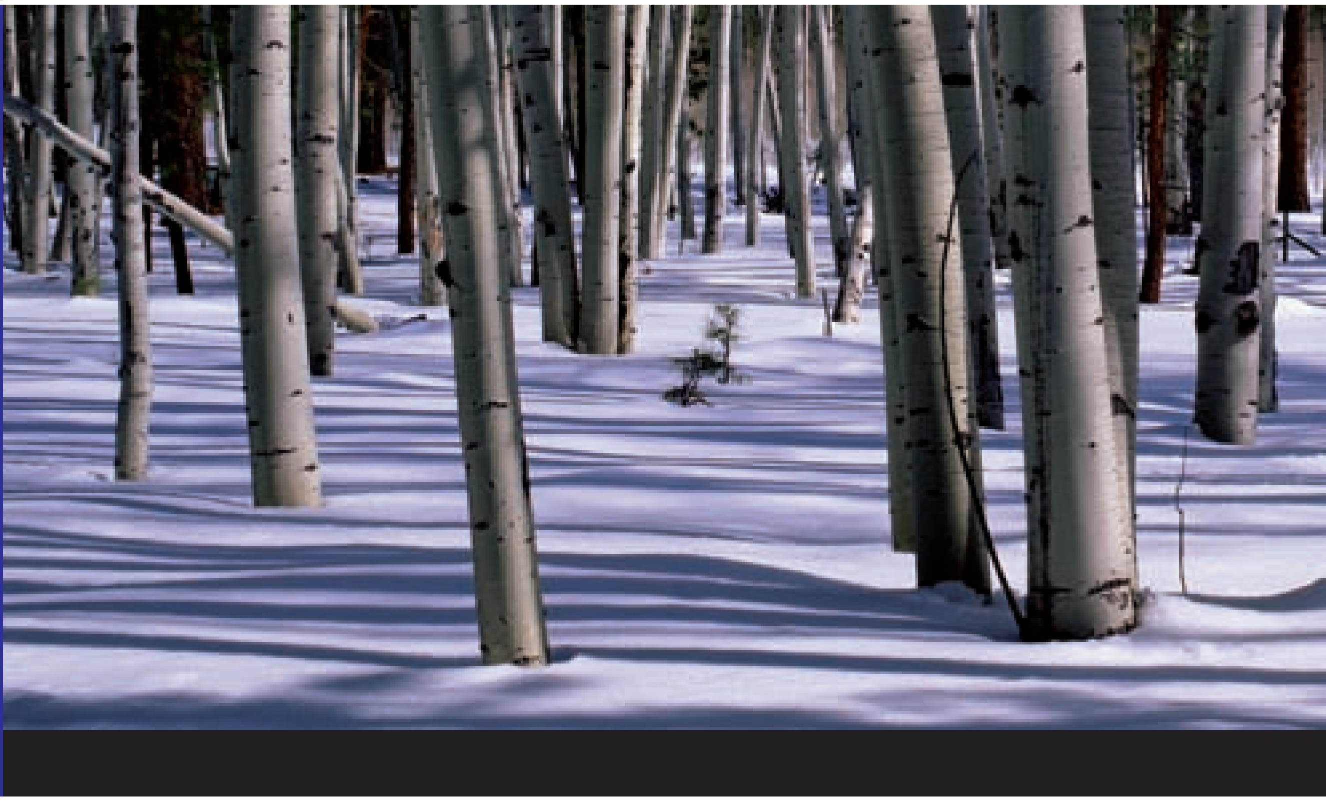
T5

Assessment of the status
of the development of the standards for the
Terrestrial Essential Climate Variables

GTOS

Essential Climate Variables

GTOS 60



SNOW

Snow cover

WMO UNESCO UNEP ICSU FAO FIAT PANIS

T5

ASSESSMENT OF THE STATUS
OF THE DEVELOPMENT OF THE STANDARDS FOR THE
TERRESTRIAL ESSENTIAL CLIMATE VARIABLES

SNOW

Snow cover

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List of Acronyms

AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
AOPC	Atmospheric Observation Panel for Climate
CBS	Commission for Basic Systems (WMO)
CDIAC	Carbon Dioxide Information and Analysis Center
CliC	Climate and Cryosphere (WCRP)
CLPX	Cold Land Processes Field Experiment
CRYSYS	Cryosphere System in Canada
CSCC	Campbell Scientific Canada
DMSP	Defense Meteorological Satellite Program
EASE-Grid	Equal Area Scalable Earth Grid
ESDIM	Environmental Services Data and Information Management
GCM	Global Climate Model or General/Global Circulation Model
GCOS	Global Climate Observing System
GCW	Global Cryosphere Watch (WMO)
GSN	Ground Station Network
GTN-H	Global Terrestrial Network for Hydrology
GTOS	Global Terrestrial Observing System
GTS	Global Telecommunications System
HDF-EOS	Hierarchical Data Format - Earth Observing System
HSDSD	Historical Soviet Daily Snow Depth
HWR	Hydrology and Water Resources
IACS	International Association of Cryospheric Sciences (IUGG)
IMS	Ice Mapping System
IUGG	International Union of Geodesy and Geophysics
MODIS	Moderate Resolution Imaging Spectroradiometer
MSC	Meteorological Service of Canada
NASA	National Aeronautics and Space Administration
NDSI	Normalized Difference Snow Index
NESDIS	National Environmental Satellite Data Information Service
NH	Northern Hemisphere
NISE	Near Real-Time Ice and Snow Extent
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
NWS/COOP	National Weather Service Cooperative Observer Program
RSE	Random square error
SMMR	Scanning Multifrequency Microwave Radiometer

SNOTEL	Snowpack Telemetry
SR	Sonic Ranger
SSM/I	Special Sensor Microwave Imager
SWE	Snow Water Equivalent
TOPC	Terrestrial Observing Panel for Climate (GTOS)
UDG	Ultrasonic Depth Gauge
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
MERIS	Medium Resolution Imaging Spectrometer

Executive Summary

Seasonal snow can cover more than 50 percent of the Northern Hemisphere land surface during a single winter resulting in snow cover being the land surface characteristic responsible for the largest annual and interannual differences in albedo. Surface temperature is highly dependent on the presence or absence of snow cover, and temperature trends have been shown to be related to changes in snow cover. In turn, because of the obvious dependency of snow cover on temperature, long-time series of snow cover trends serve as indicators of climate change. Snow cover, with its high albedo and low conductivity, moderates the transfer of energy at the land surface and exerts a significant effect on the land surface water budget. Realistic simulation of snow cover in climate and hydrologic models and forecast schemes is essential for correct representation of the surface energy balance, as well as for understanding winter water storage and predicting year-round runoff. Improvements in methods for estimating real-time snow cover will translate into improved ability to forecast atmospheric and hydrologic variables in many regions of the world.

Interest in global snow cover data extends beyond typical climate applications. For example, in a warming climate scenario early melt leads to less stream flow during high requirement periods of mid- and late-summer, while the amount of snow and its variability influences the timing of soil freeze/thaw cycles. In addition, the aerial extent of snow cover is important to the study of atmospheric trace gas fluxes such as evaluating the impact of varying snow cover extent on the regional to global ozone budgets and carbon fluxes. Other applications of snow data range from the obvious examples of winter recreation industry, highway and railway maintenance, and avalanche hazard mitigation, to the study of wildlife migration and breeding patterns, and the management of domestic livestock during snow disasters.

The four main units for snow cover are: snow cover, snow cover extent, snow cover depth and snow water equivalent. A number of *in situ* and remote sensing measurement methods are available and can be seen in Armstrong, R.L. and E. Brun (ed.), 2008. Snow and Climate, Cambridge University Press. A complete description of measurement methods, including respective advantages and limitations, can be found in: Armstrong, R.L. and Brun E. (ed.), 2008. However, currently there are no standard intercomparison methods and intercomparisons are done on an ad hoc, or case-by-case basis. Published results could be found in the open literature by searching on measurement or instrument type.

Satellite remote sensing offers the opportunity to monitor and evaluate various snow parameters and processes at regional to global scales. During the past four decades important information on continental to hemispheric scale snow extent has been provided by satellite remote sensing in the visible wavelengths. Since 1966 the National Oceanic and Atmospheric Administration (NOAA) has produced weekly snow extent charts for Northern Hemisphere land surfaces using visible-band satellite imagery. Due to the ability to penetrate most clouds, provide data during darkness, and to provide a measure of snow depth or water equivalent, passive microwave remote sensing can enhance snow measurements based on optical data alone. Similar sensors are employed on aircraft, typically with higher spatial resolution, but limited to regional scales and always intermittent in time. Details on current satellite measurement techniques can be found in Armstrong, R.L. and E. Brun 2008. Validation studies for particular retrieval algorithms are numerous, but are typically very location or "snow climate" specific. A systematic procedure for the intercomparison and validation of certain satellite-derived snow cover products is being proposed by the WMO GCW.

There is a need for the development of snow products that blend multiple data sources and are globally applicable. The research community through WCRP-CliC could help lead such an effort. A global snow product generated from the blending of *in situ* and satellite data is one of the goals of the ESA GlobSnow project. The TOPC in consultation with the AOPC, WCRP-CliC and WMO CBS needs to establish standards and protocols, design an optimum network, and recommend International Data Centre and analysis centre responsibilities. The guidelines on snow cover measurements provided in WMO guide No. 168 should be considered as potential methodologies for establishing ISO standards. GCOS/GTOS current cryosphere activities can provide a starting point, but this activity would require dedicated funding for meetings/workshops to agree on standards and protocols, funding for report preparation, and funding for filling gaps in the networks. With regard to satellite remote sensing, there is a need to establish standard methods to validate and quantify the accuracy of passive microwave retrieval algorithms.

Recommendations:

- WMO GCW, in collaboration with GCOS/GTOS, should establish a forum to define best practices, develop guidelines and standards for *in situ*, airborne or satellite snow cover measurements.
- TOPC, in consultation with the AOPC, WCRP-CliC and WMO CBS should establish standards and protocols, provide guidelines for the design of optimal networks, and recommend International Data Centre and analysis centre responsibilities.
- Strengthen and maintain existing snow cover and snowfall observing sites and recover historical data.
- Compile and archive global *in situ* snow measurements in a central location.
- Achieve optimal integration of appropriate satellite and *in situ* snow products.
- Improve accuracy of SWE retrievals from active and passive satellite sensors.
- Promote assimilation of snow albedo into numerical weather and climate models.
- Increase observation of trace gas fluxes through snow to better understand net carbon balance.
- Obtain integrated analyses of snow cover over both hemispheres through continuous coordination within Space Agencies through WMO/WCRP CliC, with advice from TOPC, AOPC and IUGG IACS.
- Encourage and support data submission to national centres such as the National Snow and Ice Data Center (USA) and to World Data Services.

1. Introduction

Approximately one third of the Earth's land surface may be covered seasonally by snow. Up to 50 percent of the Northern Hemisphere land surface has snow cover during the Northern Hemisphere winter. It has major effects on surface albedo and energy balance and modifies the overlying atmospheric thickness and surface temperatures. Snow cover has a number of important physical properties that exert an influence on global and regional energy, water and carbon cycles. Snow makes up a significant fraction of the water available for agriculture and water supply in many semi-arid regions of the world where changes in snow cover conditions can have serious economic and social impacts. Hence, regular monitoring of snow cover (extent, depth and water equivalent) has been identified as a high priority activity for global climate monitoring.

Snow depth is an important property of snow cover, influencing surface radiative exchange and heat transfer and affecting frozen ground and permafrost distribution and moisture recharge. It also has important operational and ecological implications and observations of this variable are used for a multitude of applications. Examples include roof snow load computations, assessment of winter survival of crops, biological studies, calculation of forest fire indices, validation of satellite algorithms and land surface process models and snow depth analyses in support of numerical weather prediction. Knowledge of the snow water equivalent (SWE) is critical in the assessment of the energy and water cycle in the climate system, in validating GCM snow cover simulations and for hydrology and water resource planning.

In the past decades, the growing importance of the climate change issue has prompted new needs for snow cover information over a wide range of spatial and temporal scales for climate change detection, for development of snow process models, and for validation activities (e.g. satellite snow cover products; physical snow models; output from global and regional climate models). Validation of multi-layer physical snowpack models requires detailed information on snowpack structure, surface albedo (reflectivity), temperature profiles, snowmelt and surface energy fluxes. The inclusion of small-scale processes such as canopy interception and sublimation in physical snow cover models (e.g. Pomeroy *et al*., 1998) has prompted a new need for information on the mass of snow intercepted and stored in the vegetation canopy. At a larger scale, land surface process and hydrological models (e.g. Verseghy, 1991; Cline *et al*., 1998) require information on the spatial distribution of snow cover properties to develop and validate methods and approaches to take account of subgrid scale variations in snow with terrain and vegetation cover (e.g. Essery, 1997). At even larger scales, global climate models (GCMs) have generated new needs for information on the global distribution of snow cover and water equivalent at monthly and climatologically-averaged time-scales for validating snow cover simulations. Barry (1997) provided an overview of the requirements and status of cryospheric data for model validation activities.

These new needs for snow cover information and snow properties over a wide range of spatial and temporal scales pose a number of challenges to the snow research community for observing and analysing snow cover information. The systematic collection of information on snow accumulation (snowfall, precipitation, precipitation type) and redistribution requires the development and application of new sensor technology and methods for sensor interpretation.

2. Definition and units of measure

SNOW COVER: in general, the accumulation of snow on the ground.

SNOW COVER EXTENT: the total land area covered by some amount of snow; typically reported in square kilometres.

SNOW COVER DEPTH: the combined total depth of both old and new snow on the ground, typically reported in centimetres.

SNOW WATER EQUIVALENT (SWE): the water content obtained from melting snow (i.e. the thickness of the layer of water that would result from melting a given snow depth) typically reported in millimetres.

SNOW COVER DURATION: This value is typically expressed as number of days of continuous, uninterrupted, snow cover at a given location for a given winter season, and sometimes simply as the number of days in total that snow existed on the ground in a given location, whether continuous or not.

Units of measure:

SNOW COVER EXTENT:	km2
SNOW COVER DEPTH:	cm
SNOW WATER EQUIVALENT:	mm

Measurements of the spatial distribution of SWE can be presented in units of kg m-2. The conversion from a mass of snow (kg m-2) to a depth of water (mm) is based on the fact that 1 mm of water spread over an area of 1 m2 weighs 1 kg.

3. Existing measurement methods, protocols and standards

Overview

It is essential for all observers to understand the importance of taking standard measurements in the prescribed consistent manner. Inconsistent observing and reporting methods result in incompatible data which can result in profoundly incorrect differences between stations and observers. For example, in support of improving the quality of snowfall, snow depth, and snow water equivalent measurements, the US National Weather Service has developed observation procedures using input from a broad array of expertise from climatologists, snow specialists, weather observers, and data users. A description of these procedures can be found in “The Snow Booklet” by Nolan J. Doesken and Arthur Judson, 1996 and see also: www.nws.noaa.gov/om/coop/snowguid.htm).

While for snow cover there is no specific global network, the parameters connected to snow, are related to the GTN-Hydrology. GTN-H is the result of the joint efforts of the WMO Hydrology and Water Resources (HWR) Department, the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS). GTN-H comprises existing networks, global databases and global data product centres, and is based around a Coordination Group, see http://gtn-h.unh.edu/.

The WMO Guide to Hydrological Practices (WMO report No. 168) 2008 – 6th Edition. Volume I: Hydrology - From Measurement to Hydrological Information, describes procedures for collecting measurements of snow cover, snow depth, and water equivalent of snow. Guidance for the location of gauges that are to be used to measure snow depth and water equivalent of snow is provided and discussion on the design of snow cover networks is given. Additional discussions on snow cover measurements is given in the WMO *Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture*.

Additional publications which describe measurement methods and standards include:

Armstrong, R.L. and Brun E. (Eds.) 2008. Snow and Climate: Physical Processes, Surface Energy Exchange and Modelling, Cambridge University Press, 219 p.

Fierz, C., R. Armstrong, Y. Durand, P. Etchevers, E. Greene, D.M. McCling, K. Nishimura, P.K. Satyawali and S. Sokratov, 2008. IACS International Classification for Seasonal Snow on the Ground, IHP-VI, Technical Documents in Hydrology, UNESCO, Paris, 2008.

Currently these types of guides are the closest thing that the snow measurement community has in regards to “standards”. However such guides may form a sound basis for developing international standards.

3.1 *In situ* measurements

3.1.1 Snow Depth

Identified GCOS requirements are for point measurements of daily snow depth at GSN (ground station network) stations but these requirements are expanded by wide ranging domestic needs for such data.

For the United States of America and other station snow depth data, consult the date archive at the National Snow and Ice Data Center (NSIDC) – http://nsidc.org and the National Climate Data Center - www.ncdc.noaa.gov/oa/ncdc.html. Manual observations, automatic snow depth sensors, are now being deployed at an increasing number of sites.

The Meteorological Service of Canada (MSC) coordinated a national hard-copy compilation of snow course observations from 1955 to 1985 (measurements by MSC, provincial water resource agencies and hydroelectric companies). At peak levels, in the early 1980s, there were over 1 700 snow course observations contributed by various agencies but this number declined to around 800 in the early 1990s. A number of agencies continued to send snow course data, in digital format, to MSC after 1985 and in 1995 a CRYSYS data rescue project was initiated to digitize all the available snow course data and place it on CD-ROM.

Coverage and frequency

Snow depth is measured at least once daily at many weather stations throughout the world, but these data are not always reported over the Global Telecommunications System (GTS). There are about 7 000 land stations in the GTS reports. Global snow depth data are available from the WMO-GTS Synoptic Reports for stations that do report that code group in real time[1]. Snowfall is not differentiated in 6-hourly/daily precipitation measurements at GTS weather stations although type of precipitation is reported in the synoptic weather code. Measurements of snow cover depth over extended areas together with an established local correlation with density make it possible to approximate the water equivalent of the snow cover.

Point- and line-measurement methods of snow depth

Manual determination of snow depths is made either by inserting a ruler or graduated probe, or by observing snow height on fixed markers. Care should be taken when using fixed markers to avoid errors because of local melt or snow drift around the marker. Sighting along the snow surface a few metres from the marker can make this error small. If snow depth is measured

1 See: ftp://ftp.ncdc.noaa.gov/pub/data/globalsod

at fixed points, care should be taken not to disturb the snow close to the markers.

Snow ruler

Depth measurements of snow accumulated on the ground can be made with a snow ruler or similar graduated rod which is pushed through the snow to the ground surface. Representative depth measurements by this method may be difficult to obtain in open areas since the snow cover undergoes drifting and redistribution by the wind, and may have embedded ice layers that limit penetration with a ruler. Care should be taken to ensure that the total depth is measured, including the depth of any ice layers which may be present. In typical examples, a number of measurements are made and averaged at each observing station.

Measurement with graduated snow stakes

The most common method for determining the depth of snow cover, primarily in regions of deep snow, is by means of calibrated stakes fixed at representative sites that can be inspected easily from distant ground points or from aircraft by means of binoculars or telescopes. The stakes should be painted white to minimize the undue melting of snow immediately surrounding them. This procedure may be acceptable if the representativeness of the site is proven and if the immediate surroundings of the site (about 10 metres in radius) are protected against trespassing. The readings are taken by sighting over the undisturbed snow surface. The entire length of the stake should be graduated in metres and centimetres. In inaccessible areas, stakes are provided with graduated crossbars so that they can be read from a distance with the aid of field glasses, telescopes, or from aircraft. In the case of measurements of snow depth from aircraft, visual readings of snow stakes may be supplemented by large-scale photographs of the snow stakes, which make the readings less subjective.

Ultrasonic ranging device

Automatic recording of snow depth can be made with ultrasonic techniques. Several relatively inexpensive snow-depth sensors with low power consumption and low maintenance requirements are now marketed. The distance from the sensor to the snow surface is determined from the time required by an emitted signal to be reflected and received by the sensor. Complementary air-temperature measurements are required to compensate for temperature dependent variations in the speed of sound in air. Anomalous results may occur during falling or blowing snow conditions. The sensor can not distinguish low-density new fallen snow from air (Lundberg *et al.* 2001). The ultrasonic snow-depth technique seems well suited for unattended, continuous and long-term measurements (Goodison, *et al.*, 1988).[2] The first sensor designed and manufactured by Campbell Scientific Canada (CSCC) had the model designation CSMAL01. The sensor subsequently had two major design changes, resulting in model designation UDG01 (Ultrasonic Depth Gauge) and most recently the SR50 (Sonic Ranger). Measurement range is 1.6 to 32.8 ft (0.5 to 10 m). It is capable of an accuracy of

2 In the early 1980's, the Atmospheric Environment Services of Environment Canada recognized the need for "a reliable, low cost automatic snow depth sensor" and subsequently developed such a sensor for operational use (Goodison *et al.*,1988). The ultrasonic wave reflection was selected as the method for measuring snow depth, a technique initially presented by Caillet *et al.* (1979), and Gubler (1981). The sensor determines the distance to a target by sending out ultrasonic sound pulses and listening for the returning echoes from a target. The time from transmit to the return of the echo is the basis for obtaining the distance measurement. Once the initial design and verification were completed, a prototype sensor and technology was licensed to Campbell Scientific (Canada) Corp. (CSCC).

±0.4” (1 cm) or 0.4% of distance to target which ever is greatest, according to the manufacturer (Campbell Scientific 2007).

Additional guidelines for measurement of snowfall and snow depth from the US National Weather Service (NWS)

The National Weather Service suggests to measure snowfall and snow depth in locations where the effects of blowing and drifting are minimized. In open areas where windblown snow cannot be avoided, several measurements may often be necessary to obtain an average depth and they should not include the largest drifts. If more than a once per day schedule is possible, it is best to make snow observation every six hours. This is the procedure followed by the US National Weather Service Forecast Offices. It is generally agreed that more than four, six-hourly observations should not be summed to determine 24-hour snowfall total. When penetrating the snow cover using a ruler or graduated probe, make sure the stick is pushed vertically into the snow until the bottom of the stick rests on the ground. Do not mistake an ice layer or crusted snow as “ground”. The measurement should reflect the average depth of snow, ice pellets, and glaze ice on the ground at a standard measurement site (not disturbed by human activities). Measurements from rooftops, paved areas, and the like should not be made. Snow depth should be reported to the nearest whole centimetre.

3.1.2 Snow water equivalent (SWE)

Snow water equivalent is one of the hydrological variables relevant to climate change that is part of the new GCOS/WMO-sponsored GTN-H (Global Terrestrial Network for Hydrology) which was implemented in 2001 to improve accessibility of already existing data.

The most commonly used approach for determining SWE is the gravimetric method which involves taking a vertical core through the snowpack, and weighing or melting the core to obtain the SWE. A variety of coring and weighing systems have been used around the world with varying lengths and diameters depending on measurement units and local snow conditions (see Sevruk, 1992). One of the earliest national SWE observing networks was established in Finland in 1909 (Kuusisto, 1984). However, systematic observation of SWE was not widespread until the middle of the twentieth century. In the US for example, the National Weather Service began regular point measurements of SWE at first-order stations during the winter of 1952/53 (Schmidlin, 1990). In order to obtain representative values of SWE, measurements are often carried out at regular marked intervals along a permanently marked transect or “snow course”. Many factors are involved in the design of a snow course (e.g. purpose, accessibility, terrain) and the reader is referred to Goodison *et al.* (1981) for a detailed discussion.

Snow water equivalent is determined at snow courses (North America) or along snow transects (Russia) at about 15-30 day or 10-day intervals, respectively. Snow courses are considered to give the most precise information about SWE for a whole catchment, but the high costs and the difficulties with access because of bad weather can lead to loss of data (Lundberg *et al.* 2001). The data are in agency archives and many are not digitized, European data are especially difficult to access (cost and other restrictions).

Snow course surveys should be undertaken at sites sufficiently accessible to ensure continuity of surveys and, if total seasonal accumulation should be measured, at elevations and exposures where there is little or no melting prior to peak accumulation. The ground surface should be cleared of rocks, stumps and bushes for two metres in all directions from each sampling point. In order to avoid any systematic error because of snow drift it may be necessary to perform an extensive survey, with long traverses and a large number of sampling points, prior to finally determining location, length and sampling distance for an established snow course.

3.2 Satellite measurements

Identified GCOS requirements for global snow cover area, or extent, specify a 25 km resolution. Stated GCOS requirements for SWE also include daily global satellite coverage at 25 km resolution. Meeting this requirement, however, necessitates satellite algorithm development and validation over all representative vegetation and terrain types, globally. Regional satellite retrievals of SWE from passive microwave data have proven successful. For example, operational SWE monitoring is undertaken by the Meteorological Service of Canada (MSC) providing detailed weekly data over the Canadian prairies, and adjacent boreal forest region, that is useful for hydrologic monitoring, water resource planning, and model validation. Work is currently in progress to apply these methods to the entire period of passive microwave data coverage (1978 onwards) to generate consistent gridded SWE datasets for this, and other, regions of Canada.

See Section 5.2 for examples of data sources for snow extent and SWE derived from satellite.

3.3 Summary of requirements and gaps

Maintenance of adequate, representative surface networks of snow observations must begin with documentation and analysis of required network densities in different environments. Resolution of the problem of data inaccessibility requires: promoting political commitment to data sharing; removing practical barriers by enhancing electronic inter-connectivity and meta-data; and data rescue and digitization. The provision of necessary resources to improve and make available existing archives of snow data will require national efforts. Development of snow products that blend multiple data sources and are globally applicable needs urgent focused attention. The research community through WCRP-CliC could help lead such an effort. A global snow product generated from the blending of *in situ* and satellite data is one of the goals of the ESA GlobSnow project. The TOPC in consultation with the AOPC, WCRP-CliC and WMO CBS should establish standards and protocols, design an optimum network, and recommend International Data Centre and analysis centre responsibilities. The guidelines on snow cover measurements provided in WMO guide No. 168 should be considered as potential methodologies for establishing ISO standards. TOPC's current cryosphere activities can provide a starting point, but this activity would require dedicated funding for meetings/workshops to agree on standards and protocols, funding for report preparation, and funding for filling gaps in networks. With regard to satellite remote sensing, there is a need to establish standard methods to validate and quantify the accuracy of passive microwave retrieval algorithms.

4. Contributing networks and agencies

Nearly all nations located in climate zones where snowfall occurs on a reasonably consistent basis through the winter season maintain some network of stations reporting snow cover information. However, the actual parameters measured, the spatial density of the reporting stations, the consistency of the reporting, and, perhaps most importantly, the availability of the data varies greatly from one country to another. The only truly global network is the WMO Global Telecommunications System (GTS), described in 3.1.1 above, where snow depth may be measured once daily at weather stations, but is not always reported over the GTS.

See the following section for examples of active networks and agencies where snow data are readily available on a timely basis and at no cost.

5. Available data and products

5.1 *In situ* data

Some examples of national products include:

(a) The Former Soviet Union Hydrological Snow Surveys are based on observations at 1 345 sites throughout the Former Soviet Union between 1966 and 1990, and at 91 of those sites between 1991 and 1996. These observations include snow depths at World Meteorological Organization (WMO) stations and snow depth and snow water equivalent measured over a nearby snow course transect. The station snow depth measurements are a ten-day average of individual snow depth measurements. The transect snow depth data are the spatial average of 100 to 200 individual measuring points. The transect snow water equivalent is the spatial average of twenty individual measuring points. This data set is available from NSIDC. (http://nsidc.org/data/g01170.html).

(b) The Historical Soviet Daily Snow Depth Version 2 (HSDSD) product is based on observations from 1881 to 1995 at 284 World Meteorological Organization (WMO) stations throughout Russia and the former Soviet Union. The area covered is 35° to 75° N latitude and 20° to 180° E longitude. The State Hydrometeorological Service in Obninsk, Russia, provided the data through the US-Russia Agreement on Co-operation in the Field of Protection of the Environment, Working Group VIII data exchange programme. (Armstrong, R. 2001. Historical Soviet Daily Snow Depth Version 2 (HSDSD). Boulder, CO, USA: National Snow and Ice Data Center. CD-ROM: http://nsidc.org/data/g01092.html.

(c) NOAA provides NWS/COOP Snow Depth and Snowfall Graphics and Data - daily snow depth and snowfall graphics (most recent 1, 2, 3 and 7 days) for the contiguous United States (National Weather Service, Climate Prediction Center, www.cpc.ncep.noaa.gov/products/season_update/snow_map/.

(d) Daily snow depth data for 1062 observing stations across the contiguous US covering the period 1871-1997 are available from the Carbon Dioxide Information and Analysis Center (CDIAC) http://cdiac.ornl.gov/ (Easterling *et al*., 1999).

(e) Daily snow depth data for Canada at several 1 000 stations covering the entire period of record up to 1999 are published on CD-ROM and are freely available for research use (Meteorological Service of Canada, 2000: Canadian Snow Data CD-ROM): CRYSYS Project, Climate Processes and Earth Observation Division, Meteorological Service of Canada, Downsview, Ontario]. Also, operational global daily snow depth analysis by the Canadian Meteorological Centre can be found at http://weatheroffice.ec.gc.ca/analysis/index_e.html.

Snow depth and water equivalent are also observed by other national, state, provincial and private networks in many countries on a daily, ten-day or monthly basis.

5.2 Satellite snow cover extent

(a) Operational products of areal extent of snow cover in the Northern Hemisphere are generated by the NOAA National Environmental Satellite Data and Information Service (NESDIS); weekly gridded data beginning in 1966 and a daily NH-extent map since May 1999, monthly statistics (frequency, anomaly) for NH, North America and Asia. Interactive Multisensor Snow and Ice Mapping System (IMS) Daily Northern Hemisphere Snow & Ice Analysis: http://orbit-net.nesdis.noaa.gov/crad/sat/surf/snow/HTML/snow.htm

(b) The NSIDC Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent product combines snow cover and sea ice extent at weekly intervals for October 1978 through the present, and snow cover alone beginning October 1966. The data set is the first representation of combined snow and sea ice measurements derived from satellite observations for the period of record. Data are provided in a 25 km equal area grid. http://nsidc.org/data/nsidc-0046.html

(c) The NSIDC Near Real-Time SSM/I EASE-Grid Daily Global Ice Concentration and Snow Extent product (Near Real-Time Ice and Snow Extent, NISE) provides daily, global near real-time maps of sea ice concentrations and snow extent. The National Snow and Ice Data Center (NSIDC) creates the NISE product using passive microwave data from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I). These data are not suitable for time series, anomalies, or trends analyses. They are meant to provide a best estimate of current ice and snow conditions based on information and algorithms available at the time the data are acquired. See http://nsidc.org/data/nise1.html

(d) The NASA Moderate Resolution Imaging Spectroradiometer (MODIS) snow products, beginning 24 February, 2000, include Level-2 swath data (MOD10_L2) at 500 m resolution, Level-3 gridded daily and 8-day composites (MOD10A1 and MOD10A2, respectively) at 500 m resolution, and Level-3 daily and 8-day global maps on a climate modeller's grid (MOD10C1 and MOD10C2, respectively) at 0.05 degree resolution. MODIS snow cover data are based on a snow mapping algorithm that employs a Normalized Difference Snow Index (NDSI) and other criteria tests. Data also contain local and global metadata http://modis-snow-ice.gsfc.nasa.gov/intro.html, and http://nsidc.org/data/modis/data_summaries/index.html

(e) The NASA Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) instrument on the NASA EOS Aqua satellite provides global passive microwave measurements of terrestrial, oceanic, and atmospheric variables for the investigation of water and energy cycles, beginning 19 June 2002. Daily, five day, and monthly Level-3 data sets contain SWE and quality assurance flags mapped to Northern and Southern Hemisphere 25 km Equal-Area Scalable Earth Grids (EASE-Grids). The standard AMSR-E SWE product has evolved from a static semi-empirical algorithm to a more dynamic algorithm that incorporates estimates of snow properties in the retrieval process http://nsidc.org/data/amsre

(f) NSIDC has produced the Global EASE-Grid Monthly Snow Water Equivalent Climatology Product. This data set comprises monthly satellite-derived snow water equivalent (SWE) climatologies from November 1978 through December 2008, updated routinely, gridded to the Northern and Southern 25 km EASE-Grids. This data set is the first available global product to merge snow water equivalent derived from SMMR and SSM/I passive microwave sensors with snow extent derived from weekly NOAA (optical sensor) snow maps. It currently is the only historical product to include Southern Hemisphere passive microwave-derived snow water equivalent. http://nsidc.org/data/nsidc-0271.html

(g) The NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC) provides comprehensive snow observations, analyses, data sets and map products for the US. www.nohrsc.noaa.gov/nsa/

- National Snow Observation Database
- Airborne Snow Surveys
- Satellite Snow Cover Mapping
- Snow Modeling and Data Assimilation
- Analyses, Maps, and Interactive Visualization Tools
- Integrated Snow Datasets for Geospatial Applications
- Applied Snow Research.

NOHRSC products and services support a wide variety of government and private-sector applications in water resource management, disaster emergency preparedness, weather and flood forecasting, agriculture, transportation and commerce. www.nohrsc.noaa.gov/snowsurvey/ The NOHRSC also measures snow water equivalent and soil moisture using gamma radiation remote sensing. This unique observing system includes two low-flying aircraft to conduct surveys in 31 states, including Alaska, as well as in eight Canadian provinces. The data are incorporated into the National Snow Analyses. Survey data, schedules, flight line locations, aerial photos, and information can be found at www.nohrsc.noaa.gov/nh_snowcover/

(h) The US Department of Agriculture, Natural Resources Conservation Service (NRCS) operates an extensive, automated system to collect snowpack and related climatic data at more than 730 sites in the Western United States called SNOTEL (for SNOwpack TELemetry). Sites are designed to operate unattended and without maintenance for a year. Basic SNOTEL sites have a pressure sensing snow pillow, storage precipitation gage, and air temperature sensor. www.wcc.nrcs.usda.gov/factpub/sntlfct1.html

(i) The NASA Cold Land Processes Field Experiment (CLPX) conducted during the period 2001-2004 was a multi-sensor, multi-scale field programme of nested study areas in Colorado and Wyoming, USA, designed to extend the current local-scale understanding of water fluxes, storage, and transformations to regional and global scales. Using ground, airborne, and spaceborne observations, the experiment emphasizes the development of a strong synergism between process-oriented understanding, land surface models, and microwave remote sensing. Data were collected during two seasons: mid-winter, when conditions were generally frozen and dry, and early spring, a transitional period when both frozen and thawed, dry and wet conditions are widespread. For more information on CLPX, see http://nsidc.org/data/clpx/intro.html

In other locations of the world where accurate snowmelt runoff forecasts are required for hydropower management, the regional-scale application of satellite data often plays a very important role. For example, Norway is one of the most active countries in the application of visible remote sensing where programmes are numerous and include e.g. Statkraft SnowSat System, the NVE Snow Cover System, the Cap Gemini Snow View Information System, Tromso Satellite Station Basic Snow Cover Map, and the Norwegian Meteorological Institute daily and weekly maps (Solberg *et al.*, 1997).

6. Conclusions

Snowfall and snow cover play a key role with respect to feedback mechanisms within the climate system (albedo, runoff, soil moisture and vegetation) and are important variables in monitoring climate change. About one third of the Earth's land surface is seasonally snow covered and seasonal snow melt is a key factor in runoff regimes in middle and high latitudes. Snow thickness and snow cover duration affect the permafrost thermal state, the depth and timing of seasonal soil freeze/thaw /break-up, and melt of on land ice and sea ice.

In spite of the importance of snow cover, many problems arise because: (a) snow cover data are collected, even within one country, by several agencies with differing goals; (b) funding support for snow research is fragmentary and not well coordinated; (c) the cost of surface networks is leading to their contraction, or automated measurement using different instrumentation whose compatibility is not yet determined, and (d) many existing data are not readily accessible.

Station networks are generally contracting – especially in the Russian Federation – and more generally, automation is changing the nature of snow-depth measurements (e.g. across Canada). An associated problem is the contraction in snowfall measurements – increasingly automated precipitation gauge measurements do not discriminate between liquid and solid precipitation. Accessible documentation is needed that describes where and when these changes have occurred. National Meteorological and Hydrological Services need to document the contraction of *in situ* observation networks and ensure that adequate coverage of representative measurements are maintained to meet GCOS/GTOS requirements, in coordination with such organizations as WCRP CliC, GTN-H, and IUGG IACS.

Currently no international standards exist for measuring snow cover. The establishment of ISO standards would therefore be desirable and should be a goal of GTOS for the basic categories of snow cover measurements. International coordination is also required to define best practices and guidelines for *in situ*, airborne and satellite snow cover measurements.

7. Recommendations

7.1 Standards and methods – *in situ*

Strengthen and maintain existing snow cover, snowfall observing sites and recover historical data through coordinated efforts by National Meteorological and Hydrological Services and research agencies, in cooperation with WMO CHy, WMO CBS and WCRP, with oversight by TOPC and AOPC and GTN-H.

7.2 Standards and methods – satellite

Assist in providing and maintaining global satellite coverage of snow extent and snow water equivalent. Optimal procedures to generate blended products of surface observations of snow cover with visible and microwave satellite data and related airborne measurements need to be agreed upon and implemented by national space agencies, and other national services, and research groups involved in snow mapping. Snow cover extent is mapped daily by operational satellites, but sensor channels change and continuing research and surface observations are needed to calibrate and systematically validate algorithms used to produce products for snow depth and snow water equivalent. The Climate and

Cryosphere Project (CliC) of the WCRP, along with the IUGG International Association of Cryospheric Sciences (IACS) should take the lead in organizing this with GEWEX and other involved working groups.

7.3 Summary of recommendations

- WMO GCW, in collaboration with GCOS/GTOS, should establish a forum to define best practices, develop guidelines and standards for *in situ*, airborne or satellite snow cover measurements.
- TOPC, in consultation with the AOPC, WCRP-CliC and WMO CBS should establish standards and protocols, provide guidelines for the design of optimal networks, and recommend International Data Centre and analysis centre responsibilities.
- Strengthen and maintain existing snow cover and snowfall observing sites and recover historical data.
- Compile and archive global *in situ* snow measurements in a central location.
- Achieve optimal integration of appropriate satellite and *in situ* snow products.
- Improve accuracy of SWE retrievals from active and passive satellite sensors.
- Promote assimilation of snow albedo into numerical weather and climate models.
- Increase observation of trace gas fluxes through snow to better understand net carbon balance.
- Obtain integrated analyses of snow cover over both hemispheres through continuous coordination within Space Agencies through WMO/WCRP CliC, with advice from TOPC, AOPC and IUGG IACS.
- Encourage and support data submission to national centres such as the National Snow and Ice Data Center (USA) and to World Data Services.

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Web Sites

Climate and Cryosphere
http://clic.npolar.no/

Cryospheric System in Canada
www.msc.ec.gc.ca/crysys/

Global Terrestrial Network for Hydrology
http://gtn-h.unh.edu/GlobSnow
http://globsnow.fmi.fi/

IGOS Cryosphere
http://igos-cryosphere.org/documents.html

International Association of Cryospheric Sciences
www.iugg.org/associations/iacs.html

National Operational Hydrologic Remote Sensing Center
www.nohrsc.noaa.gov/snowsurvey/

National Snow and Ice Data Center
http://nsidc.org

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