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North American Snow Cover Variability from Satellite Data (1972–1993) and Comparison with Model Output

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ABSTRACT

A twenty-one year record of remotely-sensed areal snow cover fluctuations for the Northern Hemisphere is examined, with particular emphasis placed on North America. No trend is apparent, but several periods of positive and negative departures are found. The mid- to late-1970s, and the mid-1980s, had large snow-covered areas. The early-1980s, and the period since 1987, are characterized by low snow cover. The most temporally extensive of these has been a period of snow deficit since 1987, particularly in spring and in eastern North America. The five lowest North American spring snow covers on record have occurred since 1987. In autumn, three of the last five years have been extremely low. Recent winters have not been anomalous. Results from one climate model are compared to observations, and are found to simulate accurately winter snow cover on the continental scale, while slightly under-estimating spring and autumn values. On the regional scale, the model is less accurate. Snow cover may be critical for model validation, improvement of parameterizations, and for prediction and detection of climate change.

INTRODUCTION

Analyses of global temperature records indicate that a warming has occurred over the past century (Bretherton, et al. 1990). However, it has not been determined whether this warming is a result of anthropogenic greenhouse gas emissions, natural forcing factors, or natural low-frequency (century or greater time-scale) variability inherent in the climate system (Wigley and Barnett, 1990). The global warming predicted by many scientists is expected to be enhanced in higher latitudes mainly due to the feedback effects of sea ice and snow cover. Greater understanding of the dynamics of these quantities is required to attain greater confidence in climate change predictions.

Snow cover observations are important for understanding global climate fluctuations. Various studies (Barry, 1985; Shine, et al., 1990; Meehl and Washington, 1990; Cess et. al., 1991), both empirical and modeling, have shown that snow cover is an important climatic variable due to its effects on energy and mass exchange between the surface and the atmosphere. It has immediate effects upon the radiative and thermal energy budget. Also, snow can have a lagged climatic effect, whereby early spring snow melt can result in low summer soil moisture (Houghton, et. al. 1990, chapter 5). Additionally, due to its dependence on temperature and dynamic variables, snow cover can be an indicator of climate fluctuations.

A weekly, digitized snow-cover areal-extent climatology for the Northern Hemisphere, derived from remotely-sensed visible imagery, is available for the period between January 1972 and March 1993. This climatology is produced by NOAA (Matson et. al., 1986) with improvements by Robinson (1993a, 1993b). These data are obtained by visual interpretation of satellite imagery. Limitations of visible imagery for snow cover detection include problems with low solar illumination, dense forest cover, steep terrain, and cloudiness (Robinson 1993b). The data are considered suitable for climatological studies during all seasons, particularly when analyzed on a monthly time frame.

In this paper fluctuations in snow cover between 1972 and 1993 in the Northern Hemisphere are discussed. Specific emphasis is placed on fluctuations in North America (including Greenland) during fall, winter, and spring, which are compared to output from NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model (GCM). The accuracy of modeled snow cover is discussed in relation to climate change prediction.

TEMPORAL FLUCTUATIONS OF NORTH AMERICAN SNOW COVER

Figure 1 shows 12-month running-means of snow-covered area over the northern hemisphere, Eurasia, and North America. The mid- to late- 1970s and mid-1980s were periods of high snow cover over both continents. The early 1980s over North America, and the period since 1987 over both continents, had low snow cover. Since 1987 both continents have been experiencing snow deficits consisting of the lowest annually-averaged values, and the most extended period of below average snow cover, for the entire record. The lowest 12-month averaged snow covered seasons (September - August) were 1987-1988 (North America) and 1988-1989 (Eurasia) as shown on table 1. The maximum snow covered seasons were 1978-1979 and 1977-1978, respectively.

The snow-cover deficit of the last six years has been most pronounced in spring, with all years since 1987 in North America showing below average spring snow cover (figure 2). For the months of March, April, and May, two of the three lowest values have occurred since 1987 (figure 3). The lowest (highest) North American snow cover years for March, April, and May have been 1988 (1978), 1987 (1979), and 1987 (1974), respectively. In North America the five lowest springs on record are 1987, 1988, 1990, 1991, and 1992.

Deficits of such duration have not occurred during fall and winter, although for each season, three of the five lowest values have occurred since 1987. Autumn snow cover in North America was above average during 1991 and 1992. Winter snow cover has been quite consistent for the entire period of record. Although the magnitude of winter snow cover fluctuations exceeds that of spring, there has been no period of consistently extreme departures. The five lowest fall seasons, in ascending order, have been 1987, 1979, 1990, 1980, and 1988. For winter they have been 1981, 1992, 1987, 1977, 1989.

Minima and maxima, by month, are shown in figure 3. For most months, the period of lowest snow cover area was between 1987 and 1993. Between March and September two of the three lowest snow-covered months on record, and none of the extreme highest, have occurred since 1987. Between October and February, the period since 1987 has been less consistently low. For example, in October and February, two of the three least snowy months in North America occurred prior to the 1987-1988 season. November of 1991, and December of 1992, were amongst the three highest on record.

Temporal fluctuations of North American snow cover have been examined with increased longitudinal resolution. The continent has been divided into seven longitudinal bands (figure 4), and time series of the total snow cover area for each band were analyzed. Figure 5 shows the extreme seasons (September through May) for each band.

Snow cover fluctuations in the seven longitudinal bands have not occurred in tandem. The heavily snow-covered years of the mid- to late-1970s is seen in almost every band, as is the snow deficit since

Table 1. Northern Hemisphere snow cover statistics

	S-O-N				D-J-F			
	mean	sd	min	max	mean	sd	min	max
N. Hemisphere	18.7	1.6	16.3	22.1	45.0	1.6	40.9	48.3
N. America	8.4	0.6	7.2	9.2	17.0	0.7	15.4	18.2
Eurasia	10.3	1.3	8.4	13.7	28.0	1.1	25.5	30.5
	M-A-M				J-J-A			
	mean	sd	min	max	mean	sd	min	max
N. Hemisphere	31.0	1.7	27.5	34.1	6.9	1.3	4.4	9.8
N. America	12.9	0.7	12.0	14.1	4.5	0.7	3.4	6.0
Eurasia	18.1	1.3	15.4	20.8	2.4	0.7	1.0	3.8
	ANNUAL *							
	mean	sd	min	min-yr	max	max-yr		
N. Hemisphere	25.4	1.1	23.6	88-89	27.5	77-78		
N. America	10.7	0.5	10.0	87-88	11.6	78-79		
Eurasia	14.7	0.8	13.5	88-89,89-90	16.1	77-78		

** Includes snow seasons 1971-1972 through 1991-1992. Snow seasons are from September through August. All values are in millions of square kilometers.*

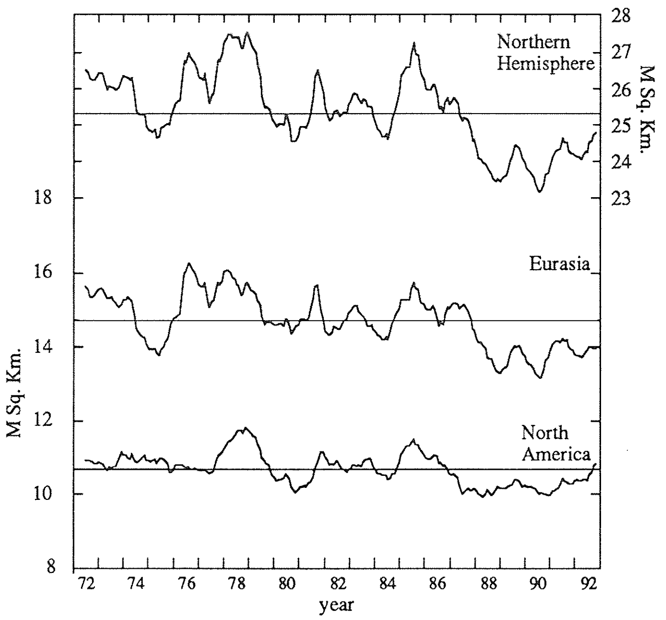
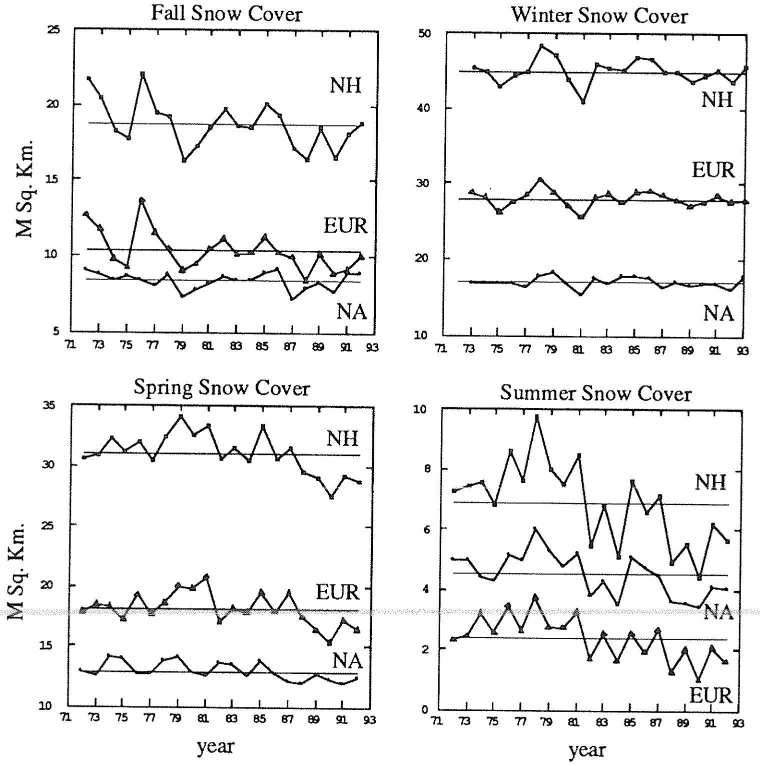


Figure 1. 12-month running means of Northern Hemisphere snow cover in millions of square kilometers.


Fall Snow Cover

Winter Snow Cover

Spring Snow Cover

Summer Snow Cover

Figure 2. Seasonal snow cover areas for fall (SON), winter (DJF), spring (MAM), and summer (JJA) in millions of square kilometers.

1987. However, in the central portion of the continent, from the Rocky Mountains to Hudson Bay (bands 3-5), the maxima of the late-1970s, the minima of the early-1980s, and maxima of the mid-1980s (bands 3 and 4 only) were pronounced, while the recent deficit is less so. In those bands the lowest season on record occurred prior to the recent snow deficit. Trend analyses on bands 3 through 5 show no trend at the 95% significance level. The eastern portion of the continent (bands 6-7), where decreasing trends are observed, experienced neither an early-1980s minimum nor a mid-1980s maximum. Rather, the east has experienced a pronounced recent snow cover deficit, with the maximum years all in the 1970s and early-1980s, and the minima all occurring since the 1987-1988 season. In the Yukon Territory and Alaska (bands 1-2), a decreasing trend has been observed, with most of the highest snow cover seasons occurring in the 1970s. The lowest season in the west (1979-1980) occurred prior to the recent deficit, although the second and third lowest have been since 1988-1989.

The twenty-one year record of remotely-sensed snow cover data is too short to look for evidence of climate change. One could, however, look for trends that would be consistent with a particular theory. No trend is apparent. In North America the four periods of most extreme snow cover departures were the late-1970s and mid-1980s (large snow-covered area), and the early-1980s and late-1980s / early-1990s (low snow covered area). By far the most temporally extensive of these has been the snow cover deficit since 1987.

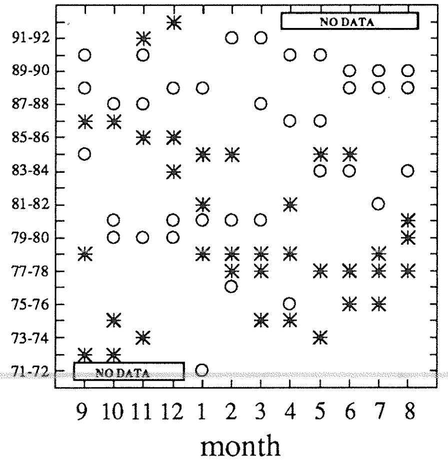


Figure 3. Maximum (*) and minimum (O) three North American snow cover seasons for each month.

Snow cover fluctuations have not been coherent across the continent. In the eastern portion of the continent, statistically significant decreasing trends in snow cover are found. In the central portion of the continent, west of Hudson Bay and the Great Lakes, and east of the Rocky Mountains, no trend is observed. In the Yukon Territory and Alaska decreasing trends are observed; however, shorter time scale fluctuations are also present.

COMPARISON TO GFDL MODEL OUTPUT

Comparisons have been made between the satellite observations (1972-1992) and results from ten years of a control run of the GFDL GCM. The version

Figure 4. Longitudinal bands 1 through 7 for analysis of North America.

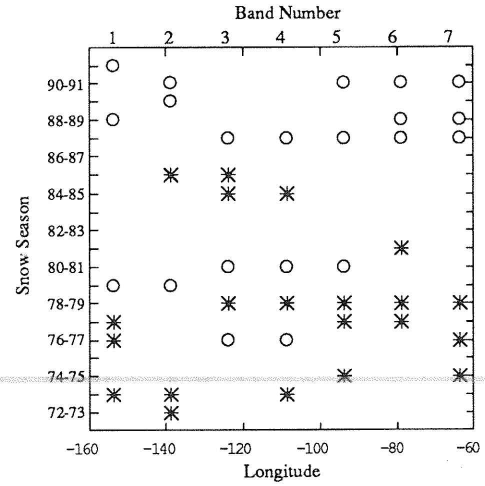


Figure 5. North American Maximum (*) and minimum (O) three snow cover seasons by longitude.

used here was an R-15 spectral model, which corresponds to a 48 by 40 global grid, 4.44° latitude by 7.5° longitude resolution. This run includes a slab ocean, with energy fluxes corrected according to the Q-flux procedure (Manabe and Wetherald 1987). These observations and model output can not be compared without making certain assumptions because the model output includes snow depth, while visible satellite imagery can be used only to determine snow location, not depth. In order to determine the modeled snow-covered area from snow depth information, a threshold value of model snow depth is chosen. A model grid box with snow depth greater than the threshold value is considered completely snow covered; a grid box with snow depth less than the threshold value is considered completely snow free.

Comparison of observations with modeling results for North America shows that for continental scale coverage, a model snow depth threshold of 15 mm agrees well with observations during months of maximum snow extent. Since comparisons of satellite to station data indicate that with visible imagery snow cover of depth less than 25 mm (1 inch) is detected (Kukla and Robinson 1981), a threshold in this range makes physical sense. Figure 6 shows the magnitude and range of snow cover area for North America, by month, derived from satellite observations and from model results. Comparison of the two reveals that the model accurately depicts snow cover between December and April, but builds up the snow pack too late in autumn and depletes the snow pack too early in spring. Considering the coarse resolution and simple snow cover parameterizations used in this model, and unknown confidence limits in the observations, we consider these results to indicate that the first order dynamical and thermodynamical mechanisms responsible for snow cover production are accurately depicted in the model.

On a regional scale the model reproduces the observations less accurately, even during months when the continental-scale climatology is simulated accurately. For example, in December (figure 7) snow cover is under-estimated over the southern snow boundary: the western, southern, and southeastern US. In addition, snow cover climatologies are under-estimated for a large portion of the Canadian Prairies, and smaller regions in Alaska and the Canadian Archipelago. Much of this is tentatively attributed to the coarse resolution of tropospheric long-wave patterns in the model.

During May, when the continental scale climatology is inaccurately simulated, the model under-predicts snow cover over much of the area south of 60N (figure 8), including the southern and eastern Laurentian shield, much of the Canadian boreal forests and Prairies, and the Rocky Mountains in the US and Canada.

Model results for the longitudinal bands discussed earlier were also compared to satellite observations. Each band corresponds to a width of two model grid boxes. Snow cover time series were calculated for each band, and Pearson Correlation coefficients were calculated between all combinations of time series.

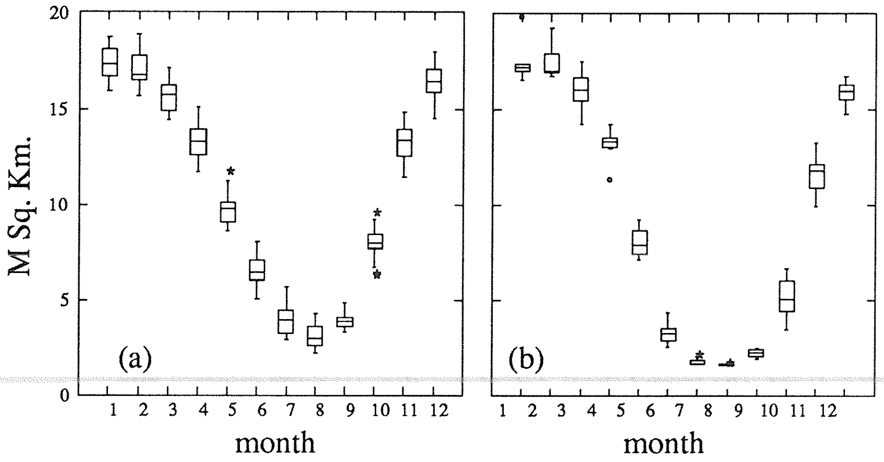


Figure 6. Box and whiskers plot of North American snow cover, in millions of square kilometers, by month from (a) visible imagery, 1/72 through 3/93, (b) GFDL GCM results, 10 year control run. Model results assume snow depth threshold value of 15 mm. See text for explanation.

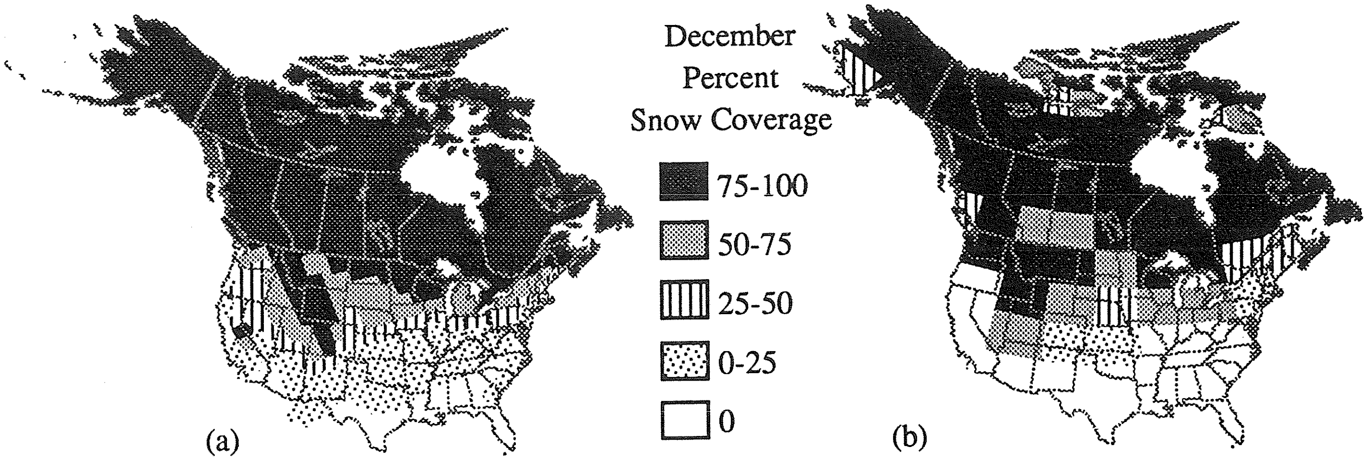


Figure 7. North American percent snow coverage for December (a) from visible imagery 1972-1992, (b) from GFDL GCM results, 10 year control run.

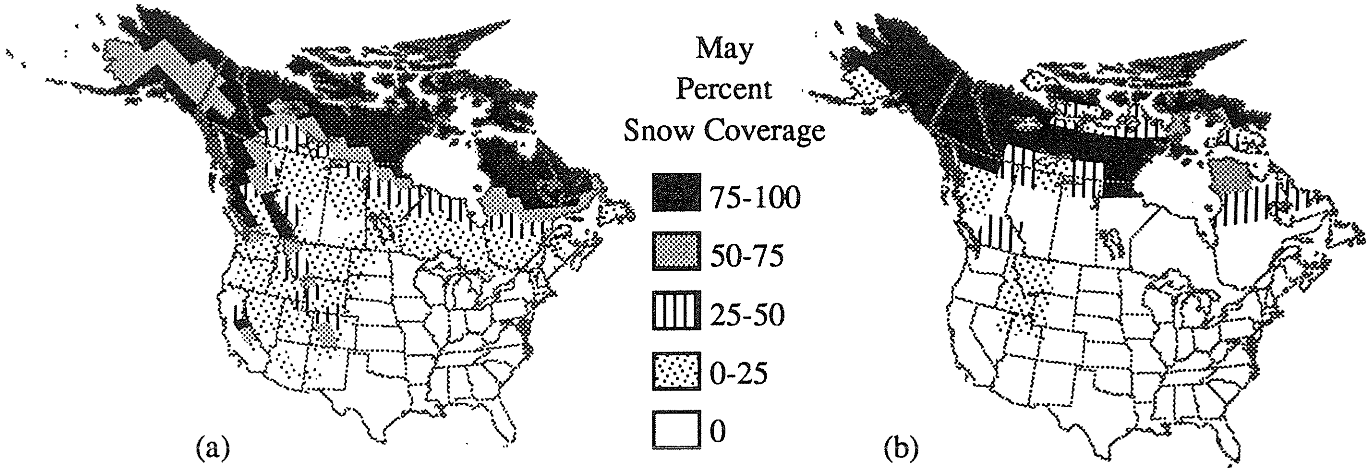


Figure 8. North American percent snow coverage for May (a) from visible imagery 1972-1992, (b) from GFDL GCM results, 10 year control run.

As discussed earlier, observations in the different bands do not all correlate in a temporal sense. Table 2 shows Pearson Correlation coefficients between the different bands for December snow cover, for both observations and modeling output. All correlations of absolute magnitude greater than 0.5 are shown. In the model, strong negative correlations exist between time series in different bands. In the observations, however, all bands are positively correlated, several with magnitudes greater than 0.5. (Similar results were found for other months but are not shown here). Thus, even during months when the model accurately reproduces the snow cover climatology, temporal interactions among smaller regions may be poorly simulated.

Validation of model simulations of the current climate are important because errors in control runs cast doubt on the validity of enhanced greenhouse predictions. A number of models agree that for mid-continental areas in the summer, the following changes are predicted for the enhanced greenhouse: soil moisture is expected to decrease by up to 50%, and temperatures are expected to rise on the order of 7 - 10 °C (Manabe & Wetherald 1987; Houghton et. al. 1990 chapter 5;). This drying and warming has been attributed to a predicted earlier spring snow melt in the enhanced greenhouse environment. However, we show that here at least one GCM under-estimates spring mid-continental snow cover in the control run, which gives us less confidence in the prediction of spring snow melt for an enhanced greenhouse simulation. The detection and improvement of inaccuracies in climate models, such as spring snow melt, may be critical for improving confidence in climate predictions.

Table 2. Pearson Correlation coefficients between December time series for longitudinal bands 1 - 7

Visible Imagery 1972-1992		GFDL control run years 1-10	
Bands	r	Bands	r
4-3	0.91	4-1	-0.59
5-3	0.58	5-1	-0.59
5-4	0.62	5-4	0.75
6-5	0.52	6-4	-0.60
7-6	0.69	7-5	-0.66

Correlations shown only for combinations of bands with |r| > 0.5. See text for discussion.

CONCLUSIONS

Examination of remotely-sensed snow cover observations since 1972 has revealed no trends in either the hemispheric or continental record. Shorter time scale fluctuations have been found, the most prominent being the snow deficit since 1987 on both continents. The deficit has been especially strong in spring, and in eastern North America (regional analysis of Eurasia was not performed). The causes for these relationships remain to be explored in order to improve understanding of climate dynamics and to enhance model accuracy and predictive capability. For example, regional variations in snow cover may be related to fluctuations in the polar vortex such as discussed by Davis and Benkovic (1993) and Angell (1992).

Comparison of observations to results from one GCM control-run reveal that on a continental scale the modeled climatology appears quite accurate, particularly for the winter season. However, spring and fall snow cover appear to be under-estimated. Regionally, simulations of snow cover climatology are less reliable for all seasons.

Comparisons of snow cover observations to modeling results are potentially important for model validation, improvement of model parameterizations, and determination of confidence in results. Studies such as this, and others that utilize results from different models (e.g., Foster, personal communication), are being used to pinpoint model inaccuracies and aid in parameterization improvement. More detailed regional analyses (i.e., principal components analyses) should be performed for both North America and Eurasia. Regional and temporal inaccuracies can perhaps be remedied with enhanced resolution and improved parameterizations.

In addition, climate change prediction and detection can be improved utilizing results of doubled-carbon dioxide and transient GCM experiments. By determining a spatially and temporally resolved prediction of snow cover change for an enhanced greenhouse environment, snow cover can be useful as a "fingerprint" (Pennell et. al. 1993) for climate change.

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