Proceedings
58th EASTERN SNOW CONFERENCE
Ottawa, Ontario, Canada, 2001
333-340

Development of a Gridded North American Monthly Snow Depth and Snow Water Equivalent Dataset for GCM Validation

R. BROWN[1], B. BRASNETT[2] AND D. ROBINSON[3]

ABSTRACT

Accurate simulation of large-scale spatial and temporal variations in snow cover is important for global climate models (GCM) as snow influences the climate system through both direct (e.g. albedo) and indirect (e.g. soil moisture) feedbacks. A snow depth analysis scheme developed by Brasnett (1999) and employed operationally at the Canadian Meteorological Center (CMC), was applied to develop a detailed monthly mean snow depth dataset for North America for validating GCM snow cover simulations for the AMIP II (Atmospheric Model Intercomparison Project) period (1979-1996). An extensive database of daily snow depth observations from U.S. cooperative stations and Canadian climate stations was assembled, which provided ~8000 observations/day to the analysis. The first-guess field used a simple accumulation, aging and melt model driven by 6-hourly values of air temperature and precipitation from the European Centre for Medium-range Weather Forecasting (ECMWF) ERA-15 Reanalysis with extensions from the TOGA operational data archive. The snow depth analysis was run at a 1/3° resolution and incorporated the effect of topography to screen out unrepresentative stations. Results from the first run of the analysis revealed several improvements over the existing snow depth climatology of Foster and Davy (1988). An improved snow aging scheme is required to replicate observed snow density information, and provide reliable estimates of snow water equivalent. This will be incorporated in a second analysis run.

Key words: Snow depth analysis, snow depth climatology, North America.

INTRODUCTION

A realistic representation of seasonal and spatial variation in snow cover in climate models is important for snow-cover climate feedbacks (albedo-temperature, snow-cloud), soil moisture, runoff and ground temperatures (Cohen and Rind, 1991; Marshall *et al.*, 1994; Lynch-Stieglitz, 1994). Previous evaluations of snow cover in GCMs (Foster *et al.*, 1996; Walland and Simmonds, 1996; Frei and Robinson, 1998) demonstrated that to a first order, GCMs capture the seasonal cycle of Northern Hemisphere (NH) snow cover extent. However, they tended to underestimate fall and winter snow extent (especially over North America) and overestimated spring snow extent (especially over Eurasia) (Frei and Robinson, 1998). A recent assessment of the representation of

---

[1] Meteorological Service of Canada, Climate Research Branch, 2121 TransCanada Highway, Dorval, Canada, ross.brown@ec.gc.ca.

[2] Meteorological Service of Canada, Canadian Meteorological Centre, 2121 TransCanada Highway, Dorval.

[3] Dept. of Geography, Rutgers University, 54 Joyce Kilmer Avenue, Piscataway, NJ 08854-8054.

snow in land surface schemes (Slater *et al.*, 2001) revealed considerable differences in snow simulation results between models, particularly in the timing of spring melt.

Validation of GCM simulations of snow cover over the NH have been hampered by a lack of reliable validation data, particularly snow water equivalent (SWE) which is the main snow cover output generated by GCMs. Existing snow depth climatologies (e.g. Schutz and Bregman (1975), Foster and Davy, 1988) are based extensively on data collected during the 1950-1980 period when snow cover was likely at 20th C maximum levels over North America (Brown, 2000). NH snow cover experienced a significant decrease during the 1980s and 1990s, and it is likely that the existing snow depth climatologies do not properly represent snow cover conditions during the more recent AMIP II period. SWE and snow depth can be readily derived over open terrain from passive microwave data, which are available from 1978. However, research is still ongoing to develop reliable algorithms for extracting SWE over forested terrain, and the resolution of the passive microwave data (25 km) is insufficient for mapping SWE in mountainous areas.

The aim of this project is to apply the snow depth analysis scheme developed by Brasnett (1999) and employed operationally at the Canadian Meteorological Center (CMC), to develop a detailed daily snow depth and SWE dataset for North America for validating GCM snow cover simulations for the AMIP II period. This is a contribution to AMIP II diagnostic subproject 28, "Snow Cover in General Circulation Models" (Robinson *et al.*, 2000). The CMC operational snow depth analysis receives a limited set of snow depth observations from synoptic stations. However, in historical analysis mode, an extensive database of daily snow depth observations from U.S. and Canadian cooperative stations can be used which provides ~8000 observations/day to the analysis. The analysis was not applied to the entire NH as there were insufficient observations from Eurasia over the full AMIP II period. The results presented here are from an initial analysis run made during April 2001 to demonstrate the validity of the approach, and to identify any weaknesses. A final run will be carried out in August 2001.

DATA SOURCES

In-situ snow depth

Canada

Regular daily ruler observations of the depth of snow on the ground have been made at most Canadian synoptic stations since the 1950s. The daily observing program was extended to climatological (cooperative) stations in the early 1980s, approximately quadrupling the number of stations in the network to over 2000. The observing network is concentrated over southern populated regions of Canada, and is biased to low elevations (Fig. 1). The number of stations reporting daily snow depth declined ~15% during the later half of the 1990s in response to budget reductions and automation. Data rescue of previously undigitized Canada snow depth data and reconstruction of missing values were carried out by Brown and Braaten (1998). The reconstructed values are required in the first 2 years of the AMIP II period (1979 and 1980) to maintain the spatial distribution of the observing network. Snow depth values from Canadian snow course reports were also incorporated into the snow depth analysis. These reports are less frequent (weekly, bi-weekly or monthly) but are an important source of information in mountainous areas of southern British Columbia and Alberta, and over northern Québec.

USA

Daily snow depth observations were taken from the National Climatic Data Center (NCDC) TD-3200 Cooperative Summary of the Day database for the 1979-1997 period. These include manual ruler measurements of snow depth from over 7500 cooperative stations across the contiguous USA and Alaska. Doesken and Judson (1997) provide a description of the US snow depth observing program. The available network of stations (Figure 1) gives excellent spatial coverage over the contiguous USA. As with Canada, there is a low elevation bias in mountainous regions such as the western Cordillera, and data coverage is sparse in Alaska. NCDC perform basic quality control of the data (outliers, internal consistency, areal consistency). A summary of the snow depth QC flags revealed the presence of 3 flags associated with bad values: '3' invalid data element, 'T' failed internal consistency check and 'U' failed areal consistency check. Values with these flags were omitted from the analysis.

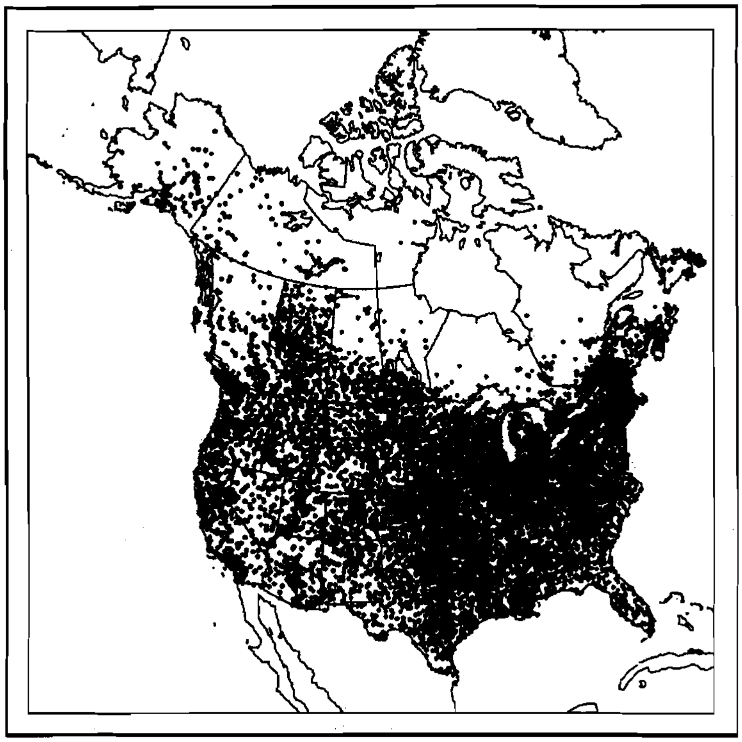

Figure 1: Station network used in the historical daily snow depth analysis.

A total of over 3 million observations were available from the USA and Canada for each year of the analysis, with ~85% of these being zero reports. Zero reports are important however, for the accurate location of the snow/no-snow boundary. Overall, a total of ~400,000 non-zero daily snow depth observations were available each year for inclusion in the analysis. Further quality control of the observations was not performed since areal consistency checks were carried out as part of the analysis process.

ECMWF Air Temperature and Precipitation

First-guess snow depth fields for the snow depth analysis were generated using a simple snowpack accumulation and melt model driven with 6-hourly 2-meter air temperature and total precipitation values from the ECMWF ERA-15 Reanalysis described by Gibson *et al.* (1997). Details of the snowpack model are provided later. Additional data for the 1994-1997 period not covered by ERA-15 were obtained from the ECMWF/WCRP TOGA operational data archive. The data were provided on a 1.125 degree latitude/longitude and were interpolated to a 1/3 degree lat/long grid for running the analysis. The ERA-15 data have been subject to extensive validation (e.g. Hanna and Valdes, 2001; Cullather and Bromwich, 2000; Serreze and Hurst, 2000) and the general consensus is that they provide a realistic representation of temperature and winter precipitation over the study area. Visualization of the ECMWF fields over the study domain revealed that a number of islands in the Sverdrup Basin were not resolved at the 1.125 degree resolution (i.e. were seen as ocean by the ERA-Reanalysis). The impact of this is that the model's 2-meter temperatures remain below freezing throughout June, July and August, causing snow depth to increase monotonically over the period of the historical analysis. The analysis results for these areas will be excluded from the final gridded output.

ANALYSIS METHODOLOGY

The daily snow depth objective analysis is based on the method of statistical interpolation (Daley, 1991), and follows the approach described in Brasnett (1999) modified to read in observations once every 24-hours instead of every 6 hours. The basic steps in this process are: (1) derivation of a "first-guess" or background field based on a simple snowpack model driven with 6-hourly values of ECMWF precipitation and 2-meter air temperature; (2) quality control of observations; and (3) statistical interpolation of the background field and observations every 24-hours. The important details of each of these steps is outlined below:

Background field

The background field is generated using a simple accumulation and degree-day melt approach using 6-hourly ECMWF forecast precipitation and analysed 2-meter air temperatures as input. The ECMWF fields were interpolated to a global 1/3° latitude-longitude grid and a saturated lapse rate of 0.006 K m^{-1} applied to adjust air temperature to the mean elevation of each grid point. New snowfall was determined to occur when the gridpoint air temperature was $\leq 0°C$, and new snowfall density was assumed a value of 100 kg m^{-3}. For the results presented in this paper, snowpack density (ρ) was updated every 6 hours following Verseghy (1991)

$$\rho = [\, \rho_{-6} - \boldsymbol{\rho}^* \,] \exp [\, -6 / \tau \,] + \boldsymbol{\rho}^*$$

where ρ_{-6} is the density from the previous 6 hours, $\boldsymbol{\rho}^*$ is the maximum possible value of snow density due to aging, and the *e*-folding time τ is 100 h. The value for $\boldsymbol{\rho}^*$ was set to 210 kg m^{-3} for needleleaf forest and 300 kg m^{-3} for other areas based on empirical data presented in McKay and Gray (1981). The vegetation dataset of Wilson and Henderson-Sellers (1985) was used to assign land cover type. For temperatures above freezing, density was assumed to increase at a rate of 0.5 kg m^{-3} K^{-1} h^{-1} (empirically derived) from melt/refreeze, to a maximum value of 700 kg m^{-3}. Snowmelt was estimated using a degree-day approach with a fixed melt factor of 0.15 mm h^{-1} K^{-1} when air temperature exceeded 0°C. This value gave good results at open sites, but melted snow too quickly over the boreal forest region. A survey of the literature revealed that degree-day melt factors can vary considerable with time of year, surface cover, and forest density (e.g. Kuusisto, 1984). The final analysis will therefore incorporate a variable melt factor that takes snow age and vegetation type into account.

It would have been preferred to use a physically based model for estimating the background snow depth such as CROCUS (Brun *et al.*, 1989). However, the required additional input data (incoming short and longwave radiation, relative humidity, wind speed) were not readily available, and a physical model would have substantially increased the required computing resources. In the configuration described here, the analysis took approximately one day to run a full year snow depth analysis over North America on a SGI Origin 2000. Validation of the simple snowpack scheme with 15 years of data from Goose Bay Airport revealed that the simplified approach gave comparable performance to CROCUS at capturing the mean (Figure 2) and interannual variability (Figure 3) in mean snow depth.

Quality control

As noted by Brasnett (1999), the inherent small-scale variability of a snow cover makes it difficult to carry out quality assurance using neighboring observations. However, the background snow depth field is spatially and temporally coherent, and can be used to check the consistency of observations. Observations were rejected from the analysis where: (1) snow was reported when the background field indicated no snow; (2) the observed snow depth was more than 40 cm less than an estimate computed from ECMWF precipitation and temperature; (3) the reported snow depth differed by more than 20 cm from an analysed value computed from neighboring observations.

Statistical interpolation

The details of the interpolation scheme are described in Brasnett (1999). This process assumes that the horizontal and vertical correlation functions for daily snow depth have *e*-folding distances of 120 km and 800 m respectively. The inclusion of the vertical correlation into the analysis restricts the influence of an observation to nearby areas with a similar elevation, and has a major impact in mountainous regions e.g. Figure 4b in Brasnett (1999). In addition, stations were excluded from the analysis if their elevation differed by more than 400 m from the mean elevation at a gridpoint.

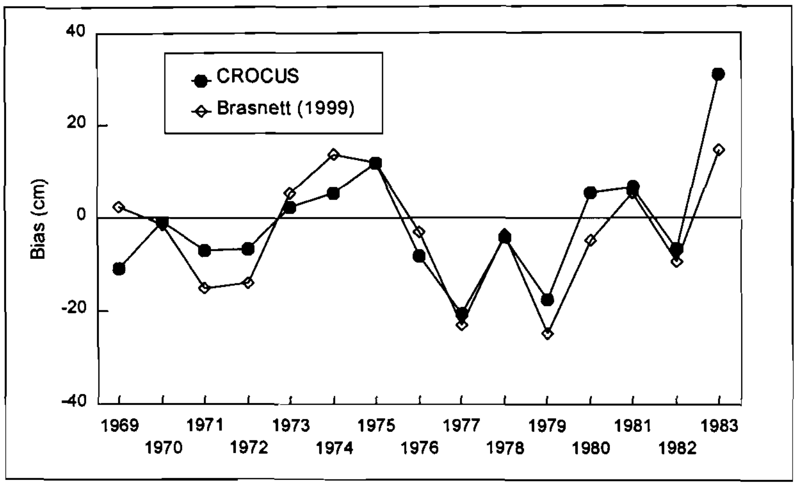

Figure 2: Annual variation in model bias computed from the difference (simulated-observed) in the observed and simulated mean snow depth over the snow season.

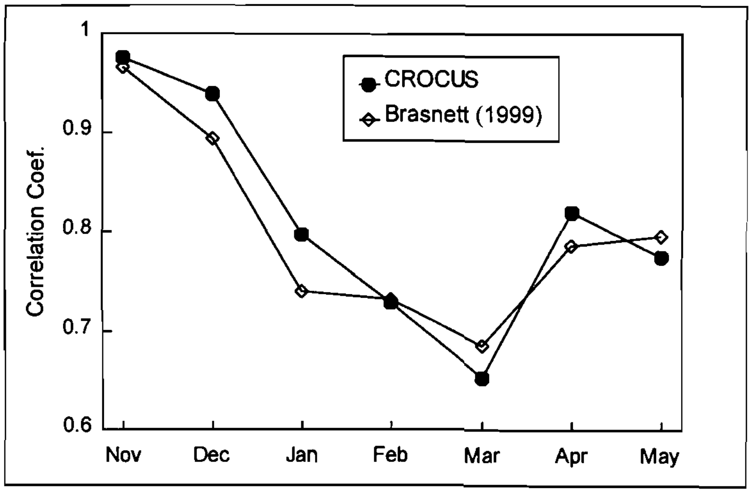

Figure 3: Correlation of observed and simulated mean monthly snow depths at Goose Bay Airport over the period 1969-1983.

RESULTS

Comparison of the 1979-1996 monthly snow depth climatology derived from the CMC daily analyses with the Foster and Davy (1988) snow depth climatology, and a 1972-1994 monthly snow cover climatology generated from the NOAA weekly satellite product (see Robinson *et al.*, 1993 for a description of these data) revealed that the new climatology provided a more realistic representation of snow accumulation in the western cordillera, and an improved placement of the October and June snowlines which are displaced northward in Foster and Davy (1988). A comparison of the results for December is shown in Figure 4. The larger snow cover extent over the southwestern and southern United States in the CMC climatology is in close agreement with mean December snow cover derived from the NOAA weekly satellite dataset (not shown).

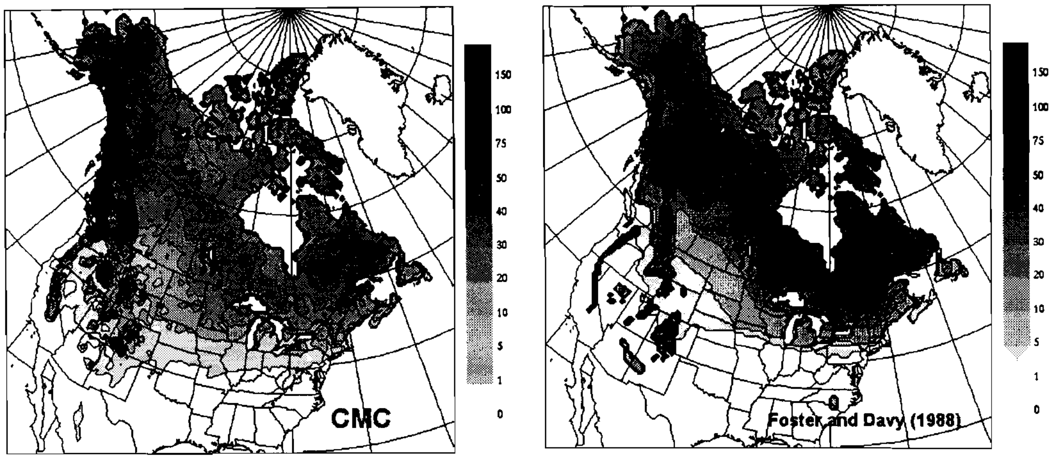

Figure 4: Comparison of December mean snow depths (cm) for the CMC climatology (1979-1996) and Foster and Davy (1988).

Comparison of continental snow covered area computed from the CMC analyses and the NOAA dataset (Fig. 5) revealed excellent agreement in winter months. Given the extensive data coverage over mid-latitudes of North America, *in situ* snow depth analyses are a useful ground truth for satellite data during the November-March period.

Mean snow density fields generated by the CMC analyses showed some agreement with observed values over Canada, but did not replicate the observed density gradients in coastal areas, and over the boreal forest zone were snow density was too high. An improved snow aging scheme following Anderson (1976) will be applied in the final run of the analysis to provide realistic estimates of snow water equivalent in addition to snow depth.

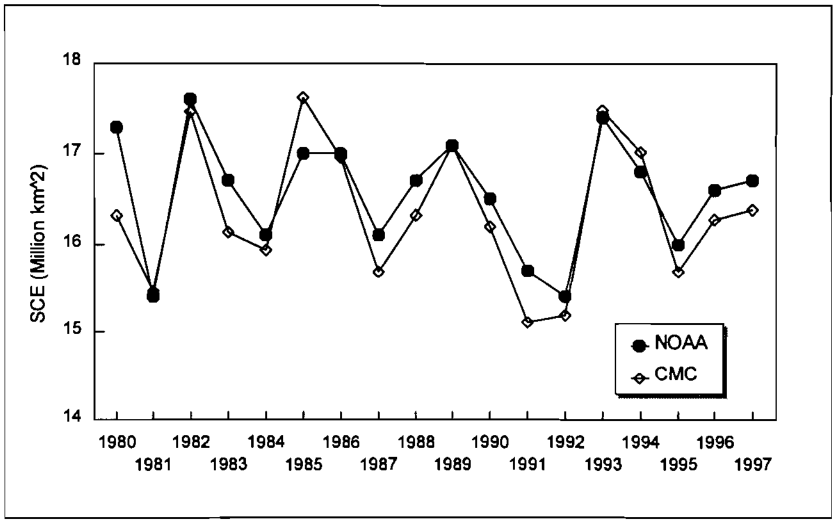

Figure 5: Comparison of North American snow covered extent (SCE) computed from the CMC daily snow depth analyses, and from the NOAA weekly satellite-derived product.

CONCLUSIONS

An extensive network of daily snow depth observations (~8000 stations) exists over much of the contiguous United States and southern Canada. These data were input to a snow depth analysis scheme developed by Brasnett (1999) and employed operationally at the Canadian Meteorological Center (CMC), to develop a detailed monthly mean snow depth dataset for North America for the AMIP II period (1979-1996). The historical snow depth analysis showed close agreement with the NOAA product during winter months, and several improvements over the existing continental-scale snow depth climatology of Foster and Davy (1988). An improved snow aging scheme will be used in a second run of the analysis to derive gridded estimates of SWE. The gridded snow depth and SWE information will represent an important source of information for validation of climate and hydrological models, satellite algorithm development, and climatological applications.

REFERENCES

Anderson, E., 1976: A point energy balance model of a snow cover. Office of Hydrology, National Weather Service, *NOAA Tech. Rep. NWS 19.*

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

Brown, R.D., 2000: Northern Hemisphere snow cover variability and change, 1915-1997. *J. Climate*, **13**, 2339-2355.

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

Brun, E., E. Martin, V. Simon, C. Gendre, and C. Coleou, 1989: An energy and mass balance model of snowcover suitable for operational avalanche forecasting. *J. Glaciol.*, **35**, 333-342.

Cohen, J., and D. Rind, 1991: The effect of snow cover on the climate. *J. Climate*, **4**, 689-706.

Cullather, R.I., and D.H. Bromwich, 2000: The atmospheric hydrologic cycle over he Arctic Basin from reanalyses. Part I: Comparison with observations and previous studies. *J. Climate*, **13**, 923-937.

Daley, R., 1991: *Atmospheric data analysis.* Cambridge University Press, 457 pp.

Doesken, N.J., and A. Judson, 1997: A Guide to the Science, Climatology, and Measurement of Snow in the United States. Colorado State University Department of Atmospheric Science, Fort Collins, CO. 86pp.

Foster, J., G. Liston, R. Koster, R. Essery, H. Behr, L. Dumenil, D. Verseghy, S. Thompson, D. Pollard, and J. Cohen, 1996: Snow cover and snow mass intercomparisons of general circulation models and remotely sensed datasets. *J. Climate*, **9**, 409-426.

Foster, D.J.Jr., and R.D. Davy, 1988: Global snow depth climatology. USAF Environmental Technical Applications Center, USAFETAC/TN-88/006, 48 pp.

Frei, A., and D.A. Robinson, 1998: Evaluation of snow extent and its variability in the Atmospheric Model Intercomparison Project. *J. Geophys. Res. - Atmospheres*, **103**, 8859-8871.

Gibson, J.K., P. Kallberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, 1997: ECMWF Re-Analysis Project Report Series – 1. Era description. European Centre for Medium-range Weather Forecasting, 72 pp.

Hanna, E., and P. Valdes, 2001: Validation of ECMWF Reanalysis surface climate data, 1979-1988, for Greenland and implications for mass balance modelling of the ice sheet. *Int'l. J. of Climatology*, **21**, 171-195.

Kuusisto, E.,1984: Snow accumulation and snowmelt in Finland. Publications of the Water Research Institute, No. 55, National Board of Waters, Finland, Helsinki, 149 pp.

Lynch-Stieglitz, M., 1994: The development and validation of a simple snow model for the GISS GCM. *J. Climate*, 7, 1842-1855.

Marshall, S., J.O. Roads, and G. Glatzmaier, 1994: Snow hydrology in a general circulation model. *J. Climate*, 7, 1251-1269.

McKay, G.A., and D.M. Gray, 1981: Distribution of snow cover. Chapter 5 in *Handbook of Snow*, Gray, D. M., and D. H. Male (eds.), Pergamon Press, 153-190.

Robinson, D.A., K.F. Dewey, and R.R. Heim, 1993: Global snow cover monitoring: an update. *Bull. Am. Meteorol. Soc.*, **74**, 1689-1696.

Robinson, D., A. Frei, R. Brown, and A. Walker, 2000: Snow Cover in General Circulation Models, AMIP II Subproject No. 28. (www-pcmdi.llnl.gov/amip/DIAGSUBS/sp28.htm).

Schutz, C., and L.D. Bregman, 1975: Global Snow Depth Data: A Monthly Summary. The Rand Corporation, Santa Monica, 1975. (Available from National Snow and Ice Data Center, University of Colorado, Boulder, Colorado.)

Serreze, M.C., and C.M. Hurst, 2000: Representation of mean Arctic precipitation from NCEP-NCAR and ERA reanalyses. *J. Climate*, **13**, 182-201.

Slater, A.G., C.A. Schlosser, C.E. Desborough, A.J. Pitman, A. HendersonSellers, A. Robock, K.Y. Vinnikov, K. Mitchell, A. Boone, H. Braden, F. Chen, P.M. Cox, P. deRosnay, R.E. Dickinson, Y.J. Dai, Q. Duan, J. Entin, P. Etchevers, N. Gedney, Y.M. Gusev, F. Habets, J. Kim, V. Koren, E.A. Kowalczyk, O.N. Nasonova, J. Noilhan, S. Schaake, A.B. Shmakin, T.G. Smirnova, D. Verseghy, P.Wetzel, X. Yue, Z.L. Yang, and Q. Zeng, 2001: The representation of snow in land surface schemes: Results from PILPS 2(D). *J. Hydrometeorology*, **2**, 7-25.

Verseghy, D., 1991: CLASS - A Canadian land surface scheme for GCMS. I: Soil model. *Int. J. Climatol.*, **11**, 111-133.

Walland, D.J., and I. Simmonds, 1996: Sub-grid-scale topography and the simulation of Northern Hemisphere snow cover. *Intl. J. Climatology*, **16**, 961-982.

Wilson M.F., and A. Henderson-Sellers. 1985: A global archive of land cover and soils data for use in general circulation models. *J. Climatology*, **5**, 119-143.