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Decadal to century scale trends in North American snow extent in coupled atmosphere-ocean general circulation models

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[1] 20th and 21st century decadal scale trends and variability in winter North American snow cover extent (NA-SCE) are investigated using coupled atmosphere-ocean general circulation model experiments participating in the upcoming Intergovernmental Panel on Climate Change Fourth Assessment Report. Significant between-model variability is found, with most models underestimating mean NA-SCE. 20th century simulations are poorly correlated with observations, and, while individual ensemble members capture the magnitude of decadal scale variability, the variability of the signal is dampened in the ensemble mean, indicating that decadal-scale NA-SCE variability is associated predominantly with internal model variability rather than external forcing. Two 21st century emission scenarios with realistic (moderate or significant) greenhouse gas emission rates produce decreasing NA-SCE trends, while one unrealistic scenario with fixed concentrations produces little or no NA-SCE trend. These results suggest that snow cover may be a sensitive indicator of climate change, and that North American snow extent will probably decrease in response to greenhouse gas emissions, although the magnitude of the response may be nonlinear. **Citation:** 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.

1. Introduction

[2] Since the early 20th century, the spatial extent of snow cover (SCE) has varied significantly across Northern Hemisphere land areas at both seasonal and interannual time scales [*Robinson and Frei*, 2000; *Armstrong and Brodzik*, 2001]. SCE is considered to be a potentially sensitive indicator of climate change; and, due to feedback processes, changes in the spatial distribution/extent of land-based snow may play important roles in determining the direction and magnitude climate changes across the globe [e.g., *Clark and Serreze*, 2000; *Derksen et al.*, 1997]. Indeed, general circulation model (GCM) results are sensitive to the treatment of snow and related processes [e.g., *Gong et al.*, 2003].

[3] Recent evaluations of snow simulations for the period 1979–1995 by fifteen atmospheric general circulation models (AGCMs) participating in the Second Phase of the Atmospheric Model Intercomparison Project (AMIP-2) found significant between-model variability in SCE [*Frei et al.*, 2003] and snow water equivalent (SWE) (Frei et al. 2005). Earlier evaluations of AGCM snow simulations using less consistent model experiments found similarly mixed results [*Foster et al.*, 1996; *Zhong*, 1996; *Yang et al.*, 1999].

[4] An unprecedented suite of coordinated 20th and 21st century climate change experiments have recently (winter/spring 2005) been released to researchers, in association with the upcoming Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4). These experiments will ultimately involve 21 global coupled atmosphere-ocean general circulation models (AOGCMs), 12 different climate scenarios, and multiple ensemble realizations. Over the past ten years, considerable effort has gone into improving global climate simulation and prediction from coupled models, driven largely by the Coupled Model Intercomparison Project (CMIP) [*Meehl et al.*, 2005]. While the overall level of CMIP model internal climate variability appears to be within the observed range [*Covey et al.*, 2003; *Coquard et al.*, 2004; *Harvey*, 2004], no studies have focused specifically on snow cover.

[5] This report provides a preliminary investigation of SCE variations and trends over North America (NA-SCE), a region for which the most reliable, long-term information is available, as simulated by IPCC-AR4 AOGCMs. We focus on decadal-to-century scale trends and variability, including 20th century simulations as well as three scenarios of 21st century climatic change.

2. Data and Models

[6] Satellite observations of Northern Hemisphere SCE are available back to 1967 [*Robinson*, 1993]. Reconstructions of large scale North American SCE variations back to the early 20th century have been performed in two studies which utilized station observations of snow depth. *Brown* [2000] derived a snow cover index using daily snow depth observations from US and Canadian stations, while *Frei and Robinson* [1999] used a combination of Principal Components Analysis and linear multiple regression, but included only U.S. stations. There is good agreement between the two data sets with regard to decadal scale variations. For this analysis, both data sets are converted from the units

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Table 1. IPCC Climate Scenarios, With Associated Time Domains and Total CO_2 Emission Rates, Used in This Analysis[a]

Scenario	Approximate Time Domain	Total CO_2 Emission Rates[b]	CO_2 Atmospheric Concentrations[b]
20C3M	1850–2000	Peaks in 2000 at ~8 GtC/yr	Peaks in 2000 at ~370 ppm
SRESA1B	2000–2100	Gradual rise to ~16 GtC/yr in 2050, then gradual decrease to ~13 GtC/yr by 2100	Gradual rise to ~720 ppm by 2100
SRESA2	2000–2100	Gradual rise to ~29 GtC/yr by 2100	Gradual rise to ~860 ppm by 2100
COMMIT	2000–2100	[not applicable]	Constant concentration of ~370 ppm

[a] Emission rates and concentrations for 20C3M scenario vary somewhat between models: see text for explanation. GtC/yr = gigatons of Carbon per year; 1 gigaton = 10^{12} kg = 10^{15} gram = 1 petagram. SRES = IPCC Special Report on Emissions Scenarios.

[b] For IPCC scenario specifications, see http://www-pcmdi.llnl.gov/ipcc/standard_output.html#Experiments and http://www.grida.no/climate/ipcc/emission/ [*Intergovernmental Panel on Climate Change*, 2001].

10^6 km^2 to fraction of area north of 20°N to facilitate comparison to climate model output (see section 4). In addition, *Frei and Robinson* [1999] values have been adjusted to include Greenland.

[7] All IPCC-AR4 AOGCM simulations are forced with a set of boundary conditions determined by scenarios of anthropogenic emissions of carbon dioxide (CO_2) and other radiatively active gases. 20th century simulations (20C3M) use a best estimate of historical emissions between 1850 and 2000; specific emission rates are left to the discretion of the individual modeling groups. 21st century climatic change simulations (COMMIT, SRESA1B, SRESA2) represent a range of socioeconomic developments and associated emissions. For these scenarios, greenhouse gas emission rates are input into separate gas cycle models which produce estimates of atmospheric concentrations for use as AOGCM input. Total CO_2 emission rates and atmospheric concentrations for each scenario are shown in Table 1 (see http://www.grida.no/climate/ipcc/emission/for details). Snow extent variations over North America were available for eleven models at the time of this writing (Table 2).

[8] To facilitate comparison of NA-SCE between different models and to observations, in which total North American land areas vary on the order of ±10%, the spatial extent of snow over North America north of 20°N latitude for each model is normalized by the total land area over the same region, resulting in units of fractional snow cover. To focus on decadal to century scale variations, each time series is filtered with a nine-year running mean. For illustrative purposes, results are shown exclusively for the month of January, which is the month of the largest mean NA-SCE; analyses for other months and for seasonal-means yield similar results.

Table 2. Ensemble Size for Each Coupled Model Scenario

Model Number	Model Acronym[a]	20C3M	Commit	SRESA1B	SRESA2
1	CGCM3.1(T47)	1	0	0	0
2	CSIRO-Mk3.0	1	0	0	1
3	GISS-AOM	2	0	2	0
4	GISS-EH	5	0	4	0
5	GISS-ER	9	1	5	1
6	FGOALS-g1.0	3	3	3	0
7	INM-CM3.0	1	1	1	1
8	MIROC3.2(hires)	1	0	1	0
9	MIROC3.2(medres)	3	1	3	3
10	MRI-CGCM2.3.2	5	1	5	5
11	CCSM3	6	4	4	5

[a] For IPCC model documentation, see http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

3. 20th Century Results: Comparison to Observations

[9] Mean simulated NA-SCE values range between ~0.55 and 0.95, compared to observed values of ~0.75 (for perspective, Greenland represents ~0.10 of North America) (Figure 1). Only two models have mean values within ±0.05 of observed values; only two models overestimate NA-SCE; and all other models underestimate NA-SCE. Neither model that overestimates NA-SCE accounts for fractional snow coverage in grid boxes. There is no apparent relationship between model spatial resolution and mean NA-SCE (not shown).

[10] Figure 1 indicates that models disagree with each other, and with observations, on the timing of decadal scale NA-SCE variations. None of the model simulations capture the observed temporal pattern or anything similar. While some models at least approximately capture the magnitude of decadal scale variations in NA-SCE, others show little or no decadal scale variability.

[11] However, with regards to the magnitude of decadal-scale variability, the disagreements between models and observations are perhaps not as great as they appear in Figure 1, which includes only ensemble-mean time series (ensemble sizes are shown in Table 2). Models which

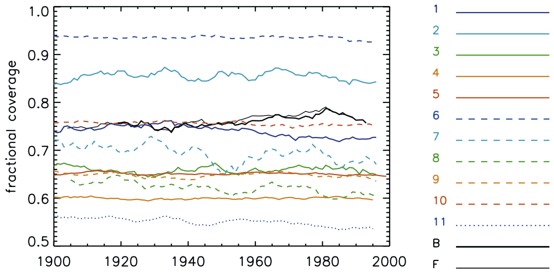

Figure 1. Nine-year running mean of 20th century January NA-SCE for IPCC-AR4 ensemble-mean model simulations and for reconstructions of observed variations. NA-SCE is defined as the fraction of the land area from 20°N–90°N and 190°E–340°E covered with snow. The legend shows the model number, which corresponds to model numbers and ensemble sizes shown in Table 2; "B" and "F" correspond to *Brown* [2000] and *Frei et al.* [1999], respectively. See text for further explanation.

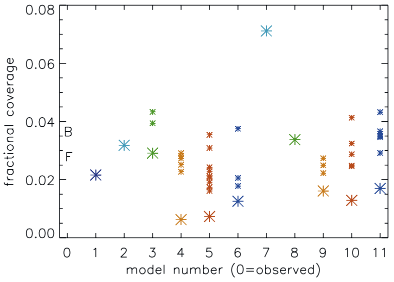

Figure 2. Decadal scale variability (DSV) of observed and modeled NA-SCE time series. DSV is defined as the range (maximum-minimum) of values in the de-trended nine-year running mean time series of January NA-SCE for the years 1919–1993. Model number zero shows observed values (B = Brown, F = Frei). Models are shown with same colors as on Figure 1; model numbers refer to those shown on Table 2. For each model, the large symbol is the DSV for the ensemble mean. For models with >1 ensemble member, individual ensemble members are shown using smaller symbols. See text for further explanation.

exhibit smaller decadal scale variability tend to include more ensemble members, and those which exhibit greater decadal scale variability tend to include only one ensemble member. In fact, the decadal scale variability exhibited by individual ensemble members tends to be much closer to the observed variability.

[12] To illustrate this point we define Decadal Scale Variability (DSV) as the range (maximum-minimum) of values in the de-trended nine-year running mean time series for the years 1919–1993 (the time domain common to all observations and models). De-trending eliminates spurious variability resulting from any long-term trends during this period; and a running mean mitigates the influence of individual high or low years, making this a robust statistic. Figure 2 shows the DSV for each model's ensemble mean and individual ensemble members, as well as the DSV for the two reconstructions. The reconstructed timeseries exhibit slightly different DSV because of the nature of the statistical methods and number of stations employed. The DSV of model ensemble means are consistently smaller than the DSV of the individual ensemble members, and the DSV of individual members tend to be closer to observed values.

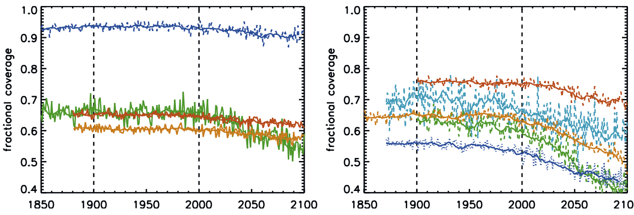

Figure 3. Annual time series (thin line), overlaid with nine-year running means (thick line), of ensemble-mean January NA-SCE, including both 20th century (20C3M) and 21st century (SRESA1B) scenarios, for nine available AOGCMs. Colors correspond to those used in Figure 1. Results are shown in two panels to aid in visualization.

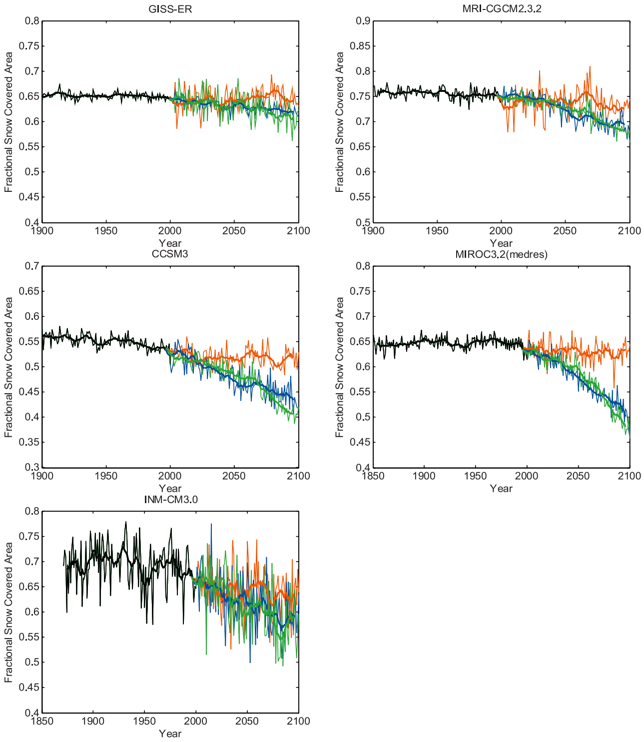

Figure 4. Annual time series (thin line), overlaid with nine-year running means (thick line), of ensemble-mean January NA-SCE for 20th and 21st century scenarios from five AOGCMs. 20C3M, COMMIT, SRESA1B and SRESA2 scenarios denoted by black, red, blue and green lines, respectively.

4. 21st Century Results: Sensitivity to Greenhouse Gas Forcing

[13] Of the eleven models identified in Table 2, output for the SRESA1B scenario was available from nine models. Initial conditions for SRESA1B experiments were obtained from the end of the 20C3M experiments, allowing 20th and 21st century simulated annual time series to be combined as shown in Figure 3. During the twenty first century, all nine models exhibit a decreasing trend in ensemble mean NA-SCE, although the magnitude of the trend varies between models. Between roughly 2000 and 2100, the simulated linear trends range from −0.021 to −0.213 per century, with an average of −0.091 per century. All SRESA1B trends are statistically significant above the 99% significance level, and are significantly different (>99% significance) than their preceding 20C3M trends. These results are insensitive to the number of ensemble members, and there is no apparent relationship between mean 20th century NA-SCE and the magnitude of the trend (not shown).

[14] Of these nine models, output for the SRESA2 and COMMIT scenarios were available from five models. Figure 4 shows the responses of NA-SCE in these models to all three 21st century emission scenarios. Although trend magnitudes again vary between models, in all cases

the decreasing trends for the SRESA1B and SRESA2 scenarios are statistically significant and comparable in magnitude to each other; and, they both decrease at greater rates than under the COMMIT scenario. For all models, under the SRESA1B and SRESA2 scenarios, NA-SCE decreases at a greater rate during the twenty first century than during the 20th century. In contrast, under the COMMIT scenario, decreasing 21st century NA-SCE trends are insignificant or very mild, and effectively indistinguishable from 20C3M trends.

5. Discussion and Conclusions

[15] This preliminary evaluation of snow extent over North American lands (NA-SCE) as simulated by coupled atmosphere-ocean general circulation models (AOGCMs) participating in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4), finds, in many respects, a wide range of results from AOGCM simulations. Significant between-model variability is found in mean NA-SCE, comparable in magnitude to the between-model variability found in AMIP-2 atmospheric GCMs [*Frei et al.*, 2003], and most of the AOGCMs in this study underestimate observed NA-SCE.

[16] In other respects there is better agreement between models. The magnitude of decadal scale variability is captured by individual ensemble members for most models. However, there is no temporal correlation in decadal scale variations in NA-SCE between ensemble members, or between model simulations and observations. As a result, the ensemble-mean time series exhibit dampened decadal scale variability compared to individual ensemble members, in addition to poor temporal correlation with observations. This suggests that in these AOGCMs, decadal scale variability of NA-SCE is associated predominantly with internal model variability (i.e. in the coupled atmosphere-ocean system) and not with changing boundary conditions (i.e. greenhouse gases and sulfur aerosols).

[17] With regards to 21st century scenarios, once again the models agree in some respects and disagree in others. For the SRESA1B scenario, a decreasing trend appears to be robust across nine available models, although the magnitude of the trend varies between models. Since NA-SCE is an integrated metric that encompasses many hydroclimatological processes and feedbacks, this suggests a strong and persistent climate change response at the land surface, related to either atmospheric changes (e.g., air temperature, precipitation) and/or land-atmosphere interactions (e.g., surface energy balance).

[18] Under the unrealistic COMMIT scenario (CO_2 stabilized at year-2000 concentrations), all five available models predict little to no change in mean NA-SCE. In both the SRESA1B (moderate CO_2 increase) and SRESA2 (significant CO_2 rate increase) scenarios, these models predict a significant decrease in NA-SCE during the 21st century, although between-model variability is found in the magnitude of the trend. In no model is there a significant difference in the rate of decrease between the two SRES scenarios, despite the large difference in CO_2 emissions. This indicates that the response of AOGCMs to greenhouse gas forcing may be nonlinear: perhaps there is a threshold in emission rate or concentrations, above which additional emissions result in no discernable snow signal during the 100-year time frame of these experiments.

[19] Our conclusion that these models predict a significant decrease in snow extent over North America during the 21st century is robust, in the sense that all available models agree for two different yet realistic SRES future emissions scenarios, while no model predicts such a decrease for the unrealistic COMMIT scenario. This is in agreement with preliminary results from analysis of the Geophysical Fluid Dynamics Laboratory coupled AOGCM (S. J. Dery and E. F. Wood, manuscript in preparation, 2005).

[20] One obvious question is: why do models differ in their response to SRES scenarios? No apparent relationship is observed in this study between model spatial resolution, mean 20th century snow extent, and the magnitude of 21st century trends. In AMIP-2 AGCMs, truncation of high elevation topography due to coarse spatial resolution plays a role in, but is not the primary cause of, errors in snow simulations [*Frei et al.*, 2005]: the same is likely to be true in IPCC-AR4 AOGCMs. The answers may lie in the relationship between snow extent and meteorological variations. As these relationships tend to be fairly complex, vary seasonally and spatially, and vary from model to model, analysis of such relationships is left to a future report.

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