Improving Climate Model Representations of Snow Hydrology

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Abstract The extent and duration of the seasonal snowpack plays an important role in determining local, regional and global climate. In this study previous work that led to an improved representation of snow albedo in regional and global climate models is broadened and expanded to include representation of the following processes: (i) partitioning of energy between melt, evaporation of meltwater, and refreezing within the snow pack (current parameterizations usually assume all available energy goes into melt only); (ii) the 'dirtiness' of snow (due to dust and other particulate loading); (iii) heat added to a snowpack by rain; and (iv) the vertical temperature profile within a snowpack. The new snow hydrology formulation is implemented into two widely used climate models: a global GCM, the NCAR CCM3/LSM, and a regional climate model, the RegCM2 version of MM4. A suite of new simulations has been made with RegCM2 for various sections of the U.S. for the 1992-1993 snow season. Calibration and validation of the new snow hydrology are accomplished by comparison to all available ground and satellite-based datasets of annual snowcover, including both mean conditions and year-to-year variability. The goal is not just to improve the simulation of the present-day seasonal cycle (which is reasonably-well simulated by many current climate models) but also to improve the predictive capability of models when used to address questions of past climate (especially those involving glaciation) and possible future climatic change.

1. INTRODUCTION

The extent and duration of seasonal snowfall plays an important role in determining local, regional, and global climates, as well as being a crucial element in determining the presence and extent of ice sheets and glaciers. For example, a positive net annual snow accumulation (more snow falls during the year than melts) is a requirement for a glacier or ice sheet to form. The magnitude of the net snow accumulation determines the rate at which a glacier or ice sheet can grow (or conversely, if the ice has advected horizontally into a region with new snow ablation, how quickly it will melt). Successful simulation of the net snow accumulation is therefore of paramount importance in any climate modeling study. Unfortunately, representation of the physical processes that determine snow accumulation and snow melt (ablation) are crudely handled in current climate models

Full treatment of the annual net balance of snow requires accurate computation of both the amount of snow that falls, and the amount of snow that melts. Computation of snowfall requires accurate treatment of the large-scale flux of water, as well as detailed cloud microphysics, and is not explicitly considered further in our work. Computation of snow melt requires accurate treatment of such factors as snow albedo, and the thermodynamics of a snow pack. It is this aspect that we concentrate on. In this paper we describe work we have been doing to improve the simulation of snow hydrology in global and regional climate models. The first step involved improving the representation of snow albedo in climate models [Marshall 1989; Marshall and Oglesby 1994]. The second step involves improving the thermodynamical representation of heating and phase changes within a snowpack. Model runs using these new snow hydrology components are validated using an observed dataset that is a blend of surface and satellite measurements.

Regional studies of the modeled snow hydrology presented here focus on three areas: (a) Western United States covering the Rocky Mountains and high plains, (b) Upper Mississippi River basin and (c) Northeastern United States. Each region represents a unique set of surface characteristics and forcings on the snowpack. We model the three regions for the same winter/spring season (December 1992 through May 1993), forcing the lateral boundaries of the regional model with ECMWF reanalyses. All regions were run both with the standard land surface package and with the improved snow albedo routine of Marshall and

Oglesby. Global climate model simulations are also used.

Results of these regional studies are being used to drive the SNTHERM point mass and energy balance model of Jordan (1991; 1996). This is done to examine the role of melt energy partitioning, meltwater evaporation, rain on snow events and vertical temperature structure of the snowpack on the snow surface energy budget and snow-atmosphere feedbacks. Calibration and validation are accomplished by comparison with available observations, including surface and satellite-generated fields. Our ultimate objective is to incorporate these processes and effects, in a sufficiently simplified manner, into regional and global climate models.

2. THE CLIMATE MODELS

2.1 NCAR Global GCMs

We utilize the National Center for Atmospheric Research (NCAR) series of global general circulation models (GCMs) called the Community Climate Model (CCM) including versions CCM0 [Marshall et al. 1994], CCM1 [Marshall and Oglesby 1994], CCM2, and most recently the newly-released CCM3 [Keihl et al. 1996]. CCM3 forms the core component of the new NCAR Climate System Model (CSM) which also includes a land surface model (LSM) and a variety of ocean and sea ice options. The LSM [Bonan 1996] uses a slightly modified version of the snow albedo formulation of Marshall and Oglesby [1994]. CCM0 and CCM1 have a spectral horizontal resolution of R15 (4.5° latitude by 7.5° longitude), with 12 levels in the vertical, while CCM2 and CCM3 have a spectral horizontal T42 resolution (2.8° latitude by 2.8° longitude) and 18 vertical levels. CCM2 and CCM3 also have considerably improved physical parameterizations (see Kiehl et al. 1996 for more details).

2.2 RegCM2/BATS Regional Climate Model

We also utilize the RegCM2 model developed by Giorgi et al. [1993a,b]. This regional climate model is based on the NCAR-Penn State Mesoscale Model version 4 (MM4) but with surface and near-surface parameterizations of radiative and heat fluxes designed for use specifically in climate studies. The surface fluxes of sensible heat and water are determined using the Biosphere-Atmosphere Transfer Scheme (BATS) of Dickinson et al. [1993], to which has been added the snow albedo formulation of Marshall and Oglesby [1994]. This model can be run at a horizontal resolution of about 20 km up to about 100 km, and requires lateral forcing provided either from observations or a GCM.

3. OBSERVATIONAL DATASETS

The primary product yielding an estimate of snowcover that is used for validation of the model snow hydrology results is the series of NOAA/NESDIS weekly northern hemisphere snow charts. These composite snow charts are based on data from the visible channel of the Advanced Very High Resolution Radiometer (AVHRR) [Robinson 1993]. AVHRR data are limited by cloud cover, thus use is also made of data from the NIMBUS-7 Scanning Multichannel Microwave Radiometer (SMMR) and DMSP Special Sensor Microwave/Imager (SSMI). These microwave channels can detect snow cover even when clouds are present, and are also used to estimate snow water equivalents for the snow pack [Goodison and Walker 1993]. Multi-year data are available such that both mean snow cover and interannual variability can be assessed. Similarly, data from surface weather stations compliment satellite measurements in regions which have a dense network of observing stations.

4. DEVELOPING A NEW SNOW HYDROLOGY

4.1 Step 1

In this first step, we improved the representation of snow albedo by explicitly accounting for the albedo dependence on grain size, which in turn is a function both of snow age and snow temperature. We furthermore improved the representation of the attenuation of solar radiation in a snowpack by making the total albedo (which depends on both albedo of snowpack and albedo of the underlying ground surface) a function of snow depth. The initial implementation of this new snow albedo formulation was into the NCAR CCM1 with subsequent implementation into the LSM component of the NCAR CSM and the BATS component of RegCM2. Figure 1, adapted from Marshall and Oglesby [1994], shows a representative seasonal cycle of snowcover for Moscow simulated with CCM1 using the control snow albedo (a linear function of temperature only) and the new snow albedo. Note the unrealistic symmetrical pattern in the control, with snow melt taking about as long as snow accumulation, but the asymmetrical 'sawtooth' pattern with the more realistic snow formulation in which snow melt occurs more rapidly than snow accumulation. The important physics needed to produce this 'sawtooth' effect is largely due to the variable snowcover fraction which produces a strong albedo feedback in the spring.

Figure 2 shows results from a regional simulation over the Great Lakes Basin for the 1992-93 winter season. The new snow albedo parameterization results in a slightly higher overall snow albedo which tends to slow the onset of melt by a few days. We find a similar effect in the RegCM2 simulations over the other regions.

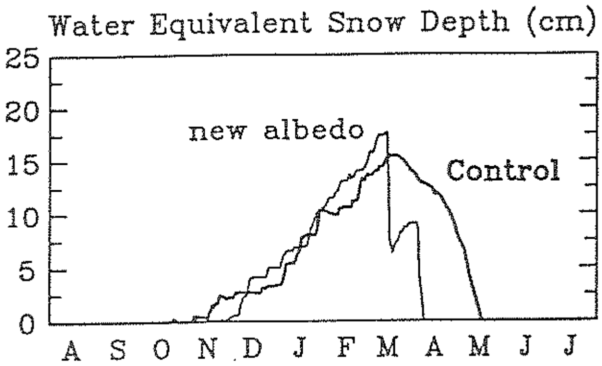


Figure 1: Water equivalent snow depth (cm) for a gridpoint representing Moscow (55.50 N; 37.50E) in CCM1 (adapted from Marshall and Oglesby 1994).

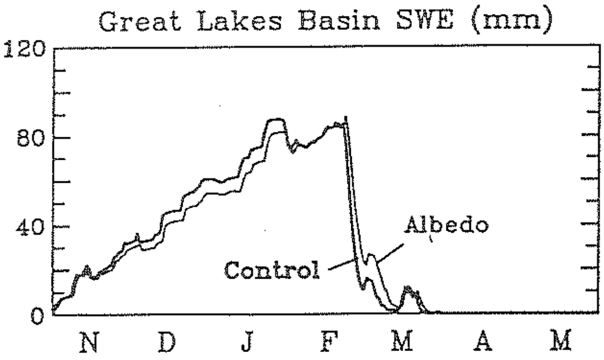


Figure 2: Area-averaged snow water equivalent (mm) over the Great Lakes basin.

4.2 Step 2

With step two, we are improving the thermodynamical representation of temperature and phase changes of water at the surface and within a snowpack. Initial work involved incorporating a thermodynamic column model, which simultaneously computed the vertically-integrated temperature of soil and snow for a gridpoint, into the Los Alamos version of CCM0 [Marshall et al. 1994]. This replaced the diagnostic "heat balance" algorithm, used by most GCMs, with prognostic equations that describe the heat storage and thermal diffusion throughout the column (soil-snow-atmosphere). With the addition of snow to the column, this allowed the surface and sub-soil temperatures to more realistically respond to flows of heat across the boundary and to more accurately account for the thermal de-coupling of the atmosphere and soil when snow covered the surface. This kept the wintertime soil temperatures much higher than what had previously been simulated by the model and dampened large fluctuations in the GCM continental skin temperature during the Northern Hemisphere winter.

More recently, we have been adopting the ideas of Ku'zmin [1972]. This approach recognizes that conventional climate models such as the NCAR CCM1 and RegCM2 estimate snow melt through use of an 'excess energy'. In this standard modeling technique, the surface energy balance is computed iteratively in the normal fashion over snow covered grid points. An estimate of sensible and latent heat fluxes is made, with the latter being equivalent to either evaporation (or as is frequently the case, condensation). If the resultant surface temperature is above freezing, the temperature is instead held at freezing, which leads to an energy surplus. This surplus, or excess, energy is then assumed to be available to melt snow. A small amount of snow is assumed to evaporate through sublimation at any temperature.

This approach is likely to underestimate the true evaporation in the presence of melting snow because, in addition to the (minimal) latent heat flux from a bare snow surface as computed via the standard approach, as described by Kuz'min [1972], the melting snow releases liquid water which is also subject to evaporation, and which can considerably enhance the total latent heat flux.The energy used to evaporate this additional water must come from the 'excess energy' and hence is not available to contribute to snow melt. In addition, the melt water can infiltrate the snow pack and refreeze. This adds latent heat to, and hence warms the snow pack, but is not directly a part of net snow melt. The above effects generally are true even if a more sophisticated soil-vegetation-atmosphere scheme (SVAT) is used.

These processes can be accounted for conceptually by defining a parameter called 'alpha' which describes that fraction of available energy which contributes to net snow melt (i.e., does not evaporate water or lead to warming of the snow pack). Empirical studies of snow cover suggest a value for alpha in the range 0.5 - 0.75 (e.g., Leavesley and Stannard 1989). Virtually all current climate models implicitly use an alpha = 1.0, that is, all available energy as defined above is applied to net snow melt (this includes the work of Marshall and Oglesby 1994). Because the latent heat of vaporization is much larger than the latent heat of fusion, an alpha = 0.5 , for example, means that only about 10% of water from melting snow is evaporated. Figure 3 shows snow cover averaged over the entire northern hemisphere as a function of season for simulations with alpha = 1.0, 0.75, and 0.50. Note that the primary period of new snow accumulation (September through February) shows relatively little difference between the three cases, but as the late winter and spring snow melt season proceeds, there is considerable variation, with the higher the alpha value the greater the rate of snow melt and the more snow overall is melted.

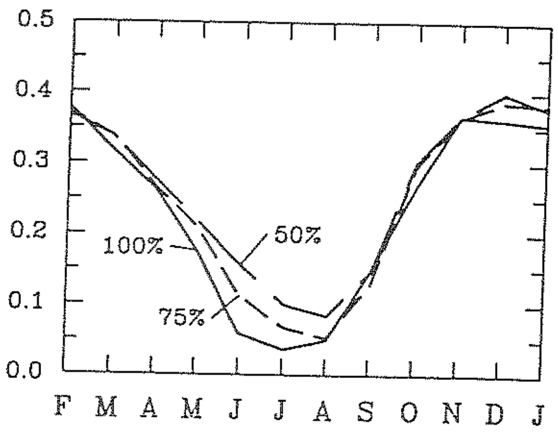
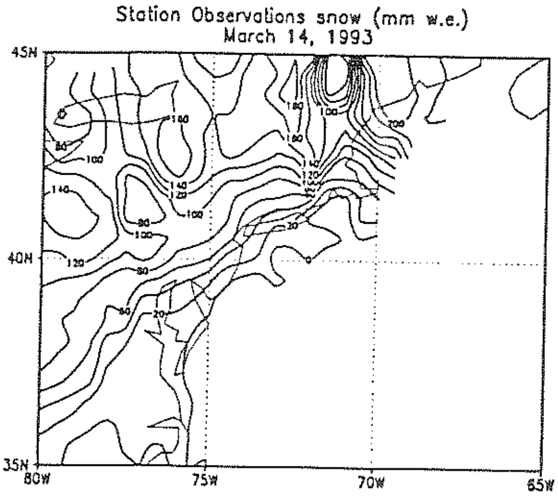


Figure 3: Seasonal cycle of the fractional area of the Northern Hemisphere occupied by snow for values of the alpha parameter (described in text).

In order to provide a more predictive assessment of alpha, we are using the latest version of the one-dimensional model of snowpack energy and mass balance, SNTHERM [Jordan 1991]. This model is based on the one-dimensional energy and mass balance model of Anderson [1976] (similar to many other current mass balance models of snow). The model solves the governing equations for energy and mass within the snowpack and is forced at the upper boundary by basic meteorological input or in our work with output from the GCM. The main changes to the latest revision [SNTHERM89.rev4, Jordan 1996] include improvements to the computation of turbulent transfer, new snow density and snow compaction, snow grain growth and snow albedo.

5. MODEL VALIDATION

Initial work using the satellite-derived snow cover estimates to validate model simulations of snow cover has focused on verifying that this is a realistic approach. We have chosen a winter season and are comparing satellite and ground data to results from several RegCM2 simulations (forced with ECMWF reanalyses) using the new model formulation of Marshall and Oglesby [1994]. Figure 4 shows snow cover obtained from ground data for March 14 1993 and as simulated by the RegCM2 for that same day. Preliminary results based on this and other comparisons suggest that overall the models do a reasonable job, certainly within the uncertainty of the observations. Locally, larger discrepancies occur, with the model tending to produce more snowfall during the winter storm of March 1993. In addition to model improvements, considerably more work is required to ground truth the satellite data and obtain data for as long a period of time as possible to ensure model-observation comparisons with as high a degree of fidelity as possible.



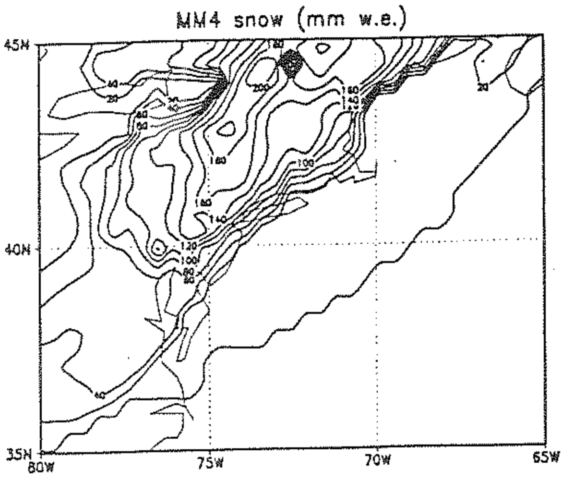


Figure 4: Water equivalent snow depths (mm) comparing station observations (top panel) and RegCM2 model output (bottom panel) for March 14, 1993.

6. CONCLUSIONS AND FUTURE WORK

The important conclusions we have obtained to date include:

(i) Improving the representation of snow albedo and short wave attenuation increases the realism of the model simulated seasonal cycle of snow, especially by providing a melt season that starts later but then proceeds more rapidly compared to the original approach.

(ii) Determining the fraction of total available energy that goes into net snow melt (the 'alpha' parameter) plays a major role in determining the rate of snow melt, and can be extremely important in determining if net annual snow accumulation or ablation occurs and therefore for climate model studies of glaciation and ice sheets.

(iii) Accurate and precise validation of model-simulated snow cover is difficult given the current state of observations although preliminary results suggest that satellite estimates of snow cover may be able to overcome this once data over a sufficient number of years with appropriate ground-truthing is available.

Ongoing and future work is aimed primarily at a more accurate determination of the alpha parameter through detailed representation of the thermodynamics of and transport within a snow pack, the use of 'excess energy' as a parameter in the study of glaciation, as well as further model validation using improved satellite-derived observations.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Aker, T.L., L.E. Buja, J.M. Rosinski and J.E. Truesdale, User's Guide to NCAR CCM3, *NCAR Technical Note, NCAR/TN-421+IA*, Boulder CO, 150pp., 1996.

Anderson, E.A., A point energy and mss balance model of a snow cover. *NOAA Technical Report NWS 19*, Office of Hydrology, National Weather Service, Silver Springs, MD, 1976

Bonan, G.B., A land surface model (LSM version 1.0) for ecological, hydrological, and atmospheric studies: Technical description and user's guide, *NCAR Technical Note, NCAR/TN-417+STR*, Boulder CO, 132pp., 1996.

Dickinson, R.E., A. Henderson-Sellers and P.J. Kennedy, Biosphere-Atmosphere Transfer Scheme (BATS) version 1e as coupled to the NCAR Community Climate Model. *NCAR Tech. Note, NCAR/TN-387+STR*, Boulder CO, 1993.

Giorgi, F., M.R. Marinucci and G.T. Bates, Development of a second generation regional climate model (RegCM2) I: Boundary layer and radiative transfer processes. *Monthly Weather Review, 121*(10), 2794-2813, 1993a.

Giorgi, F., M.R. Marinucci, G.T. Bates and G. DeCanio, Development of a second generation regional climate model (RegCM2) II: Convective processes and assimilation of lateral boundary conditions. *Monthly Weather Review, 121*(10), 2814-2832, 1993b.

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

Jordan, R., A one-dimensional temperature model for a snow cover. Technical documentation for SNTHERM.89. *Special Report 91-16*. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover NH, 1991.

Jordan, R., A one-dimensional temperature model for a snow cover. *Special report 657*. U.S. Army

Cold Regions Research and Engineering Laboratory, Hanover NH, 1996.

Kiehl, J.T., J.J. Hack, G.B. Bonan, B.A. Boville, B.P. Briegleb, D.L. Williamson and P.J. Rasch, Description of the NCAR Community Climate Model (CCM3), *NCAR Tech. Note, NCAR/TN-420+STR*, Boulder, CO, 1996.

Kuz'min, P.P., Melting of snow cover. *Proctess Tayoniya Shezhnogo Pokrova.* Translated from Russian. Israel Program for Scientific Translations, Jerusalem, 1972.

Leavesley, G.H. and C.G. Stannard, A distributed-parameter, energy-budget, snowmelt and runoff model for basin-wide applications. *EOS, Transactions, American Geophysical Union, 70*(43), 1109, 1989.

Marshall, S.E., A physical parameterization of snow albedo for use in climate models, (Ph.D. thesis) *NCAR Cooperative Thesis No. 123*, National Center for Atmospheric Research, Boulder, CO. 161 pp., 1989.

Marshall, S., J.O. Roads and G. Glatzmaier, Snow hydrology in a general circulation model. *Journal of Climate, 7*(8), 1252-1269, 1994.

Marshall S. and R.J. Oglesby, An improved snow hydrology for GCMs Part 1: Snowcover fraction, albedo, grain size, and age. *Climate Dynamics, 10*(1-2), 21-37, 1994.

Robinson, D. A., Monitoring northern hemisphere snow cover, in *Snow Watch '92: Detection Strategies for Snow and Ice,* edited by R.G. Barry, B.E. Goodison, and E.F. LeDrew, pp. 1-25, Available from Earth Observations Laboratory of the Institute for Space and Terrestrial Science, Boulder CO and the World Data Center A for Glaciology, 1993.