57th EASTERN SNOW CONFERENCE
Syracuse, New York, USA, 2000

Seasonal Snow Cover Monitoring in Canada: An Assessment of Canadian Contributions for Global Climate Monitoring

ROSS D. BROWN,[1] ANNE E. WALKER, AND BARRY GOODISON

ABSTRACT

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) was identified as a high priority activity for global climate monitoring (Cihlar et al., 1997). In 1998, a major effort was initiated in Canada to develop an Initial Observational System (IOS) for contributing to the World Meteorological Organization (WMO) Global Climate Observing System (GCOS). This has involved a detailed assessment of existing networks, evaluation of the role of remote sensing, identification of problem areas, and the development of recommendations to address them. This paper presents the results of this ongoing process, and updates the previous assessment carried out by Barry (1995).

Key Words: Global Climate Observing System, Monitoring, Snow cover

---

[1] Climate Processes and Earth Observation Division, Climate Research Branch, Meteorological Service of Canada (MSC), 2121 Trans-Canada Highway, Dorval, Qc, H9P 1J3, CANADA
email: ross.brown@ec.gc.ca

BACKGROUND

The GCOS program was established in 1992 to (1) characterize the current climate; (2) detect climate change; (3) determine the rate of change and assist in attributing the causes of change; (4) determine climate forcing resulting from changing concentrations of greenhouse gases and other anthropogenic causes; (5) validate models and assist in prediction of the future climate; and (6) understand and quantify impacts of climate change on human activities and natural systems.

Because of the large fraction of the Northern Hemisphere (NH) cryosphere included in Canada's territory, and a tradition of expertise in cryospheric data collection and research, Canada is viewed as a leader in cryospheric monitoring by the international community, especially in the area of remote sensing technology. Barry (1995) carried out an assessment of Canada's ability to contribute to cryospheric monitoring in support of GCOS and identified a number of shortcomings, notably a reduction in many of the in-situ observing networks and poor data accessibility. The purpose of this paper is to expand and update the Barry (1995) assessment for snow cover as part of a larger ongoing effort by the Canadian cryospheric community (e.g., Brown et al., 1999) to develop a Canadian Cryosphere Plan for GCOS. This activity is being led by the Meteorological Service of Canada (MSC).

INTRODUCTION

Snow cover exhibits the largest spatial extent of any component of the cryosphere in Canada, and exerts a significant influence on climate and hydrology through modification of energy and moisture transfers and the storage of water. Snow cover is considered to be an effective climate integrator and a useful component to monitor since it responds to both temperature and precipitation. Snow cover in Canada has been observed to exhibit considerable interannual and regional variability (Brown and Goodison, 1996) with significant reductions in winter snow depth and spring snow cover extent (SCE) observed over much of the country since the late 1970s (Brown and Braaten, 1998). There is a well-established negative relationship between SCE and air temperature (Robinson and Dewey, 1990), and GCM doubled-CO_2 simulations suggest extensive northward retreat in snow cover over Canada (Boer et al., 2000). A major reduction in snow cover would have widespread ecological and economic impacts (e.g., agriculture, hydropower production, drinking water, fish habitat) so there is significant interest in being able to monitor snow cover conditions in Canada and to quantify observed snow cover variability.

GCOS requirements for observing the cryosphere are outlined in the GCOS/GTOS plan for terrestrial climate-related observations (Cihlar et al., 1997). Priority 1 GCOS snow cover variables identified for climate monitoring were snow cover extent, snow depth and snow water equivalent (SWE). Snowfall and solid precipitation are also included in this discussion as these are considered equally important variables for climate monitoring in Canada. The following sections discuss GCOS needs and the status and ability of Canadian observing systems to meet these needs

SNOW COVER EXTENT (SCE)

GCOS requirements for daily monitoring of global snow cover extent at ~25 km resolution are currently met over the NH by the daily operational snow cover extent product from NOAA/NESDIS initiated in 1999 (http://www.cpc.ncep.noaa.gov/data/daily_snow/). This is a considerable improvement over the earlier weekly product (~190.5 km resolution), but it has created some homogeneity issues for snow cover monitoring (particularly in mountainous areas) that are still unresolved at this time. Within Canada, daily snow cover extent information can also be inferred from the Canadian Meteorological Centre (CMC) daily snow depth analysis, described in the snow depth section below. Information on historical variation in Canadian regional and continental snow cover extent has also been derived from reconstructed (Brown and Goodison, 1996) and observed (Brown, 2000) snow depth information.

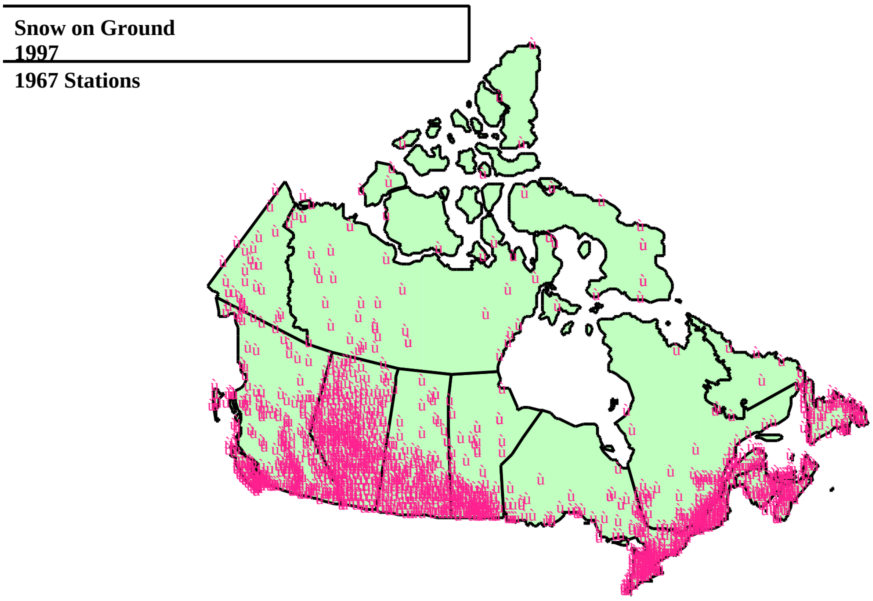

Figure 1. Current network of stations observing daily depth of snow on the ground (DLY04 element 013). Source: T. Allsop (MSC) 15/02/1999.

While continental-scale SCE is an important indicator of large-scale warming, monitoring of other snow cover properties is required for documenting regional-scale variability and change. Goodison and Walker (1993) suggested monitoring the following snow cover properties: SWE at peak accumulation, time of peak SWE accumulation, number of days with continuous snow cover, date of melt onset, and frequency of winter thaw events. Warming would also be accompanied by increased frequencies of mixed precipitation and rain-on-snow events that have implications for snowmelt, snow depth and snow density. Effective monitoring of these properties requires the integration of both in-situ and remotely sensed data. The need for comprehensive satellite/in-situ monitoring of snow cover was recently highlighted by Brown (2000) who found that April SWE and SCE over the interior of North America (NA) had trends of opposite sign (SWE decrease, SCE increase) over much of the 20th century.

SNOW DEPTH

The depth of snow on the ground is important for surface energy exchanges (e.g., albedo, surface roughness, and thermal properties), for frost penetration, and for plants and animals that depend on snow cover for shelter. Within Canada, daily snow depth data are used in many applications such as roof snow load calculations for the National Building Code, snow clearing contracts, winter survival of crops, biological studies, and calculation of forest fire severity. The research community routinely uses snow depth data for validation of satellite algorithms and for validation of the snow process models. The Canadian daily snow depth data have also been used to reconstruct snow-covered areas to extend the satellite SCE record back to the early 1900s (Brown and Goodison, 1996; Brown, 2000). GCOS requirements for snow depth are daily point measurements at existing climate and synoptic stations that comprise the GCOS surface network.

Canadian daily snow depth observing program

Regular daily ruler observations of the depth of snow on the ground have been made at most Canadian synoptic stations since the 1950s. Previously, snow on the ground only had to be measured and reported on the last day of the month, although there is some pre-1950 daily and weekly snow depth data for a small number of stations. The daily observing program was extended to climatological stations in the early 1980s, approximately doubling the number of stations in the network. The current network is inherently biased to southern latitudes and low elevations (Fig. 1). This is a significant shortcoming as alpine regions, for example, may experience differing snow cover responses to climate warming depending on latitude and elevation. For example, increased precipitation and warming may lead to a narrower, steeper snow wedge in mountainous areas which has important implications for water storage, runoff, and the ski industry.

Daily and weekly measurements of snow depth extend back to the 1930s at some stations, and these data plus missing data from some Arctic sites were digitized under a data rescue effort supported by the CRYSYS project (Goodison et al., 1999). The rescue included the filling of missing data using daily snow depth estimates derived from daily snowfall and temperature data. The updated snow depth data set is available for research purposes (http://www.msc.ec.gc.ca/crysys/) and was used by Brown and Braaten (1998) and Brown (2000) to document snow cover variability over NA since 1915. Brown and Braaten (1998) also carried out a detailed assessment of the quality of the Canadian snow depth data. The approach used followed Robinson (1989) and involved comparing daily changes in snow depth with expected changes based on reported snowfall and maximum air temperature. The results revealed that across all regions of Canada, more than 98.5% of non-zero snow depth data were internally consistent.

The Canadian daily snow depth observing program has experienced a recent decline due to automation, changes in observing practice, and closure of some manned stations. The number of stations reporting daily snow depth in the post-1996 period was down 20–30% compared to the 1981–1994 period (Fig. 2). The automation decline is related to the replacement of manned stations with READAC autostations that cannot be interfaced with available automated snow depth sensors. This has resulted in the termination of the daily snow depth record at some locations with long periods of record, e.g., Dorval Airport. The Campbell-Scientific automatic snow depth sensor is capable of providing data within the accuracy limits of GCOS, provided there is careful QC of the data. Ultrasonic sensors measure snow depth over a small footprint at a single point, which makes careful site selection essential, particularly at airport sites that are often exposed and where snow is subject to wind redistribution. An advantage of the ultrasonic sensor is consistent high temporal resolution data that are extremely useful for snow process studies (e.g., snow metamorphism and redistribution) and validation of physical snow process models.

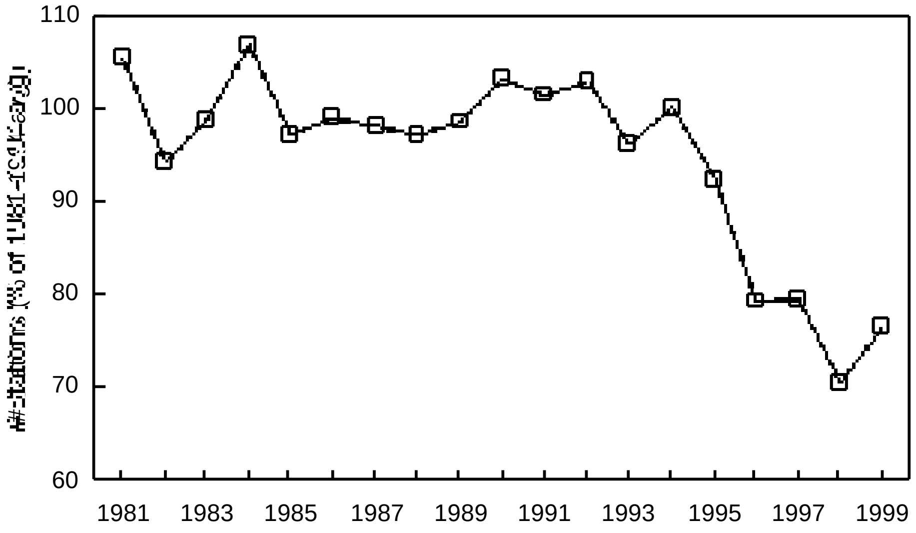

Figure 2. Number of stations with > 80% non-missing January daily snow depth data in the AES Climate Archive expressed as a percentage of the 1981–1994 mean. Source: R. Brown (MSC) 15/05/2000.

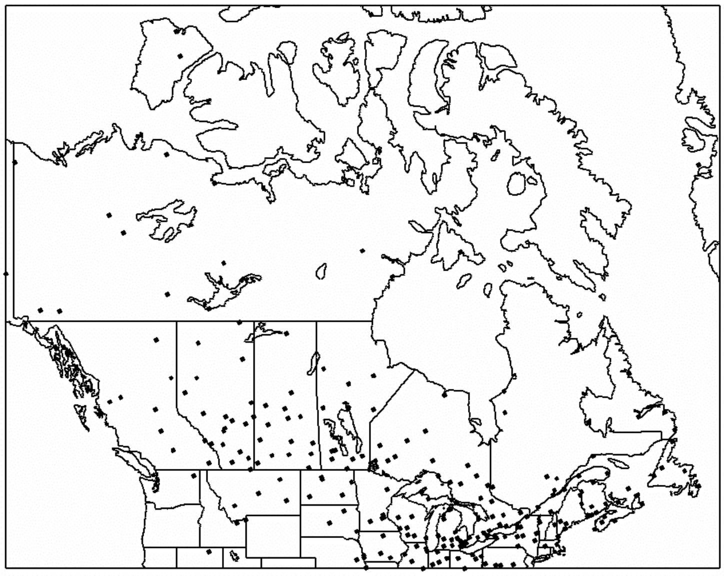

Figure 3. Distribution of stations reporting daily snow depth in synoptic messages to the CMC snow depth analysis for January 14, 1999. Source: B. Brasnett (CMC) 15/01/1999.

Canadian Meteorological Centre (CMC) daily snow depth analysis

CMC introduced a new, physically based daily snow depth analysis scheme in 1998 (Brasnett, 1999) in response to demands for more realistic specification of surface cover properties such as albedo and snow cover fraction in weather forecast models. The analysis incorporates snow depth observations included on all synoptic reports, meteorological aviation reports, and special aviation reports. The analysis is updated every six hours using the method of optimum interpolation. The effect of elevation is included in the interpolation to avoid smearing information over inappropriate elevation ranges. Precipitation forecasts (six hour) from the CMC global model are used to estimate the new snow accumulation between analysis times. The precipitation is assumed to be snow if the analyzed screen-level temperature is <0°. A melting algorithm removes mass from the snowpack at the rate of 0.15-mm SWE per hour per degree K for air temperatures above freezing. A simple snow-aging scheme is included to convert SWE to snow depth.

The CMC analysis differs substantially from the NOAA snow cover product as it is based solely on *in-situ* daily snow depth observations, with spatial and temporal continuity provided through the temperature and precipitation fields generated by the CMC global forecast model. An important point to note is that only a fraction of the total network reporting the depth of snow on the ground contributes to this product. An example of stations contributing observations on January 14, 1999, is provided in Figure 3. The CMC product has been found to compare well with the NOAA/NESDIS daily snow cover map, and in some cases to out-perform it, particularly along the snow edge over eastern NA. A known weakness is underprediction of snow depths in the lee of the Rocky Mountains related to an underprediction of precipitation by the CMC forecast model. The Brasnett (1999) snow depth analysis scheme is being used to develop a daily snow depth reanalysis for NA over the 1979–1996 period for validation of General Circulation Models.

SNOWFALL AND SOLID PRECIPITATION

There are compelling reasons for collecting accurate information on snowfall. Accurate precipitation data (adjusted for systematic errors) are essential (1) to balance the energy and water cycle in the climate system; (2) for climate monitoring; and (3) for understanding key components of the cryosphere such as snow-covered area, snow water equivalent and glacier mass balance. Precipitation is expected to increase in response to global warming (IPCC, 1996) and there is evidence (Bradley et al., 1987; Vinnikov et al., 1990; Groisman and Easterling, 1994; Mekis and Hogg, 1999) that precipitation has exhibited a significant upward trend this century. Warming is also likely to result in changes in the solid–liquid fraction of precipitation in shoulder seasons. Accurate information on precipitation intensity, timing, and solid–liquid fraction are also needed to correctly simulate snowpack development and snowmelt.

Snowfall, however, is notoriously difficult to observe accurately. Before elaborating on some of these difficulties, it is important to make clear the distinction between snowfall and solid precipitation. Snowfall is the depth of freshly fallen snow that accumulates during the observing period, and has been traditionally measured with a ruler. Solid precipitation is the amount of liquid water in the snowfall intercepted by a precipitation gauge. At manual Canadian climate stations, the depth of new snow is measured at each observation (generally twice per day) and the snowfall water equivalent is estimated assuming a fresh snowfall density of 100 kg m^{-3} for all stations in Canada. At principal and synoptic stations, snowfall is measured every six hours and recorded separately from the precipitation measurement. Introduction of the manual Canadian Nipher shielded snow gauge at synoptic stations in the early 1960s allowed for independent measurements of snowfall and solid precipitation.

Elimination of systematic errors in precipitation measurement is a major action item of GCOS and associated initiatives of the World Climate Research Program. The largest measurement errors are associated with solid precipitation (especially under-measurement due to wind). MSC has made a major contribution to quantify and develop procedures to address these errors through its own research programs and through its leadership and coordination of the WMO Solid Precipitation Measurement Intercomparison Project (Goodison et al., 1998). The results of these studies have been applied to correct six-hour precipitation totals for sites in Canada with Nipher gauges, and associated hourly wind speed observations. The results have also been incorporated into an adjustment procedure for daily snowfall data from volunteer stations, which was applied to investigate variability and trend in Canadian snowfall data (Mekis and Hogg, 1999). Adjusted monthly total rainfall and snowfall are available from http://ccrp.tor.ec.gc.ca/HCCD2/ for the period from the late 1800s to 1998. Real-time correction of autostation precipitation totals is possible if wind speed sensors are installed to measure wind speed at gauge height. This has been flagged as an important action item for meeting GCOS and Canadian needs for cryospheric monitoring.

The most serious concern with current snowfall precipitation measurement in Canada is the degradation of the observations associated with automation (change in method of measurement, accuracy, timing, decreasing network, loss of snowfall measurements). A detailed assessment of the impact of automation on precipitation measurements was provided by Goodison et al. (1998). There is no easy solution to this problem; available automated sensors are currently being assessed against MSC standards for autogauges. Adding to the difficulties for the cryospheric community is the modification of observing programs essential for climate related studies without adequate consultation with the user community.

SNOW WATER EQUIVALENT

In many applications (e.g., flood forecasting, agriculture, reservoir management), the amount of water held in the snowpack (snow water equivalent) is of primary importance. Changes in temperature and precipitation associated with climate warming will cause changes in the amount and timing of snow accumulation and melt. For example, systematic advances in the timing of snowmelt runoff have been observed over parts of California and western North America due to changes in atmospheric circulation (Aguado et al., 1992; Dettinger and Cayan, 1995). GCOS requirements for SWE monitoring are for daily satellite-based SWE monitoring at a 25 km resolution at an absolute accuracy of ± 20%, and twice-monthly in-situ snow course observations over representative terrain and land cover in the vicinity of the GCOS surface network.

Canadian snow course observing network

Within Canada, MSC, provincial water resource agencies, and hydroelectric companies make snow course observations for water resource operations and planning, e.g., flood and drought forecasting, soil moisture recharge, water supply, and reservoir management. The data are also used by the climate research community in regional water budget studies (e.g., GEWEX/MAGS), for validation of satellite SWE algorithms and physical snow models, and for generating climatological information on SWE and snow density for validation of climate model output. Many water authorities only take snow course observations during the second half of the water year to monitor peak SWE prior to melt so these do not meet GCOS requirements for regular observations over the snow season. From 1955 to 1985, MSC published hard copy annual "Snow Cover Data" summaries of data collected by agencies across Canada. These summaries were digitized under a CRYSYS data rescue project and merged with available digital snow course data to generate a national snow course data set covering the period from the early 1960s to the mid-1990s (Braaten, 1997). A CD-ROM version of these data (MSC, 2000) is now available to the snow research community (http://www.msc.ec.gc.ca/crysys/).

The number of snow course observations in the database declined substantially in 1985 with the curtailment of the MSC program to publish national data summaries. Further decreases since 1985 have taken place with the cessation of snow course measurements by many agencies (Fig. 4). At peak levels in the early 1980s, there were over 1700 snow courses operating in Canada. This number declined to around 800 in the early 1990s, and the number of MSC snow courses has sharply declined from over 100 in the early 1980s, to 30 in 2000. Snow course networks operated by other agencies are also declining due to budget pressures and increasing confidence in remotely sensed products. The spatial distribution of snow courses is similar to the snow depth network with most of the sites located in southern Canada; however, there is less of a low-elevation bias. In spite of its spatial and temporal limitations, the Canadian snow course dataset is a valuable contribution to GCOS. For example, Brown (2000) used the data to investigate historical variability in SWE across southern-central Canada.

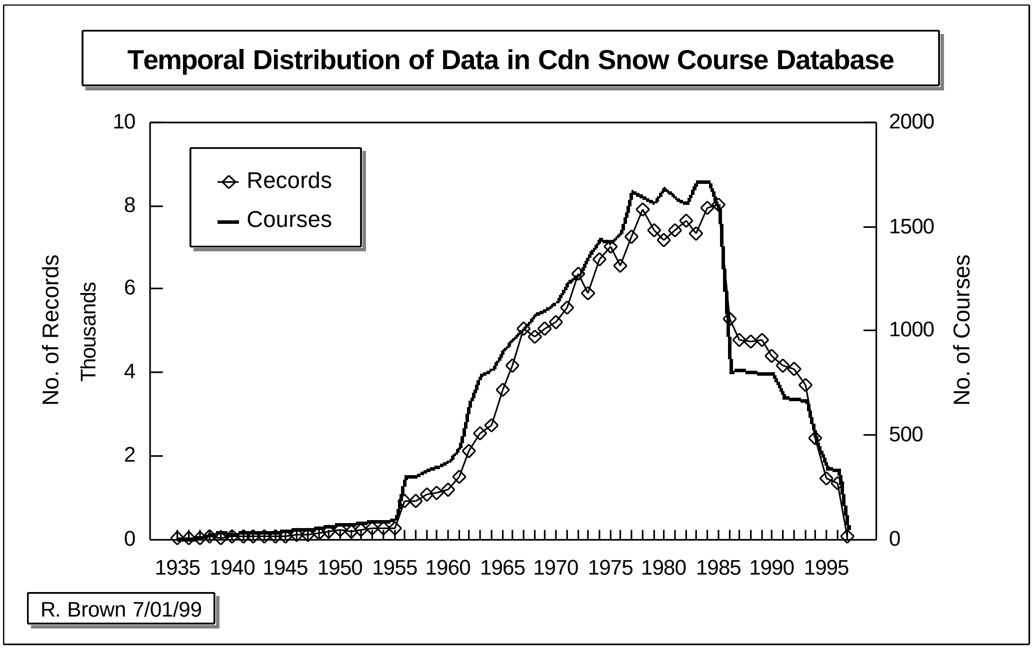

Figure 4. Temporal distribution of the number of observations and number of snow courses in the Canadian digital snow course database.

There are a limited number of snow course sites with 30 years or more of continuous data for climate monitoring purposes. However, conventional snow course data collected at sites representative of regional land cover/terrain are essential for the development and ongoing validation of remotely sensed products. Snow courses are required in alpine zones and other areas where remote sensing has not yet proven to be effective. A limitation of some MSC courses was their location at windblown airport sites that were not always representative of the surrounding region. Site maps, including information on the type of survey equipment used, are essential for accurate analysis of SWE. Biases in measurement for different types of survey equipment are known, and appropriate adjustments can be applied.

Remote sensing of snow water equivalent

Passive microwave

The Climate Research Branch of MSC has been developing methods to validate and apply passive microwave satellite data to determine snow extent, snow water equivalent, and snowpack state (wet/dry) in Canadian regions for near real-time and operational use in hydrological and climatological applications since the early 1980s. Goodison and Walker (1995) provide a summary of the program, its algorithm research and developments, and future thrusts. For the prairie region, a snow water equivalent algorithm was empirically derived using airborne microwave radiometer data (Goodison et al., 1986), and tested and validated using Nimbus-7 Scanning Multispectral Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) satellite data (Goodison, 1989). The prairie SWE algorithm has been applied to near-real time SSM/I data since 1989 to generate weekly maps of current SWE conditions for the provinces of Alberta, Saskatchewan and Manitoba in western Canada (http://www.msc.ec.gc.ca/ccrp/SNOW/snow_swe.html). The maps are used by water resource agencies and meteorological offices throughout the prairie region to monitor snow cover conditions, plan for field surveys, and make forecasts regarding spring water supply conditions, including potential flooding or drought. In the winter and spring of 1997, the maps were particularly useful for monitoring the high SWE conditions in southern Manitoba and North Dakota preceding the devastating Red River flood (Warkentin, 1997). The prairie SWE product has undergone detailed long-term validation and the accuracy has been determined as ± 10 mm compared to in-situ measurements and airborne gamma derived SWE (over relatively uniform terrain). A recent enhanced version of the algorithm includes a wet snow indicator (Walker and Goodison, 1993) which provides the capability to discriminate wet snow areas from snow-free areas and hence to provide a more accurate retrieval of snow extent during melting conditions. The prairie SWE algorithm has been applied to Nimbus-7 SMMR and DMSP SSM/I data to create a 20-year time series of maps depicting winter SWE conditions over the Canadian prairie region. It is planned to use this multiyear regional dataset for validation of GCM snow cover simulations.

Analysis of data acquired during the Boreal Ecosystem-Atmosphere Study (BOREAS) winter field campaign in February 1994 showed that a microwave vertically polarized difference index (MPDI) for 18 and 37 GHz, such as currently used for prairie SWE retrieval, can also be used to estimate SWE in a forested environment. Since the index is strongly sensitive to land cover, three separate algorithms have been developed for deciduous and coniferous forest, and open areas. Results from initial application of the forest algorithms to SSM/I data have been very encouraging (Goita et al., 1997). This research is also investigating the problem of how to estimate local-scale variations in SWE from satellite data by comparing surface, airborne and satellite microwave data collected over a range of spatial scales. Complementary research by the Université du Québec (INRS-Eau) has resulted in the development and validation of a preliminary passive microwave SWE algorithm for the La Grande Basin region (De Sève et al., 1997), an area characterized by deep snowpacks. The relationship between brightness temperature and SWE was observed to change from a negative to a positive slope at a SWE threshold of 150 mm (De Sève et al., 1999), a characteristic not seen in the experimental work in shallower snowpack areas. Operational SWE retrieval from passive microwave data for mountainous areas is not currently possible, mainly due to the coarse resolution of the satellite and the complexity of topography associated with a 25-km satellite pixel. This limitation may be addressed with future satellite sensors, such as the Advanced Microwave Scanning Radiometer (AMSR), that have an improved spatial resolution (e.g., AMSR has a 10-km resolution at 37 GHz).

Synthetic Aperture Radar (SAR)

Retrieval of SWE from SAR is complicated because snow is largely transparent to SAR frequencies unless it is wet. However, useful information can be extracted during the spring melt period, making it useful for runoff monitoring (flood control and reservoir management), and Bernier et al. (1999) have developed an approach to estimate SWE in a dry shallow snow cover from SAR-derived estimates of thermal resistance. This technique is now used operationally by Hydro-Québec for basin-wide SWE mapping in northern Québec.

CONCLUSIONS

The Barry (1995) assessment of Canada's cryospheric monitoring concluded that there were some serious deficiencies in snow monitoring, particularly the widespread curtailment of snow survey programs, and the impact of automation on snow depth and snowfall measurement. Barry (1995) also noted that the accessibility of snow depth and snow course data was unsatisfactory. This latter point has been addressed to a large extent by the development of a Canadian snow data CD-ROM that contains all the digital snow depth data from the MSC climate archive (plus a substantial amount of daily and weekly data rescued from hard copy records), as well as a comprehensive compilation of Canadian snow course data from ~1960 to 1995. In addition, homogenized snowfall data have been prepared by Mekis and Hogg (1999) for assessment of precipitation variability and change over southern Canada from 1900. All these data are now freely available to the research community. Greater access to information on Canadian snow cover conditions has also been promoted through the establishment of a "State of the Canadian Cryosphere" Web site that provides information on past, current and future snow cover conditions.

The decline of snow course networks is still a major concern. However, this in part reflects growing awareness of the utility and cost effectiveness of remotely sensed information. For example, Martin et al. (1999) were able to demonstrate significant cost/benefit advantages to Hydro-Québec for SWE monitoring with Radarsat SAR imagery. MSC is holding a special workshop with snow survey agencies in the fall of 2000 to develop a strategy to maintain a core network of snow survey locations for climate monitoring and satellite algorithm development and validation.

Automation remains a serious concern for snow depth and snowfall observations, but a quick fix is not in sight. This problem requires considerable motivation of resources and greater emphasis on climate monitoring. MSC is currently in the process of developing a National Plan for GCOS, and it is hoped that this process will generate some positive actions to improve the current situation, e.g., greater use of partnerships with data collection agencies. The following action items were identified in an early draft of the Cryosphere section of the Canadian GCOS Plan (Brown et al., 1999).

For immediate action

- Ensure that all stations in the GCOS surface network report daily depth of snow on the ground and daily snowfall.
- Develop a list of important representative snow depth stations and snow courses with the longest continuous records for climate monitoring purposes.
- Implement a strategy to develop and maintain a national snow course archive. (This is a logical activity for MSC if resources can be found to support this.)
- Improve timeliness of snow depth data updates to the MSC National Climate Archive.
- Implement automatic snow depth sensors at all auto stations; measure winter precipitation at all auto stations; measure wind speed at gauge height at auto stations

- Commit to studies to determine appropriate gauges for all season precipitation measurement and their associated measurement accuracies and limitations.

For ongoing attention

- Canada should commit to regularly contribute snow depth and snow course information to GCOS-approved data holding centres.
- The research community should continue to be encouraged to develop methods to merge in-situ and remotely sensed snow data to enhance spatial and temporal information content.
- Continue leadership in developing remote sensing technologies for snow-cover monitoring over Canadian landscapes, including forested and mountainous terrain.

For future emphasis

- Establish a coordinated Canadian cryospheric information network for access to Canadian cryospheric data, including snow cover.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the useful comments provided by the two anonymous reviewers and the extraordinary dedication of CRREL editors Mary Albert, Susan Taylor, and Janet Hardy in preparing the ESC proceedings over the past seven years.

REFERENCES

Aguado, E., D. Cayan, L. Riddle and M. Roos, 1992: Climatic fluctuations and the timing of West Coast streamflow. *J. Climate*, **5**,1468–1483.

Barry, R.G., 1995: Observing systems and data sets related to the cryosphere in Canada. A contribution to planning for the Global Climate Observing System. *Atmosphere-Ocean*, **33**, 771–807.

Bernier, M., J.-P. Fortin, Y. Gauthier, R. Gauthier, R. Roy and P. Vincent, 1999: Determination of snow water equivalent using RADARSAT data in eastern Canada. *Hydrological Processes*, **13**, 3031–3042.

Boer, G.J., G.M. Flato, and D. Ramsden, 2000: A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate change in the 21st century. *Climate Dynamics* (in press).

Braaten, R.O., 1997: The Canadian Snow Water Equivalent Dataset. Contract Report for Atmospheric Environment Service, 27 pp.

Bradley, R.S., H.F. Diaz, J.K. Eischeid, P.D. Jones, P.M. Kelly, and C.M. Goodess, 1987: Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th Century. *Science*, **237**, 171–275.

Brasnett, B., 1999: A global analysis of snow depth for numerical weather prediction. *J. Appl. Meteorol.*, **38**: 726–740.

Brown, 2000: Northern Hemisphere Snow Cover Variability and Change, 1915–1997. *J. Climate* (in press).

Brown, R.D., T. Agnew, M. Burgess, G. Cogley, M. Demuth, C. Duguay, G. Flato, B. Goodison, R. Koerner, H. Melling, T. Prowse, B. Ramsay, M. Sharp, S. Smith, A. Walker, 1999: Development of a Canadian GCOS Workplan for the Cryosphere- Summary Report. Unpublished manuscript, Meteorological Service of Canada, Climate Processes and Earth Observation Division, Dowsnview, Ontario, 34 pp.

Brown, R.D. and R.O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depths, 1946–1995. *Atmosphere-Ocean*, **36**: 37–45.

Brown, R.D. and B.E. Goodison. 1996. Interannual variability in reconstructed Canadian snow cover, 1915–1992. *J. Climate*, **9**: 1299–1318.

Cihlar, J. and others, 1997: GCOS/GTOS plan for terrestrial climate-related observations, Version 2.0, June 1997. GCOS-32, WMO/TD - No. 796.

De Sève, D., M. Bernier, J.-P. Fortin, and A.E. Walker, 1999: Analysis of microwave radiometry of snow cover with SSM/I data in a Täiga area: the case of James Bay area (Québec). *Proc. 56th Eastern Snow Conference*, Fredericton, New Brunswick, June 2–4, 1999, 31–41.

De Sève, D., M. Bernier, J.-P. Fortin, and A.E. Walker, 1997: Preliminary analysis of the snow microwave radiometry using SSM/I passive microwave data: The case of the La Grande River watershed (Québec). *Annals of Glaciology*, **25**: 353–361.

Dettinger, M.D. and D.R. Cayan, 1995: Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *J. Climate*, **8**, 606–623.

Goita, K, A.E. Walker, B.E. Goodison, and A.T.C. Chang, 1997: Estimation of snow water equivalent in the boreal forest using passive microwave data. Proc. (International Symposium: Geomatics in the Era of Radarsat), May 24–30, 1997, Ottawa, Ontario.

Goodison, B.E., R.D. Brown, M.M. Brugman, C.R. Duguay, G.M. Flato, E.F. LeDrew, and A.E. Walker, 1999: CRYSYS - Use of the cryospheric system to monitor global change in Canada: Overview and progress. *Can. J. Remote Sensing*, **25**, 3–11.

Goodison, B.E., P.Y.T. Louie, and D. Yang, 1998: WMO Solid Precipitation Measurement Intercomparison, WMO Instruments and Observing Methods Report No. 67, WMO/TD No. 872.

Goodison, B.E., and A.E. Walker, 1995: Canadian development and use of snow cover information from passive microwave satellite data. In: *Passive Microwave Remote Sensing of Land-Atmosphere Interactions*, 245–262, Utrecht, The Netherlands.

Goodison, B.E. and A.E. Walker, 1993: Use of snow cover derived from satellite passive microwave data as an indicator of climate change. *Annals of Glaciology*, **17**, 137–142.

Goodison, B.E., 1989: Determination of areal snow water equivalent on the Canadian prairies using passive microwave satellite data. *IGARSS'89*. 12th Canadian Symposium on Remote Sensing, Vancouver, Canada, July 10–14, 1989. Vol. 3, 1243–1246.

Goodison, B.E., I. Rubinstein, F.W. Thirkettle and E.J. Langham, 1986: Determination of snow water equivalent on the Canadian prairies using passive microwave radiometry. I.A.H.S. Publication 155 (Symposium at Budapest 1986 - Modelling Snowmelt-Induced Processes), 163–173.

Groisman, P.Ya, and D. Easterling, 1994: Variability and trends of total precipitation and snowfall over the United States and Canada. *J. Climate*, **7**, 184–205.

IPCC, 1996: Climate Change 1995: The Science of Climate Change. Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 572 pp.

Martin, D., M. Bernier, J.L. Sasseville, and R. Charbonneau, 1999: Évaluation financière de l'intégration de technologies satellitaires pour le suivi du couvert nival, au sein d'une entreprise hydroélectrique. *Intl. J. Remote Sensing*, **20**, 2033–2048.

Mekis, E., and W.D. Hogg. 1999. Rehabilitation and analysis of Canadian daily precipitation time series. *Atmosphere-Ocean*, **37**, 53–85.

MSC, 2000: Canadian Snow Data CD-ROM. CRYSYS Project, Climate Processes and Earth Observation Division, Meteorological Service of Canada, Downsview, Ontario, January 2000.

Robinson, D., and K.F. Dewey. 1990. Recent secular variations in the extent of Northern Hemisphere snow cover. *Geophys. Res. Letters*, **17**, 1557–1560.

Robinson, D.A., 1989: Evaluation of the collection, archiving and publication of daily snow data in the United States. *Physical Geog*., **10**, 120–130.

Vinnikov, K.Ya., P.Ya. Groisman, and K.M. Lugina, 1990: Empirical data on contemporary global climate changes (temperature and precipitation). *J. Climate*, **3**, 662–677.

Walker, A.E., and B.E. Goodison, 1993: Discrimination of wet snow cover using passive microwave satellite data. *Annals of Glaciology*, **17**, 307–311.

Warkentin, A.A., 1997: The Red River flood of 1997: An overview of the causes, predictions, characteristics and effects of the flood of the century. *CMOS Bulletin*, **25**, 128–135.