

Analysis of snow in the 20th and 21st century Geophysical Fluid Dynamics Laboratory coupled climate model simulations

Stephen J. Déry¹ and Eric F. Wood²

Received 24 November 2005; revised 18 April 2006; accepted 13 June 2006; published 13 October 2006.

[1] We evaluate the representation of the 20th century Northern Hemisphere, North American, and Eurasian snow cover extent, frequency, and mass by the Geophysical Fluid Dynamics Laboratory coupled climate model, version 2 (CM2) and then explore the 21st century trends and changes in these quantities. The CM2 simulations of 20th century climate capture the seasonal cycle in Northern Hemisphere snow cover extent and produce a mean annual snow area of 25×10^6 km² that equals the satellite-based observations for the period 1973–2000. The simulated snow cover frequency and snow mass generally decline from north to south, but longitudinal gradients in these variables are also found. Snow mass over North America, especially during spring, is underestimated by CM2. Simulations of 21st century climate using three Intergovernmental Panel on Climate Change Special Report on Emission Scenarios reveal strong trends in Northern Hemisphere snow cover extent, frequency, and mass. These simulations suggest that the annual Northern Hemisphere mean snow cover extent (total snow mass) will decrease by 12 to 26% (20 to 40%) by 2100 from their 21st century mean values. Large declines in 21st century snow cover frequency (up to 50%) and snow mass (up to 100 kg m^{-2}) arise during fall, winter, and spring over southern Canada and the northern United States, the Western Cordillera of North America, and western Eurasia compared to the 20th century CM2 simulations.

Citation: Déry, S. J., and E. F. Wood (2006), Analysis of snow in the 20th and 21st century Geophysical Fluid Dynamics Laboratory coupled climate model simulations, *J. Geophys. Res.*, *111*, D19113, doi:10.1029/2005JD006920.

1. Introduction

[2] Snow forms a distinct land surface type. The high albedo of snow implies that it reflects a large fraction of the incoming solar radiation [Cohen and Rind, 1991]. The low thermal conductivity and high emissivity of snow insulates the underlying ground and cools the overlying atmosphere [Stieglitz et al., 2001, 2003; Ellis and Leathers, 1998]. Being a reservoir for water, snow acts as a heat sink through sublimation and melting processes and as a source of atmospheric and soil moisture [Déry et al., 1998; Déry and Yau, 2002; Shinoda, 2001]. The unique properties of snow imply that a retreating and thinning snow cover induces a positive feedback to global warming [Cess et al., 1991; Holland and Bitz, 2003]. Thus snow constitutes a key element in the global climate system that requires special attention for accurate projections of future global warming and its impact on society and the environment.

[3] The Intergovernmental Panel on Climate Change (IPCC) 3rd assessment concluded that global climate model (GCM) simulations predict global surface air temperature (SAT) increases in the range of 1.4–5.8°C by 2100 [Intergovernmental Panel on Climate Change, 2001].

A concomitant acceleration of the hydrologic cycle is anticipated with the rise in global SAT [*Wetherald and Manabe*, 2002; *Yang et al.*, 2003; *Déry and Wood*, 2005a]. This will lead to changes in precipitation patterns, phases, and intensity that will alter the state of the Northern Hemisphere snow cover. Apart from its impact on the surface radiation and water budgets, changes in snow cover will affect river runoff and water resources, ground and permafrost temperatures, the duration of the growing season, and many other aspects of the global environment [*Barnett et al.*, 2005; *Déry and Wood*, 2005b; *Déry et al.*, 2005a; *Stieglitz et al.*, 2003; *Foster*, 1989; *Vaganov et al.*, 1999].

[4] The critical role of snow in the global climate system has led to its routine monitoring at the surface and from spaceborne instruments [e.g., Robinson et al., 1993; Robinson and Frei, 2000]. The resulting measurements are analyzed by various authors for the study of climate change. For instance, Frei and Robinson [1999] use satellite-based measurements to find a declining snow cover extent in the Northern Hemisphere between 1972 and 1994. Brown [2000] reconstructs the snow cover extent data prior to the satellite era and finds a decreasing trend in Northern Hemisphere snow cover extent over the period 1915–1997. Brown and Braaten [1998] and Curtis et al. [1998] find declining snow depths across most of Canada and Alaska during the 20th century. Mote et al. [2005] and Hamlet et al. [2005] report a widespread decline in snow mass in the North American Cordillera from 1925 to 2000 in response to rising surface air temperatures. Ye et al. [1998] report

¹Environmental Science and Engineering Program, University of Northern British Columbia, Prince George, British Columbia, Canada.

²Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA.

Copyright 2006 by the American Geophysical Union. 0148-0227/06/2005JD006920\$09.00

decreasing (increasing) snow depths in the zonal band $50-60^{\circ}N$ ($60-70^{\circ}N$) in Eurasia from 1936 to 1983. *Foster* [1989] and *Stone et al.* [2002] document a 20th century trend toward earlier snowmelt in Alaska, whereas *Ye and Ellison* [2003] and *Vaganov et al.* [1999] observe an opposite trend in northern Eurasia.

[5] The accumulating database of snow observations has been exploited by the GCM modeling community to validate the simulation of snow by land surface schemes designed for regional and global climate models. For instance, Foster et al. [1996] assess the performance of 7 GCMs to simulate the Northern Hemisphere snow cover extent and snow mass. Sheffield et al. [2003] and Pan et al. [2003] evaluate the simulation of snow cover extent and snow water equivalent by four land surface schemes participating in the North American Land Data Assimilation System (NLDAS). Other major research endeavors such as the Atmospheric Model Intercomparison Project (AMIP) and the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) devote considerable efforts in analyzing the representation of snow in land surface schemes of varying complexity [Frei and Robinson, 1998; Slater et al., 2001; Nijssen et al., 2003; Frei et al., 2005]. In the footsteps of PILPS, the Snow Model Intercomparison Project (SnowMIP) is a research program dedicated to the evaluation of snow models applied to four sites in Eurasia and North America [Etchevers et al., 2004].

[6] We follow these recent initiatives by evaluating the performance of the Geophysical Fluid Dynamics Laboratory (GFDL) coupled GCM in simulating the macroscale features of the Northern Hemisphere snow cover. We then proceed with an examination of the GFDL coupled climate model's projection of the 21st century Northern Hemisphere snow cover. The two main objectives of this study are (1) to analyze and evaluate GFDL coupled climate model simulations of snow cover during the 20th century using land surface and satellite-based measurements of snow cover extent and snow mass and (2) to determine trends and changes in the extent, frequency and mass of the simulated snow cover during the 21st century following three IPCC 4th assessment scenarios.

[7] The remainder of this paper is organized as follows: In section 2, we provide some background information on the GFDL coupled climate model and the simulations that form the basis of this research. Section 3 introduces the observational data sets and section 4 the methodology employed to analyze the GFDL coupled climate model simulations of snow. Section 5 presents analyses for the 20th century simulations of snow and then the simulated 21st century trends of snow cover extent, frequency, and mass. Section 6 discusses the potential implications of 21st century changes in snow and section 7 summarizes our main findings and plans for future work.

2. GFDL Coupled Climate Model and Simulations

2.1. Model Framework

[8] The GFDL coupled climate model is well documented [e.g., *Delworth et al.*, 2002; *Dixon et al.*, 2003] and widely used in the climate research community such that only a brief summary of its formulation is presented here. For complete

details of the GFDL CM2 model, the reader is referred to *Anderson et al.* [2004] for the atmosphere (version 2 or AM2), to *Delworth et al.* [2006] for the ocean (version 3 or OM3), and to *Milly and Shmakin* [2002] and *Anderson et al.* [2004] for the land surface (version 2 or LM2) modules.

[9] The AM2 is fully dynamical and includes physical parameterizations for radiative transfer, shallow and deep convection, gravity wave drag, and diffusion. Precipitation occurs when the air is supersaturated and falls as rain when the near SAT > 0°C and as snow otherwise. The atmospheric module has a horizontal resolution of 2.5° longitude by 2.0° latitude and 24 vertical levels with a model lid at 40 km above the surface. The OM3 is also fully dynamical and operates on a 1° × 1° lattice with 50 vertical levels. No flux adjustments are made between the atmospheric and oceanic components of the model.

[10] The LM2 is an updated version of the Land Dynamics (LaD) model that simulates radiative and mass exchanges between the atmosphere and land surface [Milly and Shmakin, 2002; Anderson et al., 2004]. It includes a water store for snow that varies through accumulation and ablation processes. Owing to the high computational demands of CM2, the snow model is relatively simple and does not resolve internal processes such as compaction or liquid water infiltration. Energy in the snowpack is stored as the latent heat of fusion and a simple heat conduction scheme determines the vertical temperature gradient. In LM2, snowmelt occurs only at the upper surface and melting snow is converted directly into runoff. The maximum snow mass is set to 1000 kg m⁻² to prevent the continual growth of the snowpack in regions where annual accumulation rates surpass the annual ablation rates.

2.2. Simulations

[11] A series of simulations were conducted using the GFDL CM2 for the IPCC 4th assessment. Here 20th and 21st century simulations are employed for the analyses:

[12] 1. Historical or "20th Century Climate in Coupled Models" (20C3M) simulations were conducted with the GFDL CM2 that employs time-varying CO₂, CH₄, N₂O, O₃, halons, anthropogenic tropospheric sulfates, black and organic carbon, dust, sea salt, volcanic aerosols, solar irradiance, and the distribution of land surface types. Three ensemble members are averaged to provide seasonal snow cover data for the period 1901–2000. Hereinafter, this set of simulations is referred to as "20C3M" following the IPCC convention.

[13] 2. Twenty-first century climate simulations were performed with the GFDL CM2 assuming an absence of volcanic aerosols, steady state land surface types, and solar irradiance that follows a climatological seasonal cycle. In these simulations, atmospheric CO_2 increases in time during the 21st century and stabilizes in 2100 at 550, 720, or 850 ppm according to the "B1," "A1B," and "A2," IPCC Special Report on Emission Scenarios (SRES). The data used in these analyses are available online from the GFDL data portal (http://nomads.gfdl.noaa.gov/).

3. Observational Data Sets

[14] The land surface area covered by snow is an important parameter in the global surface radiation and water budgets. Monthly mean snow cover extent data for the



Spring



Figure 1. Mean seasonal frequency of snow cover in the Northern Hemisphere for the GFDL 20C3M simulation. The bold outline encloses regions with an observed climatological snow cover frequency >50% in each season.

Northern Hemisphere, North America, and Eurasia spanning the period 1973–2004 from the National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center (CPC) (http://www.cpc.ncep.noaa.gov/data/ snow/) are therefore employed. Continental-scale snow cover extent data derived from satellite measurements have undergone quality control and are considered to be sufficiently accurate at the continental scale for climate-related studies [*Wiesnet et al.*, 1987]. However, uncertainties are known to exist in the satellite data, especially for spring

Table 1. Observed (OBS) and Simulated (CM2) Seasonal and Annual Mean and Standard Deviation (σ) of Snow Cover Extent in the Northern Hemisphere, North America, and Eurasia, 1973–2000^a

	OBS	CM2	MAE	RMSE	$\sigma_{\rm OBS}$	$\sigma_{\overline{\text{CM2}}}$	$\overline{\sigma_{\rm CM2}}$	
Northern Hemisphere								
Winter	44.0	41.7	2.42	0.55	1.36	1.02	1.54	
Spring	29.8	34.6	4.78	1.00	1.56	1.12	1.62	
Summer	6.2	3.8	2.31	0.51	1.23	0.28	0.44	
Fall	18.7	19.5	1.65	0.40	1.52	0.89	1.51	
Annual	24.7	24.9	0.89	0.22	0.94	0.64	0.83	
	North America							
Winter	16.6	16.3	0.58	0.15	0.60	0.50	0.93	
Spring	12.7	13.3	1.01	0.24	0.72	0.78	1.08	
Summer	4.2	2.8	1.32	0.29	0.66	0.18	0.33	
Fall	8.3	7.9	0.64	0.16	0.58	0.51	0.98	
Annual	10.4	10.1	0.47	0.11	0.43	0.36	0.51	
Eurasia								
Winter	27.4	25.4	2.05	0.46	0.97	0.76	1.15	
Spring	17.2	21.3	4.11	0.85	1.21	0.67	1.05	
Summer	2.0	1.0	1.01	0.23	0.63	0.17	0.24	
Fall	10.4	16.3	1.52	0.37	1.23	0.58	1.07	
Annual	14.2	14.8	0.77	0.19	0.66	0.41	0.57	

^aThe mean absolute error (MAE) and root mean square error (RMSE) are also listed. All values are in units of $\times 10^6$ km². See text for the definition of $\sigma_{\overline{CM2}}$ and $\overline{\sigma_{CM2}}$.

over northern Canada, and hence must be used judiciously [*Wang et al.*, 2005].

[15] In addition, maps of Northern Hemisphere snow cover were obtained from the Rutgers University Global Snow Lab (http://climate.rutgers.edu/snowcover). The monthly data span the period from November 1966 to December 2005 and are represented on a 89 × 89 grid using a polar stereographic projection of the Northern Hemisphere [*Robinson et al.*, 1993; *Robinson and Frei*, 2000].

[16] Snow mass forms an important reservoir of water on the land surface that can be quickly released during the ablation period contributing significantly to annual river discharge rates at continental scales [Barnett et al., 2005]. Thus monthly mean snow mass (in kg m^{-2}) over the period 1979-1997 at a resolution of 0.3° from the Canadian Meteorological Centre (CMC) is used in the analyses [Brown et al., 2003]. The gridded snow mass data are based on \approx 8000 daily observations as well as a simple snow accumulation, aging, and ablation model driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-15) data set to supplement measurements in data sparse regions (typically above 55°N). Since the snow mass data exclude Greenland, parts of the Canadian Arctic Archipelago, and western Alaska, the evaluation of snow mass is limited to a region bounded by latitudes from 20 to 70° N and by longitudes 55 to 140° W.

4. Methodology

[17] For snow cover extent, the 20C3M simulation is evaluated over three regions of interest: the Northern Hemisphere, North America, and Eurasia. Comparisons between observed and simulated snow cover extent over the period 1973–2000 are conducted. For snow mass, the analysis period is restricted to 1979–1997 and the study area to North America owing to the shorter time series and spatial coverage of the *Brown et al.* [2003] data. Averaging multiple ensemble members of GCM simulations reduces the modeled variability of snow cover extent and snow mass [*Frei and Gong*, 2005]. Thus for the examination of the variability in snow simulations, two variables are defined: (1) $\sigma_{\overline{CM2}}$ represents the standard deviation of the ensemble mean and (2) $\overline{\sigma_{CM2}}$ denotes the standard deviation inferred from the mean variance of the 3 ensemble members. Thus for $\sigma_{\overline{CM2}}$ we average the seasonal and annual simulations of snow and then compute the centuryscale variance and standard deviations from this new time series. For $\overline{\sigma_{CM2}}$, we first determine the variance for each of the three time series of simulated snow data before calculating their century-scale average variance, and then infer the corresponding standard deviation. These two quantities provide information on CM2's ability to depict the annual and seasonal variability of snow cover extent and snow mass.

[18] The three simulations of 21st century climate are used to explore trends in snow cover extent and mass. Monotonic trends are inferred using the nonparametric Mann-Kendall test [*Mann*, 1945; *Theil*, 1950; *Kendall*, 1975]. The determination of the trends and their statistical significance follow the methodology outlined in the appendix of *Déry et al.* [2005a]. Percent changes in snow cover extent and snow mass are with respect to their 21st century means.

[19] Following the methodology used in the IPCC 2nd assessment [Intergovernmental Panel on Climate Change, 1995], a grid point with $\geq 10 \text{ kg m}^{-2}$ of snow over a given season is considered fully snow covered. Although the seasonal frequency of snow cover depends on the specified threshold, the investigation of snow mass in addition to snow cover extent provides a comprehensive picture of changes in snow cover from the 20th to the 21st century. For the purpose of this study, the months of December, January and February compose winter, March, April and May form spring, June, July and August compose summer, and September, October, and November form autumn. The focus of this study is on the Northern Hemisphere land surface such that snow over sea ice is not considered. Results from the analyses are presented on a polar stereographic projection for latitudes above 20°N where most of the Northern Hemisphere seasonal snow cover exists. The simulated snow cover by CM2 is also evaluated with the 1966-2005 climatological snow lines that are represented by the 50th percentile of observed snow cover for a given season. Points where the snow mass reaches the specified maximum of 1000 kg m⁻² are masked out of the difference analyses since this may otherwise lead to ambiguous outcomes. Results for the 21st century focus on the SRES A1B simulation to show the intermediate effects of rising atmospheric CO₂ concentrations on the Northern Hemisphere snow cover.

[20] The accurate simulation of snow cover extent and snow mass depends largely on the modeled SAT and precipitation. Validation of these important variables is presented elsewhere [e.g., *Anderson et al.*, 2004] and is not repeated here; however, model biases in SAT and precipitation are discussed when relevant to the snow analyses.

5. Analyses of GFDL Coupled Climate Model Simulations

5.1. Analysis of 20th Century Simulations

[21] Figure 1 illustrates the mean seasonal frequency of snow cover over the Northern Hemisphere for the 20C3M



Figure 2. Mean seasonal snow mass (kg m^{-2}) in the Northern Hemisphere for the GFDL 20C3M simulation.

Table 2. Observed (OBS) and Simulated (CM2) Seasonal and Annual Mean Snow Mass Over North America for the Period August 1979 to June 1997^a

	OBS	CM2	MAE	RMSE	$\sigma_{\rm OBS}$	$\sigma_{\overline{\text{CM2}}}$	$\overline{\sigma_{\rm CM2}}$
Winter	52.0	45.3	7.0	1.9	4.3	2.5	4.7
Spring	56.6	44.4	12.2	3.3	4.9	3.9	5.5
Summer	4.2	0.9	3.3	0.8	1.1	0.3	0.6
Fall	6.9	6.4	1.1	0.3	1.2	0.6	1.2
Annual	30.0	24.3	5.7	1.6	1.5	1.5	2.4

^aThe mean absolute error (MAE) and root mean square error (RMSE) are also listed. All values are in units of kg m⁻². See text for the definition of $\sigma_{\overline{\text{CM2}}}$ and $\overline{\sigma_{\text{CM2}}}$.

simulation. Snow reaches its greatest extent during winter, then decreases during spring, attains a minimum during summer, and begins its expansion during fall. There is a permanent snow cover over the ice sheets of Greenland and some of the Canadian Arctic Islands. Large latitudinal gradients in snow cover frequency are correctly simulated by the GFDL CM2 [cf. *Karl et al.*, 1993].

[22] The match between the simulated snow cover and the climatological snow lines is quite good globally except for spring and fall when the 20C3M snow extends further south into Eurasia. The simulation has a more extensive snow cover over the Tibetan Plateau, especially during spring, suggesting that the CM2 winter snow accumulation is too

high. During fall, the modeled snow cover extent in Québec is also larger than observed.

[23] Table 1 provides a comparison of the observed and simulated snow cover extent and its variability in the Northern Hemisphere, North America, and Eurasia over the period 1973–2000. For the Northern Hemisphere, the greatest discrepancies between the observed and simulated values occur during spring. The ablation period is a season that many snow models have difficulty representing [e.g., Slater et al., 2001; Déry et al., 2004, 2005b, 2005c] and for which the largest uncertainties in the satellite data exist [Wang et al., 2005]. On an annual basis, the GFDL coupled climate model simulates the Northern Hemisphere snow cover extent to be 25×10^6 km², matching the observations. Both the mean absolute errors (MAE) and root mean square errors (RMSE) are minimized for the annual snow cover extent, suggesting that the GFDL CM2 is accurately depicting the annual climatology of snow cover extent. In all seasons, however, the ensemble mean shows less interannual variability than the observations, especially during summer; however, the variability of the individual ensemble members nears the observed variability in snow cover extent except during summer. Over North America and Eurasia, the model also captures the annual climatological snow cover extent, but again the ensemble mean underestimates its interannual variability, especially over Eurasia.



Figure 3. Time series of seasonal and annual mean observed and simulated snow cover extent in the Northern Hemisphere. Bold solid (dashed) lines denote time series with (without) significant trends at the p < 0.05 level.

	20C3M (1901-2000)	20C3M (1973-2000)	Observed (1973-2000)	B1 (2001–2100)	A1B (2001–2100)	A2 (2001–2100)
Winter Spring	-0.017 -0.032	-0.09^{b} -0.19	-0.09^{b} -0.35	-0.088 -0.128	-0.226 -0.278	-0.192 -0.258
Summer	-0.072	-0.11 ^b	-1.42	-0.232	-0.377	-0.397
Fall	-0.032	-0.06^{b}	0.13 ^b	-0.180	-0.266	-0.397
Annual	-0.026	-0.12^{b}	-0.20	-0.121	-0.257	-0.259

Table 3. Observed and Simulated Changes in the Seasonal and Annual Snow Cover Extent Over the Northern Hemisphere According to the Mann-Kendall Test^a

^aChanges are given in % yr⁻¹.

^bA trend not significant at the p < 0.05 level.

[24] Figure 2 presents the mean seasonal snow mass based on the GFDL 20C3M simulation over the same domain. Snow mass generally decreases from north to south, but longitudinal gradients are also evident. For instance, the model simulates more snow mass in western Eurasia than in central Siberia during winter and spring. Similarly, there is a regional maximum in snow mass over northern Québec and Labrador with much lesser snow in central Canada during winter and spring. Snow mass attains its specified maximum of 1000 kg m⁻² over parts of Greenland and some of the Canadian Arctic Islands where annual accumulation rates exceed annual ablation rates.

[25] Table 2 provides an analysis of snow mass from the GFDL 20C3M simulation compared to the observationbased data generated by Brown et al. [2003] for the period 1979-1997 over North America. The CM2 model has a slight negative (positive) SAT bias over eastern (western) North America and a slight positive precipitation bias during winter [Anderson et al., 2004]. The comparison shows that the GFDL CM2 underestimates snow mass, especially during spring when the observed maximum accumulation of 56.6 kg m⁻² occurs. On an annual basis, the model exhibits a mean absolute (root mean square) error of 5.7 (1.6) kg m⁻² compared to the observations. Apart from the model biases in SAT and precipitation as well as inaccuracies in the Brown et al. [2003] data, the underestimates in snow mass may be the result of the simple snow scheme used in the simulations. A possible source for these inconsistencies is the lack of internal snowpack physics in combination with the direct transfer of meltwater into streamflow that may reduce snow accumulation in the model simulations. Variability in snow mass in the ensemble mean is less than observed, whereas the individual ensemble members exhibit greater variability than observed.

5.2. Analysis of 21st Century Simulations and Comparison With 20th Century Observations and Simulations

[26] Figure 3 shows time series of the mean annual snow cover extent based on satellite measurements (1973–2004) and on 20th (20C3M) and 21st (B1, A1B, and A2) century CM2 simulations. Table 3 provides the slopes of the Kendall-Theil robust lines [see *Déry et al.*, 2005a, appendix] that are shown in Figure 3 by the bold lines. Over the period 1973–2000, the linear trend in observed snow cover extent over the Northern Hemisphere shows an annual decrease of 0.20% (Table 3). This trend is greater (in absolute terms) than that for the 20C3M simulation.

[27] Three SRES simulations all exhibit strong, negative trends in Northern Hemisphere snow cover extent. Over the 21st century, the simulations project a 12 to 26% decline in

the mean annual area covered by snow. The 1973–2004 linear trend of the measured snow cover extent translates to a 17% reduction in Northern Hemisphere snow cover extent over the century. This trend is more pronounced than in the SRES B1 scenario. If global warming accelerates the retreat of snow cover in the Northern Hemisphere during the 21st century, then the observed trend may approach that found in the A1B and A2 climate simulations.

[28] Note also the discrepancies in the seasonal trends of Northern Hemisphere snow cover extent. Table 3 shows that the 20C3M simulation fails to reproduce the observed expansion of snow cover extent during autumn, and the sharp decrease in summer snow cover extent. In contrast to the historical satellite measurements, the 21st century simulations all show nearly uniform declines in seasonal snow cover extent.

[29] Figure 4 reveals the seasonal differences in Northern Hemisphere snow cover frequency between the 21st (A1B) and 20th (20C3M) century GFDL CM2 simulations. For all three 21st century scenarios, a decline in the frequency of snow cover is expected compared to the 20th century. Declines of up to 50% in snow cover frequency are anticipated during spring over western Eurasia, south central Canada, and the western United States. There are also prominent decreases in the seasonal frequency of snow cover during fall and winter, but few changes during summer when snow is generally infrequent. These decreases in snow cover frequency occur at the southern boundaries of the seasonal continental snowpack where air temperatures are closest to freezing and most susceptible to warming. All three 21st century scenarios depict similar spatial patterns in the changes in snow cover frequency with minor differences in the intensity of these changes (not shown).

[30] Figure 5 represents the zonally averaged differences in snow cover frequency between the 21st (A1B) and 20th (20C3M) century GFDL CM2 simulations. This shows that the most significant reductions in zonally averaged snow cover frequency are expected to occur during spring between 50° and 60°N. Large declines in winter (40° to 50° N) and fall (60° to 70° N) are also anticipated, with lesser changes during summer.

[31] Figures 6 and 7 show time series of the seasonal and annual total snow mass from the 20th (20C3M) and 21st (B1, A1B, and A2) century CM2 simulations for the Northern Hemisphere and North America, respectively. Observed snow mass data for North America based on the work of *Brown et al.* [2003] are included in Figure 7. Table 4 also provides the slopes for the Kendall-Theil robust lines shown in Figure 6. For all simulations, the linear trends in Northern Hemisphere snow mass are negative



Figure 4. Difference between the seasonal frequency of snow cover in the Northern Hemisphere for the GFDL CM2 simulation of scenario A1B (2001-2100) and the 20C3M simulation (1901-2000). The bold outline encloses regions with an observed climatological snow cover frequency >50% in each season.



Figure 5. Difference between the seasonal zonal snow frequency in the Northern Hemisphere for the GFDL CM2 simulation of scenario A1B (2001–2100) and the 20C3M simulation (1901–2000).



Figure 6. Time series of seasonal and annual simulated total snow mass in the Northern Hemisphere. Bold solid lines denote time series with significant trends at the p < 0.05 level.



Figure 7. Time series of seasonal and annual observed and simulated total snow mass in North America. Bold solid (dashed) lines denote time series with (without) significant trends at the p < 0.05 level.

and statistically significant. For the B1, A1B, and A2 scenarios, CM2 projects century-scale reductions of 20% to 40% in the total annual snow mass relative to the Northern Hemisphere 21st century means.

[32] Figure 8 presents differences between the 21st (A1B) and 20th (20C3M) century simulations of snow mass by the GFDL CM2. Large decreases in snow mass during winter and spring are anticipated by the model. At latitudes above 60°N in Eastern Eurasia and the Canadian Archipelago, increases in snow mass are anticipated during the 21st century. The spatial variation in snow mass trends are consistent with observed data. For instance, Ye et al. [1998] find decreasing snow depth between 50° and 60°N but increasing snow depth between 60° and 70°N in Eurasia from 1936-1983. In North America, Brown and Braaten [1998] report declining snow depths over much of Canada for the period 1946-1995, in accord with the simulated trends for the 21st century. Note also that the GFDL CM2 anticipates significant reductions in snow mass over Greenland in all four seasons. As for snow cover frequency, the B1 and A2 simulations provide similar spatial patterns in snow mass changes with slight departures in their magnitudes (not shown).

[33] Figure 9 shows differences (expressed as percentages) in total, zonal snow mass between the 21st (A1B) and 20th (20C3M) century simulations. Snow mass losses are relatively largest during summer and decrease northward in all seasons. There is relatively less change in snow mass between 60° and $75^{\circ}N$ but the greatest absolute losses in snow mass occur over Greenland (from 75° to $85^{\circ}N$) in all seasons (not shown).

6. Discussion

[34] The 21st century GFDL CM2 climate simulations project strong, negative trends in snow cover extent, fre-

Table 4. Simulated Changes in the Seasonal and Annual TotalSnow Mass Over the Northern Hemisphere According to theMann-Kendall Test^a

	20C3M (1901-2000)	B1 (2001–2100)	A1B (2001–2100)	A2 (2001–2100)
Winter	-0.023	-0.160	-0.287	-0.299
Spring	-0.026	-0.193	-0.336	-0.355
Summer	-0.062	-0.309	-0.553	-0.625
Fall	-0.046	-0.261	-0.460	-0.524
Annual	-0.034	-0.207	-0.364	-0.393

^aChanges are given in % yr⁻¹. All trends are significant at the p < 0.05 level.



Figure 8. Difference between the seasonal snow mass (kg m⁻²) in the Northern Hemisphere for the GFDL CM2 simulation of scenario A1B (2001–2100) and the 20C3M simulation (1901–2000).

quency, and mass across the Northern Hemisphere. If these trends materialize, as the short record of satellite measurements seems to indicate for snow cover extent, the loss of snow will have important repercussions on the global environment. At regional scales, declining snowpacks are associated with earlier spring freshets, reductions in soil moisture and water resources, and amplification of drought conditions [*Shinoda*, 2001; *Stewart et al.*, 2005]. Less snow also increases the surface albedo and the amount of solar radiation absorbed by the surface, thereby providing a positive feedback to global warming [*Cess et al.*, 1991]. Through large-scale teleconnections, changes in Eurasian and/or North American snow cover can affect remote regions. For instance, *Déry et al.* [2005d] found statistically



Figure 9. Percent differences between the seasonal zonal snow mass in the Northern Hemisphere for the GFDL CM2 simulation of scenario A1B (2001–2100) and the 20C3M simulation (1901–2000).

significant connections between snow cover extent in Eurasia and snow mass and river discharge in northern Québec and Labrador. Other important repercussions of a declining snow cover on the global environment are summarized by *Barnett et al.* [2005].

[35] The strong negative trends in 21st century snow cover extent simulated by the GFDL CM2 are consistent with the results of other GCMs involved in the IPCC 4th assessment. For instance, Frei and Gong [2005] report decreases of ≈ 5 to 15% in 21st century North American snow cover extent simulated by 11 GCMs for the SRES A1B and A2 scenarios. Holland and Bitz [2003] report a weak dependence between polar amplification of climate change and a decreasing Northern Hemisphere snow cover as produced by 13 GCMs participating in the second generation of the Coupled Model Intercomparison Project (CMIP2). Ye and Mather [1997] find negative trends in Northern Hemisphere snow depths as simulated by 3 GCMs in a 2 \times CO₂ scenario. Thus GCM simulations of 21st century climate suggest a continuation of declining snow cover in the Northern Hemisphere.

7. Summary

[36] The analysis of the simulated extent, frequency, and mass of the Northern Hemisphere snow cover during the 20th century reveals that CM2 captures its observed macroscale features. Specifically, the model represents accurately the observed mean annual snow cover extent of 25×10^6 km² for the period 1973–2000. The frequency of the simulated snow cover decreases with latitude in accordance with satellite measurements. However, a deficiency in the CM2 simulations is the underestimate of North American snow mass compared to the available observational data. The source of this negative bias in snow mass remains unknown. Apart from model biases in SAT and precipitation and uncertainties in the observation-based snow mass data, the relatively simple snow physics resolved

by CM2 may be responsible for the simulated underestimates in snow mass. Further detailed simulations and analyses are required to pinpoint the source of the negative snow mass biases in CM2.

[37] This work provides an assessment of the GFDL CM2's performance in simulating the macroscale features of the Northern Hemisphere snow cover. For future work, we will expand the analysis to all GCMs participating in the IPCC 4th assessment to verify the ability of GCMs to simulate the Northern Hemisphere snow cover and to better understand the range of projections in its future state.

[38] Acknowledgments. The authors thank the Land Model Development group at GFDL for their comments and access to the simulation data, R. Brown at CMC for the North American snow mass data, T. Estilow at the Rutgers University Global Snow Lab for the monthly grids of Northerm Hemisphere snow data, A. Frei at Hunter College, and two anonymous referees for their useful comments. This report was prepared by S. Déry under award NA17RJ2612 from National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. The statements, findings, conclusions, and recommendations are those of the author and do not necessarily reflect the views of NOAA or the U.S. Department of Commerce. The lead author acknowledges additional support from the Natural Sciences and Engineering Research Council of Canada and the Canada Research Chair program of the Government of Canada.

References

- Anderson, J. L., et al. (2004), The new GFDL global atmosphere and land model AM2-LM2: Evaluation with prescribed SST simulations, *J. Clim.*, 17, 4641–4673.
- Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, 438, 303–309.
- Brown, R. D. (2000), Northern Hemisphere snow cover variability and change, 1915–97, J. Clim., 13, 2339–2355.
- Brown, R. D., and R. O. Braaten (1998), Spatial and temporal variability of Canadian monthly snow depths, *Atmos. Ocean*, *36*, 37–54.
- Brown, R. D., B. Brasnett, and D. Robinson (2003), Gridded North American monthly snow depth and snow water equivalent for GCM evaluation, *Atmos. Ocean*, *41*, 1–14.
- Cess, R. D., et al. (1991), Interpretation of snow-climate feedback as produced by 17 general circulation models, *Science*, 253, 888–892.
- Cohen, J., and D. Rind (1991), The effect of snow cover on the climate, J. Clim., 4, 689-706.

- Curtis, J., G. Wendler, R. Stone, and E. Dutton (1998), Precipitation decrease in the western Arctic, with special emphasis on Barrow and Barter Island, Alaska, *Int. J. Climatol.*, 18, 1687–1707.
- Delworth, T. L., R. J. Stouffer, K. W. Dixon, M. J. Spelman, T. R. Knutson, A. J. Broccoli, P. J. Kushner, and R. T. Wetherald (2002), Review of simulations of climate variability and change with the GFDL R30 coupled climate model, *Clim. Dyn.*, 19, 555–574.
- Delworth, T. L., et al. (2006), GFDL's CM2 global climate models. Part I: Formulation and simulation characteristics, *J. Clim.*, *19*, 643–674.
- Déry, S. J., and E. F. Wood (2005a), Observed twentieth century land surface air temperature and precipitation covariability, *Geophys. Res. Lett.*, 32, L21414, doi:10.1029/2005GL024234.
- Déry, S. J., and E. F. Wood (2005b), Decreasing river discharge in northern Canada, *Geophys. Res. Lett.*, 32, L10401, doi:10.1029/2005GL022845.
- Déry, S. J., and M. K. Yau (2002), Large-scale mass balance effects of blowing snow and surface sublimation, J. Geophys. Res., 107(D23), 4679, doi:10.1029/2001JD001251.
- Déry, S. J., P. A. Taylor, and J. Xiao (1998), The thermodynamic effects of sublimating, blowing snow in the atmospheric boundary layer, *Boundary Layer Meteorol.*, 89, 251–283.
- Déry, S. J., W. T. Crow, M. Stieglitz, and E. F. Wood (2004), Modeling snow-cover heterogeneity over complex Arctic terrain for regional and global climate models, *J. Hydrometeorol.*, 5, 33–48.
- Déry, S. J., M. Stieglitz, E. C. McKenna, and E. F. Wood (2005a), Characteristics and trends of river discharge into Hudson, James, and Ungava bays, 1964–2000, J. Clim., 18, 2540–2557.
- Déry, S. J., V. V. Salomonson, M. Stieglitz, D. K. Hall, and I. Appel (2005b), An approach to using snow areal depletion curves inferred from MODIS and its application to land surface modelling in Alaska, *Hydrol. Processes*, 19, 2755–2774, doi:10.1002/hyp.5784.
- Déry, S. J., M. Stieglitz, A. K. Rennermalm, and E. F. Wood (2005c), The water budget of the Kuparuk River Basin, Alaska, *J. Hydrometeorol.*, *6*, 633–655.
- Déry, S. J., J. Sheffield, and E. F. Wood (2005d), Connectivity between Eurasian snow cover extent and Canadian snow water equivalent and river discharge, J. Geophys. Res., 110, D23106, doi:10.1029/ 2005JD006173.
- Dixon, K. W., T. L. Delworth, T. R. Knutson, M. J. Spelman, and R. J. Stouffer (2003), A comparison of climate change simulations produced by two GFDL coupled climate models, *Global Planet. Change*, 37, 81– 102.
- Ellis, A. W., and D. J. Leathers (1998), The effects of a discontinuous snow cover on lower atmospheric temperature and energy flux patterns, *Geophys. Res. Lett.*, 25, 2161–2164.
- Etchevers, P., et al. (2004), Validation of the energy budget of an alpine snowpack simulated by several snow models (SnowMIP project), *Ann. Glaciol.*, *38*, 150–158.
- Foster, J. L. (1989), The significance of the date of snow disappearance on the arctic tundra as a possible indicator of climate change, *Arct. Alp. Res.*, 21, 60–70.
- 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. Clim.*, 9, 409–426.
 Frei, A., and G. Gong (2005), Decadal to century scale trends in North
- Frei, A., and G. Gong (2005), Decadal to century scale trends in North American snow extent in coupled atmosphere-ocean general circulation models, *Geophys. Res. Lett.*, 32, L18502, doi:10.1029/2005GL023394.
- Frei, A., and D. A. Robinson (1998), Evaluation of snow extent and its variability in the Atmospheric Model Intercomparison Project, J. Geophys. Res., 103, 8859–8871.
- Frei, A., and D. A. Robinson (1999), Northern Hemisphere snow extent: Regional variability 1972–1994, Int. J. Climatol., 19, 1535–1560.
- Frei, A., R. Brown, J. A. Miller, and D. A. Robinson (2005), Snow mass over North America: Observations and results from the second phase of the Atmospheric Model Intercomparison Project (AMIP-2), J. Hydrometeorol., 6, 681–695.
- Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier (2005), Effects of temperature and precipitation variability on snowpack trends in the western United States, J. Clim., 18, 4545–4561.
- Holland, M. M., and C. M. Bitz (2003), Polar amplification of climate change in coupled models, *Clim. Dyn.*, 21, 221–232, doi:10.1007/ s00382-003-0332-6.
- Intergovernmental Panel on Climate Change (1995), *Climate Change 1995: The Science of Climate Change*, edited by J. T. Houghton et al., 572 pp., Cambridge Univ. Press, New York.
- Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., 944 pp., Cambridge Univ. Press, New York.

- Karl, T. R., P. Y. Groisman, R. W. Knight, and R. R. Heim (1993), Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations, *J. Clim.*, 6, 1327–1344.
- Kendall, M. G. (1975), *Rank Correlation Methods*, 202 pp., Oxford Univ. Press, New York.
- Mann, H. B. (1945), Non-parametric test against trend, *Econometrika*, 13, 245-259.
- Milly, P. C. D., and A. B. Shmakin (2002), Global modeling of land water and energy balances. Part I: The land dynamics (LaD) model, J. Hydrometeorol., 3, 283–299.
- Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier (2005), Declining mountain snowpack in western North America, *Bull. Am. Meteorol. Soc.*, 86, 39–49.
- Nijssen, B., et al. (2003), Simulation of high latitude hydrological processes in the Torne-Kalix basin: PILPS phase 2(e) - 2: Comparison of model results with observations, *Global Planet. Change*, *38*, 31–53.
- Pan, M., et al. (2003), Snow process modeling in the North American Land Data Assimilation System (NLDAS): 2. Evaluation of model simulated snow water equivalent, J. Geophys. Res., 108(D22), 8850, doi:10.1029/ 2003JD003994.
- Robinson, D. A., and A. Frei (2000), Seasonal variability of Northern Hemisphere snow extent using visible satellite data, *Prof. Geogr.*, *52*, 307–315.
- Robinson, D. A., K. F. Dewey, and R. R. Heim (1993), Global snow cover monitoring: An update, *Bull. Am. Meteorol. Soc.*, 74, 1689–1696.
- Sheffield, J., et al. (2003), Snow process modeling in the North American Land Data Assimilation System (NLDAS): 1. Evaluation of model-simulated snow cover extent, J. Geophys. Res., 108(D22), 8849, doi:10.1029/ 2002JD003274.
- Shinoda, M. (2001), Climate memory of snow mass as soil moisture over central Eurasia, *J. Geophys. Res.*, *106*, 33,393–33,403.
- Slater, A. G., et al. (2001), The representation of snow in land surface schemes: Results from PILPS 2(d), *J. Hydrometeorol.*, 2, 7–25.
- Stewart, I. T., D. R. Cayan, and M. D. Dettinger (2005), Changes toward earlier streamflow timing across western North America, J. Clim., 18, 1136–1155.
- Stieglitz, M., A. Ducharne, R. Koster, and M. Suarez (2001), The impact of detailed snow physics on the simulation of snow cover and subsurface thermodynamics at continental scales, J. Hydrometeorol., 2, 228–242.
- Stieglitz, M., S. J. Déry, V. E. Romanovsky, and T. E. Osterkamp (2003), The role of snow cover in the warming of Arctic permafrost, *Geophys. Res. Lett.*, 30(13), 1721, doi:10.1029/2003GL017337.
- Stone, R. S., E. G. Dutton, J. M. Harris, and D. Longenecker (2002), Earlier spring snowmelt in northern Alaska as an indicator of climate change, *J. Geophys. Res.*, 107(D10), 4089, doi:10.1029/2000JD000286.
- Theil, H. (1950), A rank-invariant method of linear and polynomial regression analysis, *Indagationes Math.*, 12, 85–91.
- Vaganov, E. A., M. K. Hughes, A. V. Kidyanov, F. H. Schweingruber, and P. P. Silkin (1999), Influence of snowfall and melt timing on tree growth in subarctic Eurasia, *Nature*, 400, 149–151.
- Wang, L., M. Sharp, R. Brown, C. Derksen, and B. Rivard (2005), Evaluation of spring snow covered area depletion in the Canadian Arctic from NOAA snow charts, *Remote Sens. Environ.*, 95, 453–463.
- Wetherald, R. T., and S. Manabe (2002), Simulation of hydrologic changes associated with global warming, J. Geophys. Res., 107(D19), 4379, doi:10.1029/2001JD001195.
- Wiesnet, D. R., C. F. Ropelewski, G. J. Kukla, and D. A. Robinson (1987), A discussion of the accuracy of NOAA satellite-derived global seasonal snow cover measurements, in *Large Scale Effects of Seasonal Snow Cover*, edited by B. E. Goodison, R. G. Barry, and J. Dozier, *IAHS Publ.*, *166*, 291–304.
- Yang, F., A. Kumar, M. E. Schlesinger, and W. Wang (2003), Intensity of hydrological cycles in warmer climates, J. Clim., 16, 2419–2423.
- Ye, H. C., and M. Ellison (2003), Changes in transitional snowfall season length in northern Eurasia, *Geophys. Res. Lett.*, 30(5), 1252, doi:10.1029/ 2003GL016873.
- Ye, H., and J. R. Mather (1997), Polar snow cover changes and global warming, *Int. J. Climatol.*, 17, 155–162.
- Ye, H., H. R. Cho, and P. E. Gustafson (1998), The changes in Russian winter snow accumulation during 1936–83 and its spatial patterns, J. Clim., 11, 856–863.

S. J. Déry, Environmental Science and Engineering Program, University of Northern British Columbia, 3333 University Way, Prince George, BC, Canada V2N 4Z9. (sdery@unbc.ca)

E. F. Wood, Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA.