Challenges in Snow Measurement: Solid Precipitation and Snow Cover

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This summary is intended to provide readers with an overview of some of the issues in measuring solid precipitation and snow cover. There are selected references and recommended reading provided at the end. This summary is meant to accompany the presentation made at the meeting.

Snowfall constitutes a significant part of yearly total precipitation over the globe's cold climate regions, which makes it an important indicator for climate change and variation. Snowfall is critical in basin- and regional-scale water cycle and water resources, for glacier and ice sheet accumulation, in influencing the large-scale land-surface radiation and energy budget and for ecosystem dynamics, water resource engineering, and human societies and activities, including transportation, disaster prevention, agriculture, tourism and recreation. Snowfall, snow depth, snow cover and solid precipitation are important measurements to be made in cold climate regions, each having their unique challenges of measurement, whether from in-situ or remotely sensed sensors. It is especially important to remember that precipitation includes the sum of the accumulated depths of the water equivalent of all precipitation over a horizontal unit area between observing periods, from rain and snow. Methods of measurement are different for rainfall, snowfall, total precipitation, snow depth and the water equivalent of snow cover (SWE). It is useful to refer to the WMO Guide to Hydrological Practices and WMO Guide to Climatological Practices for standards and practices recommended by WMO Commissions.

It is important to make clear the distinction between snowfall and solid precipitation measurements. Snowfall is the depth of freshly fallen snow that accumulates during the observing period. Snow rulers have been traditionally used for snowfall observation in national or regional networks and provide the depth of freshly fallen snow only, not the water equivalent of the snowfall. In many countries, solid precipitation is estimated from daily total snowfall assuming a fresh snowfall density of 100 kgm^{-3}, but density commonly exhibits large temporal and spatial variations (Goodison et al., 1981). Doesken and Judson (1997) provide a good overview of some of the practical problems associated with observing snowfall.The ruler is also used to measure the depth of snow on the ground – a measure of net accumulation. .

Solid precipitation is the equivalent liquid water of the snowfall, commonly measured by a precipitation gauge with the measurement being influenced by the catch characteristics of the particular gauge. The precipitation gauge can range from a standard rain gauge to a specially shielded snow gauge. *In-situ* methods of measurement of solid precipitation include manual and automatic methods, and are the core of national and regional observing networks. Manual and all-weather automatic gauges can measure the water equivalent of snowfall. Manual gauges can measure rate of snowfall at 6-hourly to daily time intervals (synoptic or climate observation periods), and auto gauges can provide hourly (or sub-hourly) snowfall precipitation (rate) information.

A fundamental problem of gauge measurement of snow precipitation is that most precipitation gauges catch less falling snow than the "true" amount because accelerated wind flow over the top of the gauge reduces the number of snowflakes able to enter the orifice. Precipitation gauges, shields and observing practices vary considerably from country to country, and over time (Goodison et al., 1998). The recent trend toward increased automation of climate observations has important consequences for the homogeneity of precipitation measurement series. Weighing gauges were found to be the most practical but these can introduce a "timing" error due to snow or freezing precipitation sticking to the inside of the gauge and melting at some later time. Automated gauges, like manual ones, can also catch blowing snow and provide no information on the liquid/solid fractions of precipitation. These problems complicate the real-time interpretation of the data as well as the application of procedures to adjust for systematic errors. Users of these data must consider potential errors in measurement when they use data from cold climate regions.

A WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998) was conducted to assess national methods of measuring solid precipitation against methods whose accuracy and reliability were known, including past and current procedures, automated systems and new methods of observation. The intercomparison was especially designed to: determine wind related errors in national methods of measuring solid precipitation, including consideration of wetting and evaporative losses; derive standard methods for adjusting solid precipitation measurements; and introduce a reference method of solid precipitation measurement for general use to calibrate any type of precipitation gauge. Systematic errors for manual catchment-type gauges are primarily wind (with some temperature effect), wetting loss, evaporation loss, non-zero trace, capping of gauge orifice and blowing snow. Fig 1 shows the results for four of the most commonly used snow gauges. It shows the challenge of getting consistent network measurements over time or between countries using different methods. Automation introduces another set of potential errors, which certainly affects consistency of data over time as new methods are introduced. This definitely affects consistency of data for model evaluation, assessing reanalyses and for using network data in data assimilation.

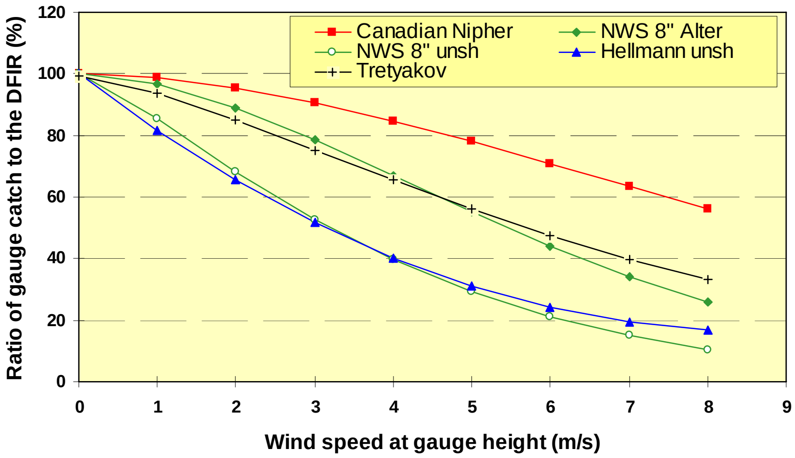

Figure 1 Catch Efficiency vs Wind for the 4 most widely used gauges

Using this knowledge, Yang, Legates and Kane have developed a Bias-Corrected Precipitation Database and Climatology for Arctic Regions (http://www.uaf.edu/water/faculty/yang/bcp/index.htm). As well the Global Precipitation Climatology Centre (GPCC) has worked on developing methods for correcting daily precipitation records at synoptic stations (http://www.dwd.de/en/FundE/Klima/KLIS/int/GPCC/GPCC.htm). An example of a new product is shown in Fig 2.

Logically, one would like to obtain estimates of falling snow from satellites. Gruber and Levizzani conducted an assessment of global precipitation derived from satellite and in-situ methods, and especially the products of the Global Precipitation Climatology Project (http://cics.umd.edu/~yin/GPCP//ASSESSMENT/assessment.html). Satellite estimation of falling snow remains a challenge in snow and ice covered regions. They note that in general there is a decrease in accuracy as the precipitation becomes light, the environment becomes more polar, and/or the surface becomes icy or frozen. Despite the relatively high quality ascribed to passive microwave estimates, all current algorithms falter in cold-land, icy-surface, and polar conditions. There is a need to determine snow rate using remotely sensed data and accurate precipitation in complex terrain, the latter being a problem for remote sensing techniques and gauges. For snowfall precipitation, it is in the data sparse regions of the high latitudes, alpine zones and cold climates that both satellite and gauge measurements remain a challenge, hindering our accurate determination of precipitation in these regions. Another possibility in the future is the application of data assimilation methods to observed and modeled precipitation in order to obtain a dynamically, physically and hydrologically consistent field of precipitation. This would require a collaborative research effort among data producers and modelers.

A WCRP Workshop (CliC/GEWEX) on determination of Solid precipitation in Cold Climate Regions (CliC, 2002 - http://clic.npolar.no/disc/) assessed issues, gaps and challenges in the measurement of precipitation. These still are valid, and are as follows:

- Adjustment of measured precipitation across national boundaries, collaboratively among nations
- Comparison of adjustment approaches for different applications
- Error analysis of adjusted products
- Adjustment of measured precipitation on a global scale. Validation? Role for GPCC.
- Determining precipitation for mountainous regions and ice sheets, e.g. Antarctica. Measured and modelled?
- Evaluate the validity of the bias correction procedures for the polar regions. WCRP (CliC) sponsored intercomparisons?
- Development of on-line metadata

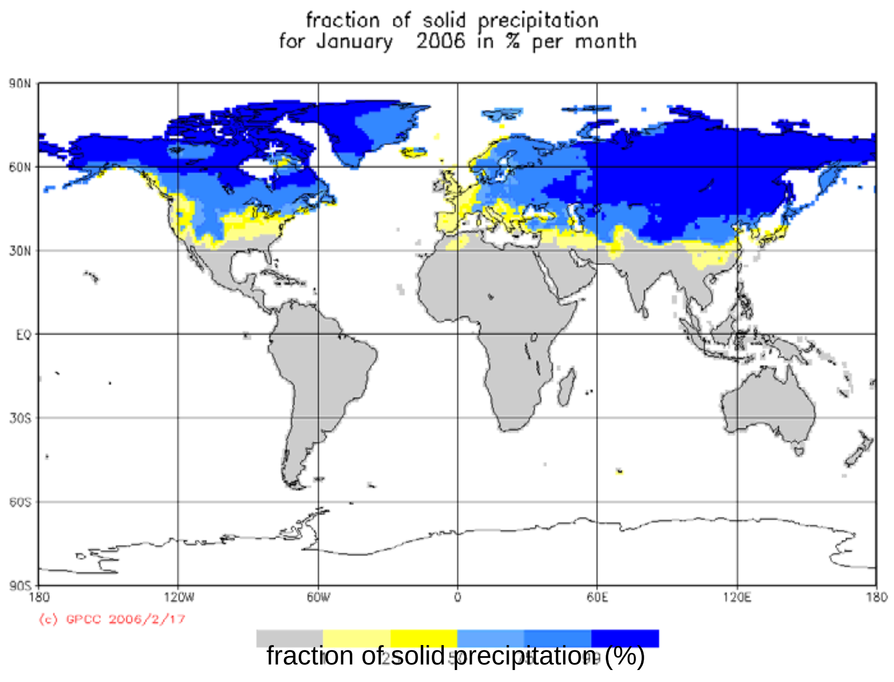

Figure 2: New gridded precipitation product produced by GPCC

- Determination of precipitation amount and type in data sparse regions in a changing climate
- Automation of precipitation measurements (instruments, errors, adjustment, archiving, GTS data, etc)
- Development of gridded, regional precipitation products (scale of RCM, hydrological model) for validation of climate model simulations and for initializing distributed hydrological model
- Development of integrated ("fused") precipitation products from in-situ, satellite, radar, models
- Human resource capacity, especially for measurement issues
- Ability of Global Precipitation Measurement System to "measure" solid precipitation

Today, we can still ask:

- What can we do for determining precipitation in polar regions for the IPY (March 1 2007-March 1 2009)
- What do modellers need to validate precipitation in cold climate regions; can gauge data be confidently used in data assimilation?
- Validation of precipiation measurements remains a real need

Snow depth is the most obvious property of a snowpack. Manual observations of daily snow depth, normally with a ruler, have been carried out in association with regular meteorological observation programs at principal and climate stations in most countries with a seasonal snow cover. It is important to remember that snow depth observations are subject to the same sources of inhomogeneity as other climatological elements e.g. changes in station location, changes in observing time, changes in measuring units, changes in observers, and urban effects (warming and dirtying of snow from pollution). It is also important to note that many *in situ* snow depth observing sites are in open locations (e.g. airports) and may not be representative of snow conditions over the surrounding area, especially in surrounding vegetated areas. This is an issue when comparing *in situ* snow depth observations to snow cover information derived from remotely sensed sources. Automated *in situ* snow depth measurements can be made with ultrasonic snow depth sensors. These are especially useful at remote stations. There are challenges in deploying these sensors to obtain a "representative" measurement, but they offer the capability of obtaining data more frequently. Users of snow depth data should ensure they know how the measurements were obtained as manual and automatic methods will provide different values, especially for open environments where snow is easily redistributed

Observations of snow-cover extent from visible, near-infrared, and microwave sensors on polar orbiting and geostationary satellites. NOAA has mapped the areal extent of snow cover in the Northern Hemisphere on a weekly basis using optical satellite imagery (e.g., AVHRR, GOES). This data set is the longest satellite-derived record (> 30 years) of snow extent and has been used as the basis for many analyses of snow cover variability and change on a hemispheric and continental basis. Continuation of this record now is based on AVHRR and MODIS optical/infrared data and SSM/I and AMSR/E and is expected to continue in the future. Space-based capabilities for observing snow depth and SWE are more limited than extent. Snow depth information has been estimated from passive microwave satellite data (e.g. Chang *et al.*, 1987), which has the advantage of all-weather coverage. Passive microwave data are not routinely used for snow depth mapping as they are sensitive to liquid water in the snow, vegetation cover, and seasonal changes in snowpack structure. The derivation of snow depth from passive microwave data also requires that certain assumptions be made about snow density and grain size.

Snow water equivalent (SWE) is defined in the International Classification for Seasonal Snow on the Ground as the depth of water if a snow cover is completely melted, expressed in millimeters, on a corresponding horizontal surface area. 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. Goodison *et al*. (1981) and Pomeroy and Gray (1985) provide discussions on the design of snow courses and issues related to variability related to siting, terrain and vegetation. Automated surface-based observations of SWE are possible from devices such as snow pillows that measure the mass of snow over a small area from displaced fluid or a pressure transducer.

SWE information can also be derived from a variety of aircraft or satellite sensors with varying degrees of success (Rango *et al.*, 2000). Environment Canada produces a weekly product for open areas in western and northern Canada using passive microwave data, and the information is used operationally by water, agriculture and hydropower agencies. Currently the most accurate estimates are obtained from region-specific empirical algorithms, where limiting the geographic domain helps to reduce the variation of sensitive factors. SWE algorithms are not currently considered reliable over mountainous and dense forest while over open tundra SWE retrieval is affected by highly variable snow distribution, wind slab, and lake ice. Wet snow also prevents accurate retrievals of SWE. Comparisons against AVHRR data and model simulations showed good agreement over tundra when SWE retrievals were converted to snow covered area. Synthetic aperture radar (SAR) observations overcome the resolution problem, but current sensors operate at frequencies too low to be useful for most snowpacks.

Although there is a strong desire and need to develop methods for the use of satellite data, surface observing networks are still the backbone for precipitation and other cryospheric data in cold climate regions. Evaluation and validation of measurement methods is an ongoing need, as it is in modelling. Some thoughts that affect our way forward include:

- **automation** is a major challenge
- **networks aren't sexy**… hard to attract the investment needed to keep current networks operating – long term monitoring costs should not be under estimated, including decommissioning
- Funding is often short term – data monitoring is long term
- **Who should operate** monitoring networks – operational agencies who have the mandate – eg WMO members
- don't underestimate the **resources needed to maintain an effective national data archive**
- unless data and information are easy to obtain (e.g. online free access) and have well-documented meta-data, the huge investment in observing systems is being wasted
- **avoid custom solutions** to data management; open source is the way to go.
- **Partnerships** in operating sites provide significant opportunities in a northern environment

Many relevant and related cryosphere documents may be accessed from the site http://stratus.ssec.wisc.edu/cryos/documents.html. Readers are urged to reference the IGOS-P cryosphere document (Key et al., 2006) for further information on current observation procedures and discussion of gaps and future needs. The presentation drew on these documents and recent results and contributions from CliC Science Steering Group members and other cryospheric scientists. This presentation would not have been possible without these contributions.

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