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A Global Cryosphere Watch

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ABSTRACT. There is now an unprecedented demand for authoritative information on the past, present, and future states of the world's snow and ice resources. The cryosphere is one of the most useful indicators of climate change, yet is one of the most under-sampled domains in the climate system. The Sixteenth World Meteorological Congress (Geneva, 2011) decided to embark on the development of a Global Cryosphere Watch (GCW) as an International Polar Year (IPY) legacy. Through WMO and its partners, GCW is now being implemented for sustained cryosphere observing and monitoring and provision of cryosphere data and information. GCW will ensure a comprehensive, coordinated, and sustainable system of observations and information that will allow for a full understanding of the cryosphere and its changes. It will initiate a surface-based cryosphere observing network called "CryoNet" that will establish best practices and guidelines for cryospheric measurement, data formats, and metadata by building on existing efforts. A complementary task involves developing an inventory of candidate satellite products that are mature and generally accepted by the scientific community. GCW is establishing interoperability between data management systems, and the GCW data portal will provide the ability to exchange data and information with a distributed network of providers.

Key words: cryosphere; snow; ice; permafrost; Arctic; Antarctic; observing system

RÉSUMÉ. Il existe maintenant une demande sans précédent d'information faisant autorité sur l'état passé, présent et futur des ressources en neige et en glace de la planète. La cryosphère constitue l'un des indicateurs les plus utiles au sujet du changement climatique et pourtant, il s'agit de l'un des domaines du système climatique les plus sous-échantillonnés. Le seizième Congrès météorologique mondial (Genève, 2011) a décidé de mettre au point un système de surveillance mondiale de la cryosphère (Global Cryosphere Watch – GCW) en guise de legs à l'Année polaire internationale. Grâce au concours de l'Organisation météorologique mondiale (OMM) et de ses partenaires, le GCW est en train d'être mis en œuvre en vue de l'observation et de la surveillance durables de la cryosphère ainsi que de l'obtention de données et d'informations sur la cryosphère. Le GCW donnera lieu à un système exhaustif, coordonné et durable d'observations et d'informations qui permettront de comprendre à fond la cryosphère et les changements qui s'y rapportent. Il comprendra un réseau d'observation de la cryosphère en surface appelé « CryoNet », réseau qui établira les pratiques et les lignes directrices exemplaires en matière de mesure cryosphérique, de formats des données et de métadonnées en s'appuyant sur les efforts actuels. Une tâche complémentaire consiste à dresser l'inventaire des produits satellitaires évolués et généralement acceptés par le monde scientifique. Le GCW établit l'interopérabilité entre les systèmes de gestion des données, et le portail des données du GCW donnera la possibilité d'échanger des données et des informations avec un réseau de fournisseurs interconnectés.

Mots clés : cryosphère; neige; glace; pergélisol; Arctique; Antarctique; système d'observation

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INTRODUCTION

The cryosphere collectively describes elements of the Earth system that contain water in its frozen state. It includes solid precipitation, snow cover, sea ice, lake and river ice, glaciers, ice caps, ice sheets, permafrost, and seasonally frozen ground. The cryosphere is global, existing not just in the Arctic, Antarctic, and mountain regions, but in various forms at all latitudes and in approximately 100 countries. The cryosphere provides some of the most useful indicators of climate change, yet is one of the most under-sampled domains of the Earth system. Improved cryospheric monitoring and integration across cryospheric domains are essential to fully assess, predict, and adapt to climate variability and change.

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Changes in the cryosphere have major impacts on health, water supply, agriculture, transportation, freshwater and marine ecosystems, hydropower production, and cryosphere-related hazards such as floods, droughts, avalanches, and sea-level rise. The amount of snow and the rate of snowmelt help to govern the timing and characteristics of runoff. For example, as much as 75% of the water supply in the western United States comes from snowmelt (Stewart et al., 2004), and most central Asian countries or regions rely on meltwater for agriculture, domestic, and industrial uses. Sea level rise is a major concern for populated coastal areas and is critical for a number of small island nations. Although the volume equivalent of glaciers in terms of global sea level rise is small (0.41 m) compared to that of the ice sheets of Greenland (7.4 m) and Antarctica (58.3 m), their relative contribution to recent global sea level rise has been much larger (Vaughan et al., 2013). Melting of glaciers and ice caps in the second half of the 20th century led to about a 2.5 cm rise in sea level, in contrast to the loss of ice from the Greenland and Antarctic ice sheets, which added about 1 cm to sea level. However, loss is accelerating: the Intergovernmental Panel on Climate Change has estimated glacier loss to be equivalent to 0.83 ± 0.37 mm yr^{1} of sea level between 2005 and 2009 and loss from both ice sheets as 1.2 ± 0.4 mm yr^{1} between 2007 and 2011 (Vaughan et al., 2013).

Wave-induced undercutting of permafrost leads to coastal erosion by the action of waves and currents. Reduction of the sea ice cover, and especially of the fast ice, corresponds to increased fetch of waves, which allows them to grow and become more destructive as they approach the coast. Shortened periods of seasonal ice cover, resulting from later development of the fast ice and its earlier breakup, expose coastlines to more severe storms that occur during transition seasons. Local coastal losses to erosion on the order of 30 m per year have been observed in some locations in both Siberia and Canada.

Transportation is affected by changes in snow cover, freshwater, sea ice extent and thickness, and the degradation of permafrost. Persistent reductions in Arctic multiyear sea ice cover would benefit marine transportation and related socioeconomic developments, but represent a risk for marine ecosystems. Snowfall frequency and magnitude directly affect road and rail traffic and aircraft operations. River and lake ice provide winter roads for essential access to remote areas.

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 land-use planning and engineering design in permafrost regions. The development of oil and gas deposits in ice-covered seas and shelves depends on the ice regime and the presence of icebergs, which together determine the economic feasibility of exploration and production projects.

Other sectors such as wildlife, recreation, and tourism are significantly affected by short-term and long-term changes in snow and ice conditions. The insurance industry is facing increasing risks associated with a changing cryosphere. Cryosphere-related hazards include avalanches, catastrophic spring floods from the rapid melting of snow, the high variability of lake and river ice breakup and freeze-up dates that affect transportation, infrastructure damage from thawing permafrost, and icebergs in shipping lanes.

Changes in the cryosphere contribute to global climate change. Albedo changes from the loss of sea ice and snow cover, along with accelerating methane emissions from thawing permafrost, are heating the planet at a rate equivalent to approximately three billion metric tons of carbon dioxide (CO_2). This amount is comparable to about 42% of U.S. global warming emissions. Heating from the melting Arctic will grow significantly over the coming decades: it is projected to more than double by 2100 when expressed in CO_2 equivalents (Goodstein et al., 2010).

Snow and ice data are required for weather forecasting, climate prediction and projection, and research and in many types of practical applications such as engineering, services to society, and various types of land and marine resource management. Solid precipitation, snow cover, snow water equivalent, snowstorms, icing, and river-, lake-, soil-, and sea-ice freeze-up and breakup times are components of weather forecasting in cold-climate regions. The performance of numerical weather forecasts strongly depends on the accuracy of initial conditions for predictive models. Ice services provide forecasts for navigation and offshore activities. Cryospheric data also play a critical role in climate reanalyses.

It is not surprising, therefore, that the cryosphere, its changes, and its impacts have received increased attention in recent years. Today it receives constant coverage by the media, creating a demand for authoritative information on the state of the world's snow and ice resources, from polar ice to tropical glaciers, based on data from the paleoclimate record, current observations, and future projections.

THE GLOBAL CRYOSPHERE WATCH

The World Meteorological Organization (WMO, Geneva, Switzerland), with the cooperation of other national and international bodies and organizations and using its global observing and information exchange capability, is in a position to provide an integrated, authoritative, continuing assessment of the cryosphere—a Global Cryosphere Watch (GCW). At its 16th World Meteorological Congress in 2011, WMO considered the GCW Implementation Strategy, which outlined the next steps for developing GCW, and decided to embark on GCW development as an IPY legacy with the goal of an operational cryosphere observing program. Support for GCW was expressed by representatives of countries from all six WMO regions.

GCW is an international mechanism for supporting all key in situ and remote sensing observations of the cryosphere. GCW will provide authoritative, clear, and useable

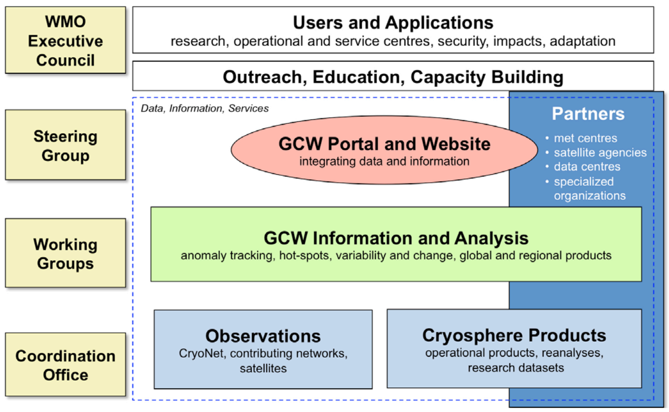

FIG. 1. The conceptual framework for GCW operation.

data and information for analyses of the past, current, and future states of the cryosphere. GCW will have a positive impact on prediction, thus supporting assessments of the future state of the cryosphere. In its fully developed form, GCW will include observation, monitoring, assessment, product development, and research. It will provide the framework for reliable, comprehensive, sustained observing of the cryosphere through a coordinated and integrated approach on national to global scales to deliver quality-assured global and regional products and services. GCW will help bridge the gaps between research and operations and between scientists and practitioners. GCW implementation encompasses:

- *Requirements*: Update the requirements identified in the Integrated Global Observing Strategy (IGOS) Cryosphere Theme; contribute to the WMO Rolling Review of Requirements (RRR) process and the requirements of scientific bodies;
- *Integration*: Provide a framework to assess the state of the cryosphere and its interactions within the Earth system, emphasizing integrated products using surface- and space-based observations;
- *Standardization and assessment*: Enhance the quality and authority of data by improving standards and best practices for measuring and observing essential cryospheric variables, by addressing differences and inconsistencies in current practices, and by fully assessing error characteristics of in situ and satellite products;
- *Access*: Improve access to and exchange and use of observations and products from WMO observing systems and those of its partners;
- *Coordination*: Foster research and development activities and coherent planning for future observing systems and global observing network optimization, especially within the WMO Integrated Global Observing System (WIGOS).

The observing component of GCW is one of the four components of WIGOS. GCW will coordinate cryospheric activities with the Global Climate Observing System (GCOS), which includes the climate-related components of the Global Ocean Observing System and the Global Terrestrial Observing System (GTOS). The WMO Information System (WIS) will provide a vehicle for data and product collection and dissemination within and outside the WMO community. Through WIGOS and WIS, GCW will also provide a fundamental contribution to the Global Earth Observation System of Systems (GEOSS). GCW will not assume the mandate of any of its partners or collaborators and will avoid duplication of effort. Instead, GCW will enable partners and collaborators to exercise their mandates effectively.

FRAMEWORK

The conceptual framework for GCW is given in Figure 1. Collaboration and cooperation through co-sponsorship and partnership are essential. Cryospheric data, information, products, and knowledge will be provided not only from national meteorological and hydrological services, but also from national and international partner organizations, agencies, and the scientific community.

GCW data include basic measurements and higher-level products. The GCW Data Portal is a web interface that contains information about datasets (metadata), but generally not the data themselves. Instead, the portal links to data that are stored at partner data centers, which may or may not be already registered in WIS as National Centers or Data Collection or Production Centers. It is compatible with WIS and the Global Change Master Directory (GCMD). The GCW Data Portal will be connected to WIS, and the WMO Global Telecommunication System (GTS) will be used for operational real-time exchange of data when demanded by the GCW user community. Information and analysis products will be derived from surface and satellite observations, operational products, reanalyses, and research datasets. GCW will include an effective interface with the user community, and capacity building and training will be included in all aspects of the GCW framework.

WMO's Executive Council Panel of Experts on Polar Observations, Research and Services guides the development of GCW. The GCW Steering Group, Working Groups, and Task Teams are central to GCW operations. The GCW Steering Group will provide high-level guidance on GCW development and implementation.

Three Working Groups have been established: 1) the Observations Working Group, 2) the Integrated Products Working Group, and 3) the Information and Services Working Group.

Working groups will establish teams, as needed, to address the priority tasks defined in the work plans of each group. Initially, the Observations Working Group includes the CryoNet Team, the Best Practices Team, and the Solid Precipitation Team. The Integrated Products Working Group includes the Snow Watch Team. The Information and Services Working Group contains the Portal Team, the Terminology Team, and the Website and Outreach Team. All working groups and teams will facilitate interaction between the operational and research communities.

Working group and team members will be selected experts nominated by sponsors, partners, and contributors to GCW. Working groups and teams may be joint working groups with GCW partners and contributors. The teams and their scope and activities will evolve as GCW moves toward the operational phase.

The Observations Working Group will address capabilities and needs for surface-based and satellite observations. It will be responsible for establishing and coordinating operations of the GCW surface-based observational network, including the core network CryoNet. The group will develop a network strategy and procedures for becoming part of the GCW network, evaluate proposed sites, and determine data availability. To establish CryoNet, it will define the types of sites on land or sea that operate a sustained, standardized program for observing and monitoring as many cryospheric components and variables as possible. This group will compile best practices, guidelines, and standards, facilitate instrument intercomparisons, and promote interaction and collaboration between the scientific and operational communities. It will conduct an inventory of measurement methods and infrastructure at sites that measure components of the cryosphere. The Observations Working Group will assess user needs, periodically review and update observing system requirements and capabilities and contribute to the WMO Rolling Review of Requirements database, and liaise with the Polar Space Task Group (PSTG).

The Integrated Products Working Group will identify key GCW datasets and develop an inventory of candidate in situ and satellite products for GCW that are mature (product quality) and generally accepted (credible) by the operational and scientific communities. The group will facilitate the harmonization of products (e.g., multiple sea ice estimates) and product intercomparisons and oversee development of data policies for GCW, including data exchange by WMO Members. The group will consider data homogeneity, interoperability, and compatibility of GCW observing and monitoring systems and derived cryospheric products.

The Integrated Products Working Group and the Observations Working Group will engage users to help determine which cryospheric observations are most important, identify the spatial, temporal, and knowledge gaps, and address other aspects of data usability such as error assessments and data formats. Users will be engaged through dedicated workshops and comprehensive surveys. User needs may vary regionally.

The Information and Services Working Group will be responsible for the ongoing development and operation of the GCW Data Portal and its data catalogue, cryospheric metadata and terminology, the GCW website, and outreach activities. The group will manage linkages to data contributors, work with national focal points, and develop documentation for outside use. It will work through interoperability issues with data centers and other programs. Group members will be available to speak to the media and policymakers, provide guidance for outreach products, and work with social media. A variety of outreach materials will be developed to educate the public, members, funding agencies, and policymakers on the cryosphere and its importance to society.

Prioritization of tasks will be accomplished through meetings with the cryosphere community, guidance from the Steering Group, and task team workshops. For example, the First GCW Implementation Meeting (November 2011, Geneva) was effectively a meeting of an ad hoc GCW community of practice. Near-term tasks were suggested, discussed, and prioritized. Similarly, tasks for the surface network and for snow products were prioritized in the First CryoNet workshop (November 2012, Vienna) and the First Snow Watch Workshop (January 2013, Toronto). Future workshops such as these will provide essential guidance on GCW priorities and their implementation.

CRYONET

Achieving sustained observation and monitoring of the cryosphere and related environmental variables is a key task in the development of GCW. A comprehensive cryosphere observing system must combine ground-based instrumentation, satellite remote sensing, aircraft measurements, modeling, and data management (Fig. 2). Surface and airborne observations provide data that cannot currently be measured from space, more detailed information in critical areas, and observations with which to calibrate and validate satellite retrievals and model outputs. Satellite instruments are essential for delivering sustained, consistent observations of the global cryosphere and are a key to extending local in situ measurements. Surface-based measurements and satellite products are the two main components of the GCW observing framework.

National weather, hydrological, and ice services, space agencies, and research groups are critical to the implementation of GCW and ultimately to its success. These agencies provide the basic observations for GCW, but also influence measurement practices, observational requirements, and product selection. GCW will establish Cryonet, a core standardized cryosphere observing network of surface measurement sites in cold climate regions, on land or sea, operating a sustained program for observing and monitoring as many cryospheric components at a site as possible. Cryonet will apply agreed-upon GCW observing practices. Initially, it will build on existing cryosphere observing programs or add standardized cryospheric observations to existing facilities to create supersite environmental observatories.

CryoNet covers all components of the cryosphere: glaciers, ice shelves, ice sheets, snow, permafrost, sea ice, river and lake ice, and solid precipitation. Some of these

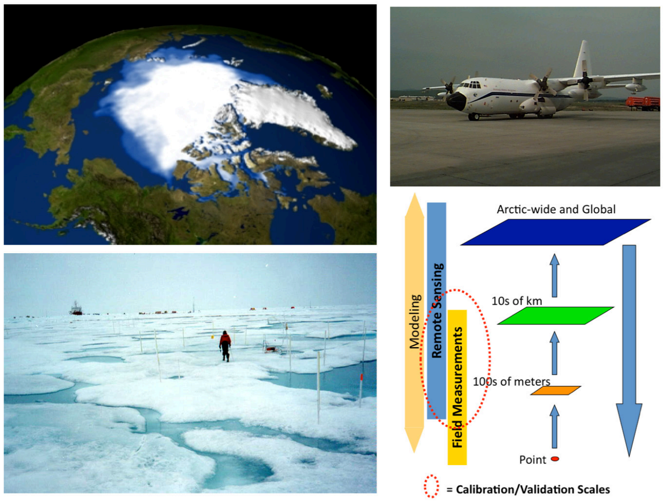

FIG. 2. The various observational system types—satellite, aircraft, and in situ—and the scales of operation. Sources clockwise from upper left: NASA, J. Key, B. Goodison, W. Abdalati (NASA).

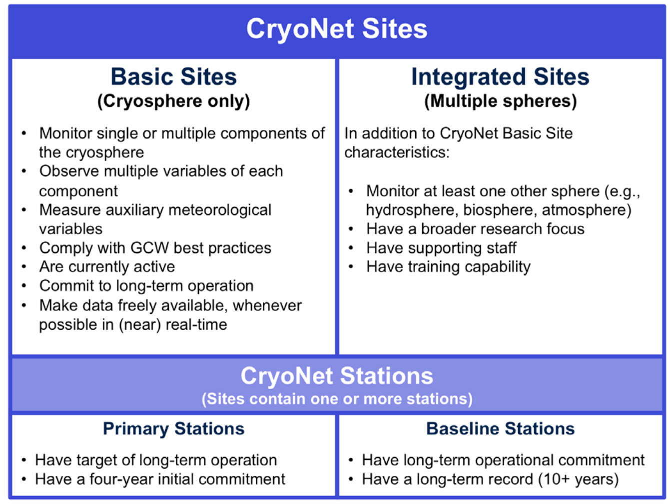

FIG. 3. Proposed CryoNet site and station types and characteristics. "Sphere" refers to the different components of the climate system (e.g., cryosphere, atmosphere, biosphere).

cryospheric components are already measured by existing networks (e.g., WMO Global Observing System for measurement of snow-related parameters, the Global Terrestrial Network [GTN] for permafrost [GTN-P], and GTN-G for glaciers); however, other components (e.g., sea ice) are not integrated into equivalent networks. Two types of sites (basic and integrated) are envisioned, each defined by the number of "spheres" (e.g., cryosphere, atmosphere, hydrosphere, biosphere) that are monitored (Fig. 3). CryoNet Basic Sites monitor one or more components of the cryosphere (glaciers, ice shelves, ice sheets, snow, permafrost, sea ice, river or lake ice, and solid precipitation) and observe multiple variables (properties) of each component. Basic Sites also measure auxiliary meteorological variables, comply with GCW best practices, are actively taking measurements, have a long-term financial commitment, make data freely available, and make data available in near-real-time whenever possible. CryoNet Integrated Sites, in addition to the Basic Sites characteristics, monitor at least one other sphere, have a broader research focus, have support staff, and have training capability. Integrated Sites are particularly important for the study of feedbacks and complex interactions between the atmosphere, cryosphere, biosphere, and ocean.

CryoNet Sites contain one or more CryoNet Stations. Primary Stations have a target (intent) of long-term operation and an initial commitment of at least four years. Baseline Stations have a long-term operational commitment and long-term (more than 10 years) data records.

CryoNet sites must meet a minimum set of requirements:

1. The site location is chosen to be representative of the surrounding region for the cryospheric components measured.
2. User needs have been considered in the observation design process.
3. CryoNet sites must be active and perform sustained observations according to CryoNet best practices and commit to continue these measurements for a minimum of four years.
4. Personnel must be trained to operate and maintain the site.
5. The responsible agencies are committed, to the extent reasonable, to sustaining long-term observations of at least one cryosphere component, including auxiliary meteorological variables.
6. The relevant CryoNet observations are of documented quality. The measurements are made and quality controlled according to CryoNet best practices.
7. Associated standard in situ meteorological observations of documented quality are made when necessary for the accurate determination and interpretation of the GCW variables.
8. A station logbook to record observations and activities that may affect observations is maintained and used in the data validation process.
9. The data and metadata, including changes in instrumentation, traceability, and observation procedures, are submitted in a timely manner to a data center that is interoperable with the GCW portal.
10. The site characteristics and observational program information are kept up-to-date in the GCW station information database. Station metadata are also provided to the WIGOS Information Resource and updated regularly.

Many WMO members have proposed contributing to GCW through their sites in China, Finland, the United States, Austria, and elsewhere. For example, China has established supersites in the "Third Pole" region, where the High Asian cryosphere serves as the Asian "water tower" for more than a billion people. Finland's Sodankylä-Pallas

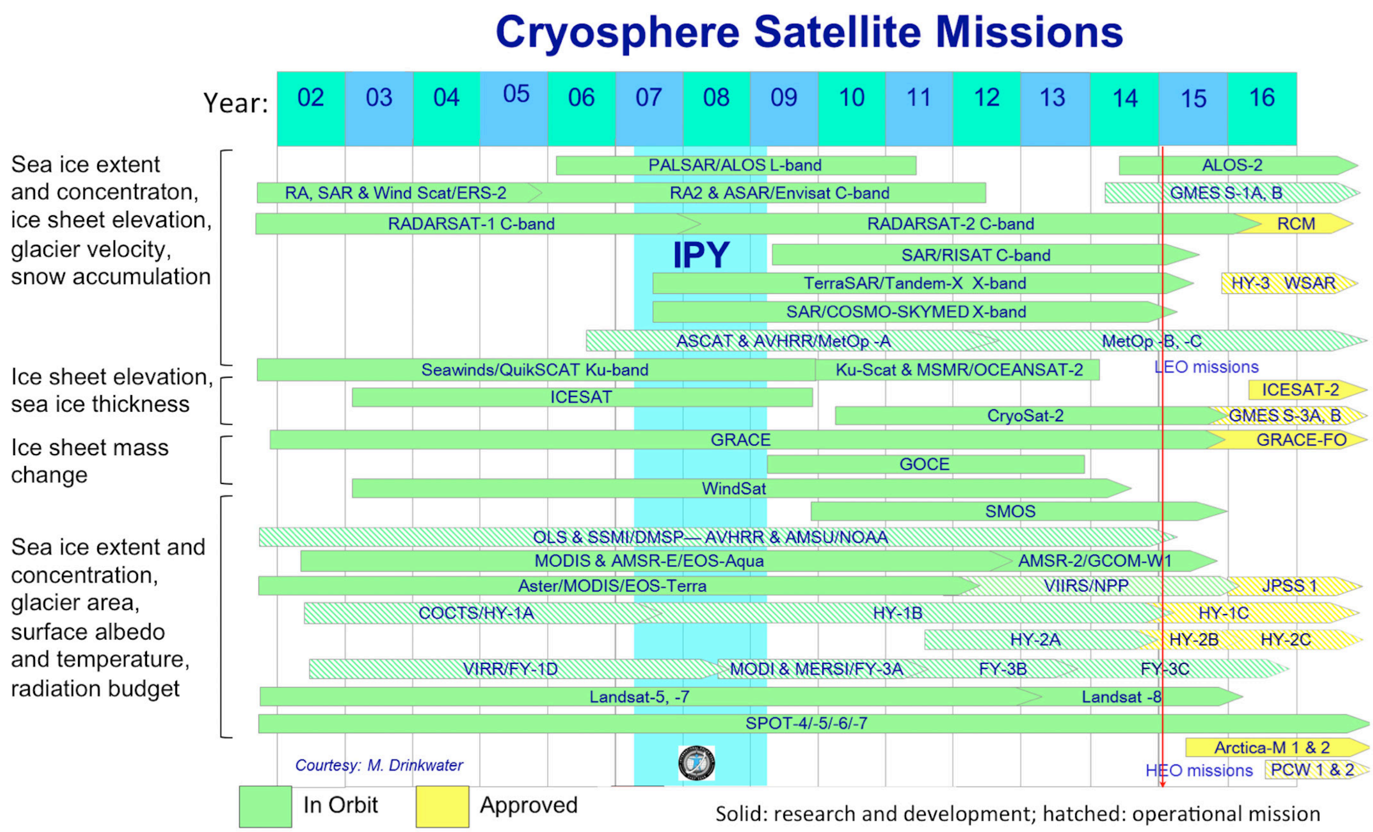

FIG. 4. Timeline of satellites used for measuring and monitoring the cryosphere, as of October 2012. (Modified version of a figure by M. Drinkwater, European Space Agency.)

site in the boreal forest provides reference measurements for satellite sensors. Some of the atmospheric observatory sites operated by the International Arctic Systems for Observing the Atmosphere program are being expanded to include measurements of surface properties, including permafrost, which makes them ideal for inclusion in CryoNet. To date, more than 100 sites have been proposed as potential CryoNet sites. Additionally, the GCOS/GTOS Networks for Permafrost (GTN-P), Glaciers (-G) and Hydrology (-H) may offer potential reference sites while providing key observations from their global networks. The World Glacier Monitoring Service (WGMS), for example, has expressed its willingness to support GCW with data, information, and expertise from within the GTN-G.

SATELLITE PRODUCTS

The satellite observing system for the cryosphere is already robust, as shown in Figure 4. Many satellite-based snow and ice products exist, and many new products are planned. The WMO PSTG, with its direct connection to space agencies, is a GCW partner that is helping to identify new products in support of GCW services. It is anticipated that satellite agencies, particularly through the PSTG, will provide guidance in developing the surface-observing network, given the importance of in situ observations for the validation of satellite products.

Since there are often multiple satellite products for the same geophysical variable (e.g., sea ice, snow cover) and similar products from surface measurements and models, intercomparison efforts are needed in order to evaluate the strengths and weaknesses, error characteristics, and overall maturity of each product. GCW's "Snow Watch" project is comparing various snow cover products. An example is shown in Figure 5, a plot of near-real-time snow cover extent (SCE) in the Northern Hemisphere that incorporates data from two operational snow analyses: the daily snow depth analysis of the Canadian Meteorological Centre and the daily snow cover analysis (24 km resolution) of the NOAA/National Ice Center Interactive Multi-Sensor Snow and Ice Mapping System. The "normal" range for SCE was determined from the NOAA monthly Climate Data Record product maintained at Rutgers University. GCW encourages and supports workshops for the intercomparison of satellite and other products.

Some unique satellite products will be created for GCW. For example, the Finnish Meteorological Institute created a GCW "SWE Tracker" that illustrates the current Northern Hemisphere snow water equivalent compared to a long-term mean and is updated daily (Fig. 6). This product, a blend of satellite and in situ data, is part of the GlobSnow project.

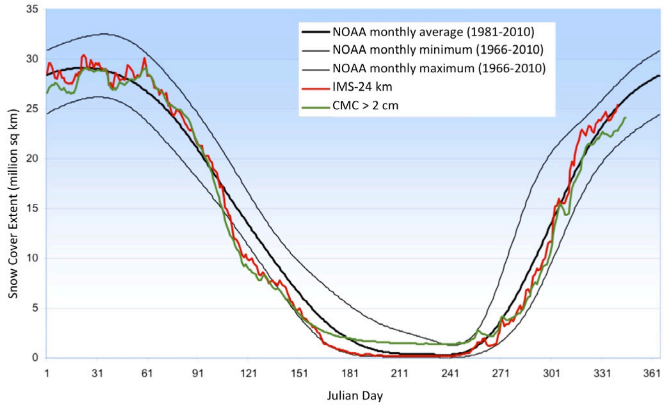

FIG. 5. Plot of Eurasian snow cover extent in 2011 derived from multiple products that monitor snow cover. (Courtesy of R. Brown, Environment Canada.)

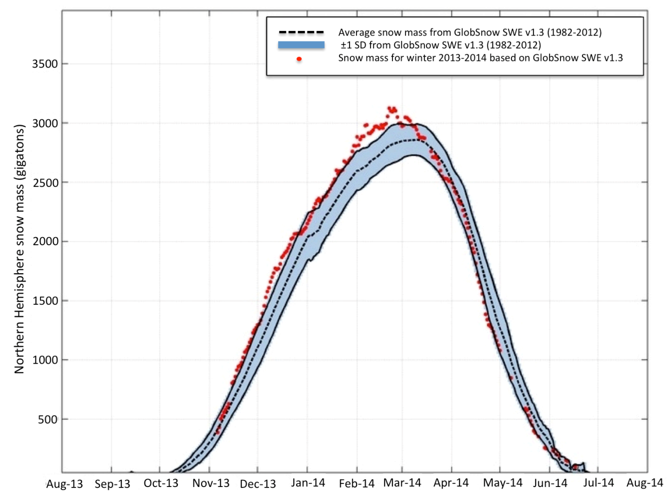

FIG. 6. Total snow mass for the Northern Hemisphere (excluding mountains), August 2013 to August 2014. Data are derived from the GCW/FMI SWE Tracker of the Finnish Meteorological Institute, a product based on GlobSnow snow water equivalent (SWE). The plot illustrates the current Northern Hemisphere snow water equivalent in relation to the long-term mean and variability.

MEASUREMENT PRACTICES

To ensure consistent, high-quality observations, measurements of snow and ice properties at CryoNet sites shall be made according to accepted standards. Many measurement standards have been compiled by WMO or other networks, though the compilation is not exhaustive for snow and ice measurements. A major current effort of GCW is to establish such standards, which will be built on existing measurement practices when possible and vetted by the cryospheric science community. Establishing best practices, guidelines, and standards for cryospheric measurements will include consideration of data homogeneity, interoperability, and compatibility of observations from all GCW constituent observing and monitoring systems and derived cryospheric products. Many existing measurement standards and practices upon which GCW will build are given in Table 1.

Additionally, campaigns for the intercomparison of instruments will be conducted in order to determine performance characteristics under field or laboratory conditions, which will ultimately help to improve data compatibility and homogeneity. The current WMO Solid Precipitation Intercomparison, which includes snowfall and snow depth, is directly relevant and is recognized as a contribution to GCW. Some GCW reference sites are included in this intercomparison.

OBSERVATIONAL REQUIREMENTS

Observational requirements and capabilities will be updated periodically to meet evolving user needs, instrumentation, and error analyses. GCW observational requirements will be formulated on the basis of various sets of existing user requirements. Of particular interest is the IGOS Cryosphere Theme Report (2007), which contains the most comprehensive set of observational capabilities and requirements for the cryosphere observations.

GCW observational requirements will become part of the WMO RRR and will be accessible through the WMO's Observing Systems Capability Analysis and Review Tool. A cryosphere theme has been created in the RRR. The RRR is specified in the Manual on the Global Observing System (WMO, 2003), elaborated in the Guide to the Global Observing System (WMO, 2007), and described further on the WMO website.

GCW WEB PORTAL

GCW data and information are available to WMO members, their partners, and users through two GCW components, the website and the data portal. The GCW information website provides project information, near-real-time graphics illustrating the state of the cryosphere, scientific assessments, cryosphere news, observational requirements, measurement standards, and documents (http://globalcryospherewatch.org). The GCW Data Portal, or catalogue, is dedicated to data management and to providing specific information on datasets (http://gcw.met.no). The data management component is in part an enabling service for the information component in the sense that it identifies relevant datasets and their locations and provides an interface that can be used in the evaluation or description of GCW data and products. The portal may eventually offer simple visualization (generation of maps or diagrams like time series) and even transformations such as reformatting and re-projection of data, if the metadata identify interfaces to the data themselves.

GCW data management integrates cryospheric datasets at national, regional, and global scales and provides access to data and information on past, present, and future

TABLE 1. Existing documents for measurement standards and practices.

Cryosphere element	Documents
Snow	UNESCO/IASH/WMO, 1970; Fierz et al., 2009; CEN, 2010; MSC, 2012, 2013
Glaciers, ice sheets, ice caps	UNESCO/IASH, 1970a, b; Østrem and Brugman, 1991; Kaser et al., 2003; Paul et al., 2010; WGMS, 2012
Sea ice	JCOMM, 2004; WMO, 2004; MSC, 2005; NOAA, 2007; Johnston and Timco, 2008
Solid precipitation	Goodison, 1998; WMO, 2008; Nitu and Wong, 2010; MSC, 2012, 2013
Permafrost	Smith and Brown, 2009; GTN-P Task Force, 2012

cryospheric conditions. To achieve these results, the data portal must be attached to real-time and near-real-time data management systems and to data archives. While interfacing with existing data management systems, GCW respects partnership, ownership, and data-sharing policies of its partners.

GCW itself will produce few low-level datasets, but instead will rely on distributed data management technologies and partners to establish the GCW catalog, which will publish WIS-compliant descriptions of GCW data and products into the catalogues of WMO's Global Information System Centres. This process will create a unified interface to datasets in an otherwise fragmented terrain. No data will be kept in the GCW catalog without an agreement with the data producer. GCW data management follows a metadata-driven approach in which datasets are described through metadata exchanged between contributing data centers and the GCW catalogue.

In the GCW context, at least two types of metadata are relevant. One is "discovery" or index metadata identifying general characteristics of a dataset, including what was measured where and when, potential restrictions on data use, data custodians, and the available interfaces to the actual dataset. This is the type of metadata that will be exchanged within GCW. Another type, "use" metadata, is required when a user has accessed a dataset and begins to use it. Such metadata typically include a specification of variables, units used, how missing values are encoded, and other details on the contents of the dataset. The third type of metadata is interpretation or context metadata (e.g., data quality, instrumentation used, processing performed, and environmental conditions), which allow data to be interpreted in context. GCW will use existing metadata standards wherever possible. The emerging WIGOS metadata are addressing the need for a widely accepted, standardized context metadata specification. However, further development of metadata may be needed in order to meet the expectations of the scientific community.

The ingested metadata will be harvested from project-specific, national, and international catalogues. Some examples are given in Figure 7. In addition to harvesting existing catalogues, the data management part of the GCW portal will facilitate forms for submission of metadata on datasets not handled by existing catalogues. Currently only a few catalogues are integrated, but dialogues on integration have been established with others. Quite frequently, this exchange of metadata involves some degree of adaptation of systems on either side.

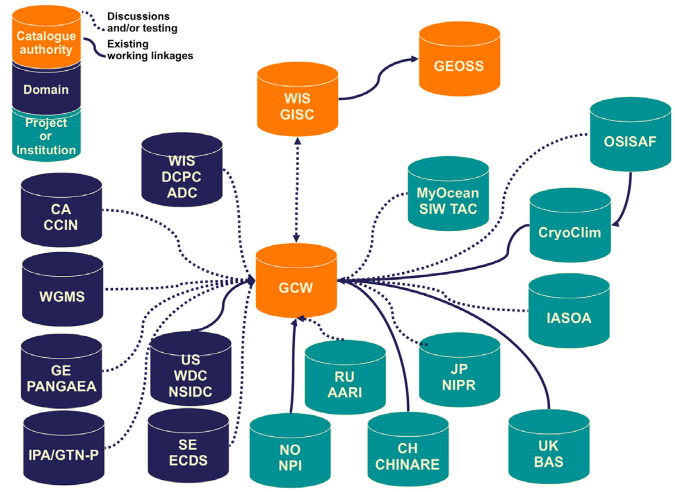

FIG. 7. Data centers being addressed within GCW data management, either currently or in the short term. Solid lines show existing linkages, while dashed lines indicate ongoing discussions or testing, or both.

Many data management frameworks addressing distributed data management have been established during the last 10 years. Some are national, some are regional (e.g., Infrastructure for Spatial Information in the European Community), and others are global (e.g., WIS, the International Council for Science World Data System, Group on Earth Observation). GCW as a WMO initiative is establishing its data management system on the principles outlined by the WMO Information System, but using the experience gained in distributed data management during the International Polar Year (2007–09) (Parsons et al., 2011). Therefore, the GCW catalogue is linked to WIS at the discovery metadata level, and WIS data dissemination components like WMO GTS may be used for real-time exchange of GCW data when requested by the GCW user community.

The linkage to WIS at the metadata level implies that GCW metadata will be included in the GEOSS catalogue, as GEOSS is currently linked at the metadata level to WIS through the WIS Global Information System Centres. This stacking of catalogues, ranging from projects through institutional and national to regional and global catalogues, raises a number of issues for operating such a system to avoid duplication of data records that may appear to be different when exchanged at different levels within the system. In the short term, this issue has to be handled through well-defined procedures and bilateral agreements with contributing data centers. Over the longer term, distributed data management technologies and frameworks are in rapid development and this issue will certainly be addressed in due course.

GCW has to act as a broker, understanding and translating between a number of metadata standards to interface with the contributing data centers. Ideally, more data centers will implement standardized interfaces to their catalogues and data repositories. Currently the level of interoperability is highly variable, with some featuring brokering while others do not support any interoperability standards. Yet another highly variable feature is the granularity of metadata, which complicates and reduces the benefit of interoperability. Many communities are moving towards ISO 19115, or the GCMD Directory Interchange Format for metadata, with ISO 19115 as the long-term goal. For the exchange of metadata, interoperability protocols like the Open Archive Initiative – Protocol for Metadata Harvesting and the Open Geospatial Consortium Catalogue Services for the Web appear to be the main candidates within the geophysical community.

The main problem with metadata currently is not exchanging the metadata, but interpreting the contents of metadata. The challenge is first how to define and use controlled vocabularies and subsequently how to map between controlled vocabularies (e.g., GCMD science keywords and Climate and Forecast (CF) standard names, see http://gcmd.nasa.gov/learn/keyword_list.html and https://marinemetadata.org/references/cfstandardnames). GCW will contribute in this area through extensions to existing vocabularies, the linking of relevant vocabularies, and definition of new vocabularies, if necessary. Essential in this context is the use of a Simple Knowledge Organization System (SKOS), which already is being supported for GCMD and CF vocabularies.

SUMMARY

The World Meteorological Organization Global Cryosphere Watch is an international mechanism for supporting all key in situ and remote sensing cryospheric observations. GCW will provide authoritative, clear, and useable data and information that is indispensable for a description of the past, current, and future state of the cryosphere. GCW will have a positive impact on predictions and projections, thus supporting assessments of the future state of the cryosphere. In its fully developed form, GCW will include observation, monitoring, assessment, product development, and research. It will provide the framework for reliable, comprehensive, sustained observing of the cryosphere through a coordinated and integrated approach on national to global scales to deliver quality-assured global and regional products and services.

Implementation of GCW began in late 2011. The core, standardized cryosphere surface observing network, CryoNet, is being developed; site selection began in early 2014. More than 100 sites have been proposed. Measurement standards and practices are being compiled, as are observational requirements.

GCW encourages and supports satellite product intercomparison projects so that the multitude of cryosphere products can be evaluated in terms of maturity, accuracy, and applicability. Recent satellite product intercomparison workshops for sea ice and for essential climate variables sponsored by the World Climate Research Programme (WCRP) have provided a framework for future GCW intercomparison workshops. A GCW "Snow Watch" group has undertaken an evaluation of various snow products and is engaged with the European Space Agency in a snow product intercomparison. The WMO Polar Space Task Group is helping identify satellite products relevant to GCW.

A GCW Web Portal has been developed by the Norwegian Meteorological Institute (METNO), building on their web-based tool for searching data. It is now pre-operational. IPY data centers and portals, such as METNO, the Canadian Cryosphere Information Network, the British Antarctic Survey, the Norwegian Polar Institute, the National Institute of Polar Research (Japan), and the U.S. National Snow and Ice Data Center are already interoperable. At present, not all are ingested in the metadatabase, but discussions on interfaces and content are ongoing. Separately, the GCW information website provides near-real-time snapshots of current cryosphere conditions, news, meetings, documents, and project information.

Partnerships are a key element in the design and development of GCW. GCW partnerships include government agencies and institutions that measure, monitor, or archive cryosphere data and information from in situ and satellite research and operational networks and model sources. International bodies and services, such as the International Permafrost Association, the World Glacier Monitoring Service (WGMS, a service of the International Association of Cryospheric Sciences), the Global Precipitation Climatology Centre, and national institutions such as the U.S. National Snow and Ice Data Center are examples of bodies that have been engaged in the development of GCW. Participation in GCW is strongly encouraged.

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