A Compilation of Recommendations from the IGOS Cryosphere Theme Report (2007)

10 November 2011

PREFACE

The Integrated Global Observing Strategy (IGOS) was a partnership of international organizations concerned with global environmental change issues. Its objectives were to link research, long-term monitoring and operational programmes, bring together the producers of global observations and the users that require them, and identify products needed, gaps in observations and mechanisms to respond to needs in the science and policy communities. The Partnership was dissolved in 2007 with the intention that the IGOS themes would be transitioned into the Global Earth Observation System of Systems (GEOSS) framework.

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 in 2004 and a Theme Team was formed. With the support of a worldwide cryospheric science community, the IGOS Partners approved the Cryosphere Theme Report in 2007.

The Report contains recommendations for all elements of the cryosphere. Here we provide a simple compilation of those recommendations with no additional background information. The IGOS Cryosphere Theme report is available at http://igos-cryosphere.org.

RECOMMENDATIONS FROM THE EXECUTIVE SUMMARY

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 higher-level polar data products from existing satellites, for 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 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).
- Coordinate near-surface, high-resolution remote sensing activities from aircraft, UAV and AUVs with satellite and in situ experiments during IPY.
- 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.

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 (SWE) 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.

RECOMMENDATIONS FROM THE REPORT CHAPTERS

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.

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.

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.

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.

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 CoreH2O 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.

Recommendations: Development of Surface Temperature and Albedo Observations

R8.1 The continued production of unified, consistent time series maps of surface temperature is recommended to add to the time series of surface skin temperature and broadband albedo 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.

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.

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:

1. continue conventional point precipitation measurements in existing networks,
2. sustain and enhance the gauge network in the cold regions,
3. develop guidelines on the minimum station density required for climate research studies on solid precipitation in cold climate regions,
4. ensure regular monitoring of the snowfall real-time data quality control and transmission,
5. undertake bias analysis and corrections of historical precipitation gauge data at regional to global scale, including the Antarctic,
6. examine the impact of automation on precipitation measurement and related QA/QC challenges, including compatibility between national data, and manual vs. auto gauge observations,
7. develop digitized metadata for regional and national networks,
8. 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,
9. encourage national research agencies to establish programs to provide support for the development of new instruments to measure solid precipitation at high latitudes,
10. expand the use of wind shields and direct measurement of winds at emerging auto gauge sites/networks, and
11. 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.

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.

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, Obtain relevant data for digital terrain models of ice sheets, ice caps and glaciers (InSAR laser, and stereo images). Plan the continuity of Landsat class optical mapping capability for world glacier monitoring. 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 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. 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.	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. 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	Sustain/Convert essential short-term/temporary post-IPY network into long-term Cryo-Net sites. Augment selected supersites, and extend essential geographic networks to obtain	Implement an integrated in situ network (CryoNet)– across range of different cryo environments. Evaluate an in situ cryospheric reference network (CryoNet) and

	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. Strengthen the support of already established monitoring networks like GTN-G or GTN-P. Develop observer networks in Native communities and involve schools.	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. Capacity building measures: regional training of local community observers and recruitment of schools, particularly for river-, lake-ice, and snow networks.	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.
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	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	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.

	forums.	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.	
Integrative Actions	Develop long-term plan and begin to augment CEOP supersites with essential CryoNet capabilities. Encourage efficient data collection and NRT (GTN) 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. Identify a Community of Practice.	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