenland will react to global warming is crucially important. Using seismic data, ice cores and radar, laser ranging and echo sounders, there will be new knowledge of the Greenland Ice Sheet and it will improve scientists' ability to model how it will react to climate change. A new drilling site that will allow an ice core to be extracted to extend the record beyond 130 000 years is in the process of being established, giving a new perspective on climate change.

Likewise, in the Antarctic, the Chinese Panda project will drill a new core at Dome A, where ice thickness was measured at over 3 000 m. It is a potential site to reconstruct a 1 200-year record of past climate. IPY was the stimulus for such studies, bringing new insight into past, present and potentially future climates in the polar regions. Information on national and international IPY projects in Greenland proper and surrounding waters is available through the Danish Polar Centre (http://www.ipy.dk).

Global warming will have a large impact on glaciers in the Arctic region. Sea-level will be affected, and substantial changes can be expected in sediment and freshwater supplies to embayments and fjords. GLACIODYN is an IPY project that will investigate the effects of global warming on a set of 20 target glaciers in the Arctic region in the years 2007-2010 (see Figure 6). It aims to improve current estimates of the contribution of Arctic glaciers and ice caps to sea-level rise through improved observational techniques and dynamic glacier modelling to model runoff changes in response to climate-change scenarios. The experience gained in the Nordic Climate and Energy project will benefit this initiative.

Global Cryosphere Watch—an IPY legacy

Fifteenth World Meteorological Congress (May 2007) supported the concept of a Global Cryosphere Watch (GCW) as a WMO legacy of IPY 2007-2008. The GCW would provide an intergovernmental mechanism for supporting key cryospheric *in situ* and remote-sensing observations, which would also serve to implement the recommendations of the IGOS Cryosphere Theme. Meeting these goals will require building links and partnerships and developing agreements between key observing systems, networks, observation and data providers, users and the research community. The GCW is envisaged as supporting the WMO Information System initiative by providing a one-stop portal for authoritative cryospheric data and information. This will facilitate assessment of changes in the cryosphere and their impact, and use of this information to aid the detection of climate change. One of the first GCW tasks would be to work with relevant WMO mechanisms to ensure that cryospheric observations, monitoring and associated research match requirements of a wide range of users throughout the world.

Discussions on the concept are now underway within WMO and with other interested institutions, agencies and scientists. Elaboration of the GCW concept and initiation of a programme of actions aimed at its creation will be initiated by the WMO Intercommission Task Group on IPY, scheduled to meet in early 2008.

Acknowledgements

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References

Atkinson, D.E. *et al.*, 2006: Canadian cryospheric response to an anomalous warm summer: a synthesis of the Climate Change Action Fund Project The State of the Arctic Cryosphere during the Extreme Warm Summer of 1998. *Atmosphere-Ocean*, 44 (4), 347-375.

Lemke P. *et al.*, 2007: Changes in Cryosphere. In: *Climate Change 2007: The Physical Science Basis. Contributions of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin et a., (Eds.)), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 43-46.

Serreze, M.C., M.M. Holland and J. Stroeve, 2007: Perspectives on the Arctic's shrinking sea ice cover, *Science*, 315, 1523 - 1536.

Serreze, M.C., A.P. Barrett, A.G. Slater, R.A. Woodgate, K. Aagaard, R.B. Lammers, M. Steele, R. Moritz, M. Meredith and C.M. Lee, 2006: The large-scale freshwater cycle of the Arctic. *J.Geophys.Res.*, Vol. 111, No. C11, C11010 10.1029/2005JC003424

Stroeve, J., M. M. Holland, W. Meier, T. Scambos and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast. *Geophys. Res. Lett.*, 34, L09501, doi:10.1029/2007GL029703.

Waliser, D., K.-W. Seo, S. Schubert and E. Njoku, 2007: Global water cycle agreement in the climate models assessed in the IPCC AR4. *Geophys. Res. Lett.*, 34, L16705, doi:10.1029/2007GL030675.