NORTHERN HEMISPHERE SNOW COVER EXTENT: COMPARISON OF AMIP RESULTS TO OBSERVATIONS

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INTRODUCTION

Snow cover plays an important role in the global energy budget by modulating the surface fluxes of sensible, latent, and especially radiative energy (Barnett et al. 1989). Modeling studies have indicated potential feedbacks between anthropogenically induced radiation perturbations, snow cover, soil moisture, and air temperatures (Houghton et al. 1990). Thus, accurate estimation of snow cover in general circulation models (GCMs) is critical for the simulation of the current climate, as well as for prediction and detection of climate change.

In this study GCMs submitted to the Atmospheric Model Intercomparison Project (AMIP) (Gates, 1992) are evaluated in terms of their ability to simulate observed snow cover extent over Northern Hemisphere lands. AMIP model runs have common values for sea surface temperatures, atmospheric CO_2 concentration, and solar insolation specified for the decade 1979 through 1988. The satellite-derived data set used in this analysis contains gridded, monthly information on snow cover areal extent over Northern Hemisphere lands. These values are generated from a digital weekly product produced by the National Oceanic and Atmospheric Administration, that is then corrected and aggregated into monthly averages according to a routine devised at Rutgers University (Robinson et al., 1993).

DIAGNOSTIC TECHNIQUE

Observations of areal snow cover extent over land are compared with output from 27 AMIP model runs (table 1) for January 1980 through December 1988 (1979 is excluded because the initialization values are inconsistent between models). Snow cover of depth one inch or greater is generally recognized in the visible satellite imagery (Kukla and Robinson, 1981). To be consistent with observations, model grid cells are considered snow covered only if snow depth is at least 3 cm: any smaller value output from a model is considered too small to be readily observed over a satellite grid cell. The AMIP standard output includes snow mass, but not depth. For comparative purposes, we assume an average snow density of 300 kg/m^3. Monthly statistics for the entire Northern Hemisphere (NH), and for North American (NA) and Eurasian (EU) land areas individually, are compiled for the 27 models. To facilitate comparison between several different model grids (each associated with a different total land area) the percentage of land area north of 20°N latitude covered with snow, rather than the absolute snow covered area, is the unit of comparison.

AMIP RESULTS

In the following sections we examine the AMIP results in terms of: 1) their ability to reproduce the observed nine-year snow cover extent climatology (with regards to central

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tendency, systematic bias, and dispersion); 2) model ability to capture interannual fluctuations; and 3) model performance as a function of model numerical properties (horizontal representation, horizontal resolution, and vertical resolution).

Table 1. Acronyms of 27 AMIP models included in snow cover analysis

1	BMR	6	DER	11	GIS	16	MGO	21	SNG	26	UKM
2	CCC	7	DNM	12	GLA	17	MPI	22	SUN	27	YON
3	CNR	8	ECM	13	IAP	18	MRI	23	UCL		
4	CSI	9	ECM_EO2	14	JMA	19	NMC	24	UGA		
5	CSU	10	GFD	15	LMD	20	NRL	25	UIU		

Numbers correspond to those appearing in figure 1.

Snow Cover Extent Climatology: Central Tendency

Figure 1a shows median values of Northern Hemisphere snow cover extent for AMIP models and observations. Fall and winter snow covers tend to be underestimated, while spring snow cover tends to be overestimated. In fall 16 models, and in winter 13 models, have median values that are within 5%, or approximately 4 million square kilometers (Mkm^2), of the observed median; most of the remaining models underestimate snow cover. In spring, only 9 models have NH median values within 5% of observations, and most of the remaining models overestimate snow cover extent. Only two models (UCL and SNG) are within 5% of observed values for the Northern Hemisphere, as well as both North America, and Eurasia for all three seasons.

Figure 2 shows distributions of NH, NA, and EU root mean square errors (RMSEs) and anomalies averaged annually and seasonally. Table 2 shows the median and minimum RMSE values. The Northern Hemisphere median annual RMSE is 7%, or approximately 5.5 Mkm^2; the second and third quartiles range between 5% and 10%. RMSEs tend to be larger, and anomalies more negative (i.e. snow cover extent is underestimated), over NA than EU for the annual average. In fall and winter the models underestimate snow cover extent on both continents, but more so over NA than EU. In spring over NA there is no

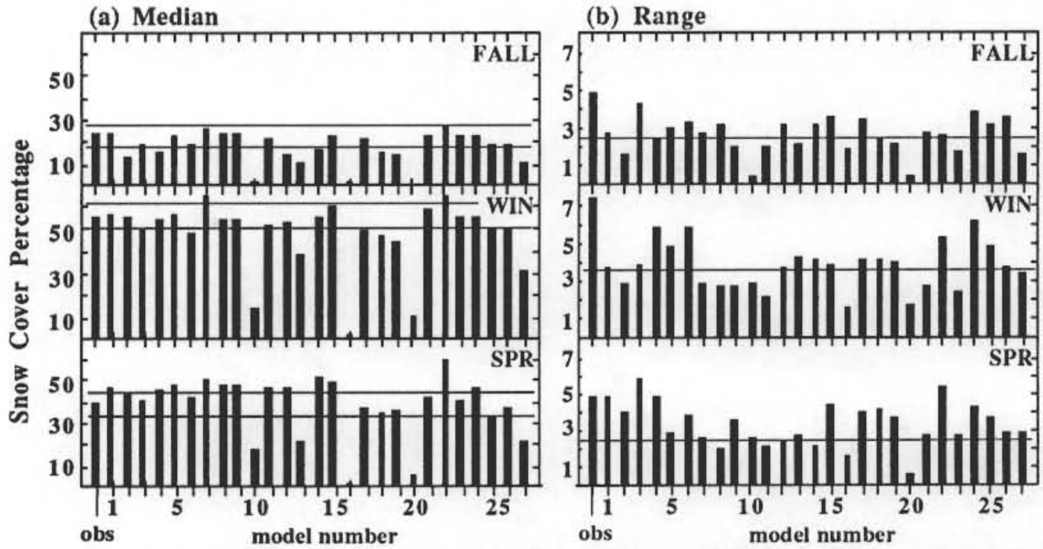

Figure 1-NH seasonal snow cover statistics for 27 AMIP models. Median and range of 9-year (1980-88) climatology for fall (S-O-N), winter (D-J-F), and spring (M-A-M). Units are percentage of land area north of 20°N covered with snow. (a) Median values for observations (obs) and models. Horizontal lines represent ±5% from observations. (b) Range (maximum - minimum) of values for observations and models. Horizontal line represent one half of observed range. See table 1 for model identification.

strong tendency for either under- or over-estimation; over EU spring snow cover extent is generally overestimated. Three models with unrealistically low snow cover extent appear as outliers in figure 2. There is no model that consistently outperforms the others across several seasons or continents.

Table 2. RMSEs of 27 AMIP models

	Annual		Fall		Winter		Spring	
	Median	Minimum	Median	Minimum	Median	Minimum	Median	Minimum
NH	7.0	3.3 (UCL)	5.4	2.4 (CSU)	5.7	2.0 (BMR)	8.5	3.3 (UKM)
NA	9.0	5.2 (UCL)	9.2	5.0 (ECM)	7.8	4.5 (CSU)	9.8	4.0 (BMR)
EU	7.0	3.4 (UCL)	5.4	2.7 (SNG)	4.7	2.3 (BMR)	9.3	3.3 (UKM)

For each geographic area (NH, NA, and EU), annual and seasonal median and minimum RMSE values are shown. Units are percentage of land area north of 20°N covered with snow. Actual areas, in Mkm^2, are approximately: NH (80), NA (24), and EU (56).

Systematic Bias

To determine whether model results or the diagnostic method employed are associated with systematic bias, two "ensemble" averages are calculated: one including 27 models and one including 24 models. The ensemble average is simply the monthly mean snow cover extent of all models; anomalies are then calculated for each month by subtracting the observed value from the ensemble average value. The 27-model ensemble anomalies (table 3a) indicate that snow cover extent tends to be underestimated. However, as these values include three models with unrealistically low values, a more meaningful evaluation is made by removing the three outliers and calculating 24-model ensemble averages (table 3b and figure 3). These results show that fall and winter snow cover extent are underestimated, especially over NA; and that spring tends to be overestimated, especially over EU. The ensemble mean underestimates annually averaged Northern Hemisphere snow cover extent

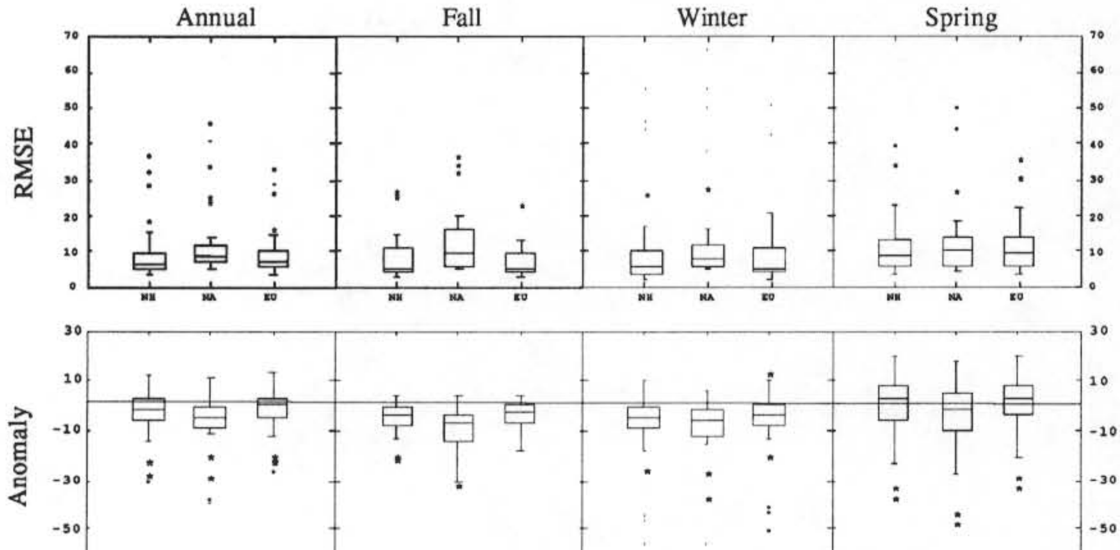

Figure 2-NH, NA, and EU annual and seasonal distributions of RMSEs and anomalies for 27 AMIP models compared to observations from 1980-1988. Units are percentage of land area north of 20°N covered with snow. Center line in box-and-whisker diagram shows median value; top (upper hinge) and bottom (lower hinge) of box delimit second and third quartiles (Hspread); whiskers show first and fourth quartiles. Outliers shown as asterisks are greater than 1.5*Hspread distant from nearest hinge; outliers shown as empty circle are greater than 3.0*Hspread distant from nearest hinge.

Table 3. Systematic bias in ensemble average

	(a) Annual Anomalies for 27 models			(b) Annual Anomalies for 24 models		
	NH	NA	EU	NH	NA	EU
mean	-3.8	-7.4	-2.4	-0.9	-3.9	0.3
median	-2.8	-6.3	-1.7	-1.1	-3.7	-0.2
sd	4.6	5.4	4.6	3.9	4.7	3.9

(a) To obtain monthly anomalies for 108 months (1980-1988), observed monthly snow cover percentages are subtracted from monthly average snow cover of 27 models. Annual mean, median, and standard deviation (sd) are calculated from 108 monthly anomaly values. (b) same as (a), except only 24 models included (see text and figure 3 for discussion).

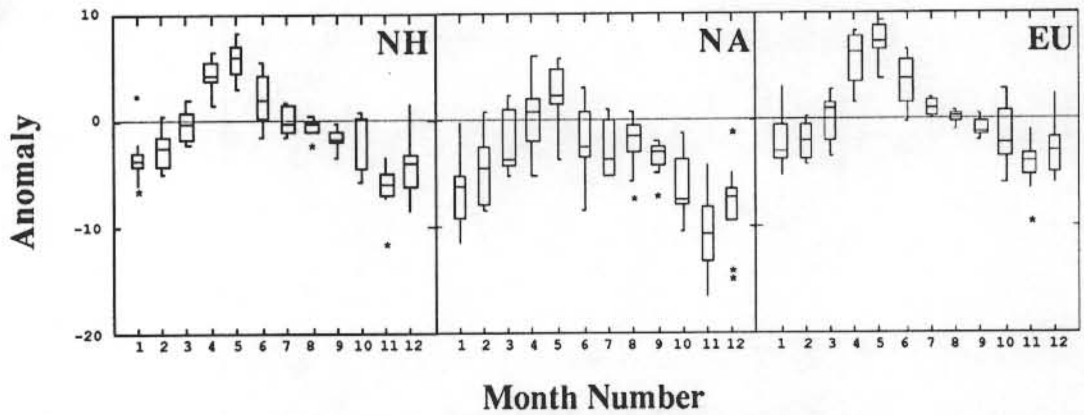

Figure 3-Distributions of NH, NA, and EU monthly anomalies in ensemble average of 24 models. Units are percentage of land area north of 20°N covered with snow. Anomalies for 108 months (1980-1988) are obtained by subtracting observed monthly snow cover extent from monthly average snow cover of 24 models. See text and table 3b for discussion. See figure 2 for explanation of box-and-whiskers.

by only 0.9% of the land surface area, or less then 0.8 Mkm^2. In addition, when models that consistently under- or over-estimate snow cover extent are re-analyzed assuming a density of 200 kg/m^3 or 400 kg/m^3, results are not significantly affected. The relatively small anomaly indicates that assumptions made in the diagnostic technique are reasonable.

Dispersion

AMIP models underestimate the year-to-year variability of snow cover extent. Figure 1b shows the range (maximum - minimum value) of modeled snow cover extent compared to the observed range. During fall and winter no models overestimate the range, and only 17 (fall) and 15 (winter) of the 27 models exhibit even half of the observed range. The spring range of modeled values is closer to, yet still below, observed values.

Interannual Fluctuations

Interannual correlations between modeled and observed time series for NH, NA, and EU snow cover extent during fall, winter, and spring are poor. Spearman rank correlation coefficients are generally 0.0 ± 0.25 for fall and winter over both continents, and 0.25 ± 0.25 during spring. The number of significant correlations (n=9, p=0.05, 1-tailed) found are as many as one would expect from an equal number of random time series. No model consistently captures interannual fluctuations over several seasons and both continents.

Poor interannual correlations between model results and observations indicate that large portions of the modeled snow cover signals are driven by variables other than AMIP boundary conditions. This is in agreement with other AMIP findings that mid-to-high latitude climates have low potential predictability (F. Zwiers, per. commun.). However, it is possible that an extreme event may emerge as a signal that is detectable above the noise (T. Barnett, per. commun.). For this reason we examine three snow covered months that are considered outliers in their monthly distributions. December 1980 and January 1981 had unusually low, and November 1985 had unusually high NH snow cover extent. Only five models have January 1981 as their first or second lowest January; nine models have December 1980 as their first or second lowest December; two models have November 1985 as their first or second highest November. These results are no more than would be expected from random time series. No model captured all three events, and only three models captured two of the three events. Thus, the models do a poor job of capturing extreme monthly values of snow cover extent.

Numerical Properties

To determine whether the type of horizontal representation (i.e.. spectral vs. finite grid), or the horizontal or vertical resolution, affect model simulation of snow cover extent, we examine the distribution of RMSEs and anomalies as a function of these properties.

Although the median anomalies for both spectral and finite difference representations are similar (figure 4a), larger positive annual anomalies are associated with spectral models, and the larger negative anomalies with finite grid models. However, examination of seasonal distributions (not shown) reveals that this relationship is strong during spring, and not apparent during fall and winter. The significance of this is not clear.

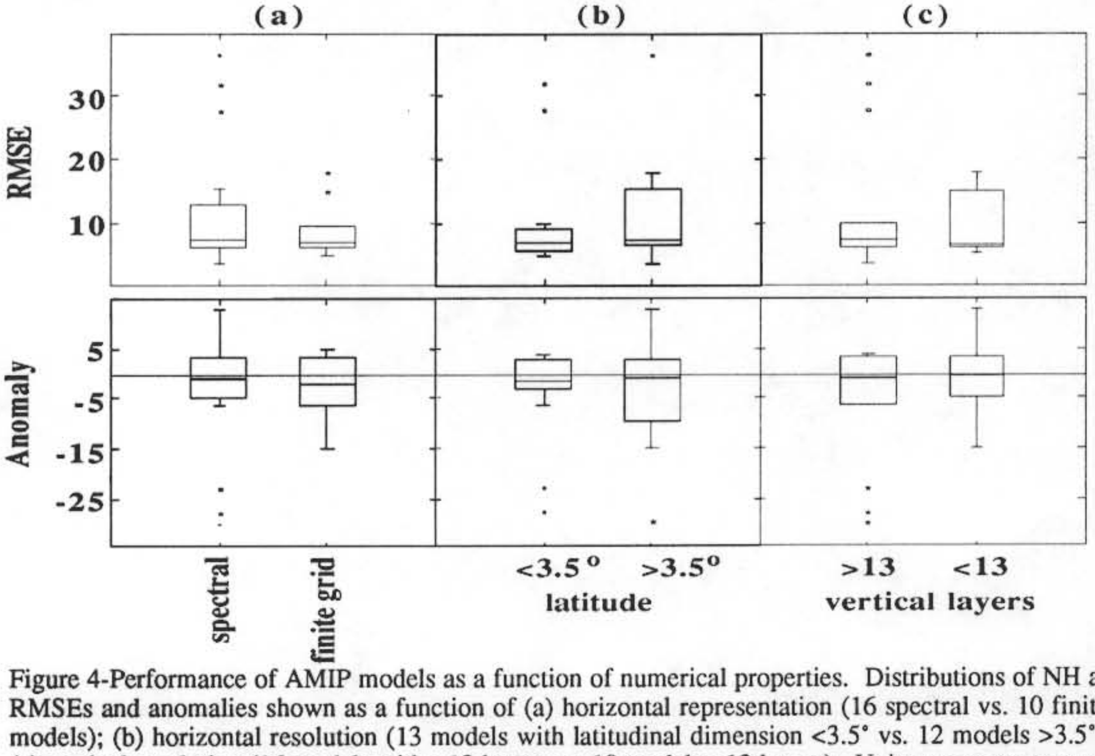

Figure 4-Performance of AMIP models as a function of numerical properties. Distributions of NH annual RMSEs and anomalies shown as a function of (a) horizontal representation (16 spectral vs. 10 finite grid models); (b) horizontal resolution (13 models with latitudinal dimension <3.5° vs. 12 models >3.5°); and (c) vertical resolution (16 models with >13 layers vs. 10 models <13 layers). Units are percentage of land area north of 20°N covered with snow. In (a) and (c) only 26 models included due to lack of information on one model. In (b) only 25 models included because one model has variable latitudinal resolution. See figure 2 for explanation of box-and-whiskers.

A comparison of higher and lower resolution models (figure 4b,c) shows that larger annual RMSEs, and anomalies of both signs, are associated with lower resolution models. Models with latitudinal grid box dimension less than 3.5° are compared to those with poorer resolution; models with greater than thirteen vertical layers are compared to those with fewer layers. These relationships are generally true over both continents for autumn, winter, and spring (not shown). The three outlier models are exceptions: all underestimate snow cover extent, yet all have spectral representation and high vertical resolution.

SUMMARY AND CONCLUSIONS

To a first order, AMIP models capture the seasonal cycle of snow cover extent. However, half of the AMIP models have annual Northern Hemisphere RMSEs of greater than 7% of the land surface area, or approximately 5.5 Mkm^2. This is significant compared to the observed mean annual Northern Hemisphere snow cover extent of 26 Mkm^2. No model performs consistently across several seasons and the two continents. Only three models (UGA, UIU, and UKM) exhibit, for all seasons over NH, NA, and EU both (a) median snow cover extent within 10% of the land surface area compared to observations; and (b) even half of the observed variability. In general, models underestimate fall and winter snow cover extent. During spring, models do not melt snow fast enough and therefore overestimate snow cover extent. No model consistently captures observed interannual fluctuations, including extreme values.

These results corroborate those of other investigators, namely that mid-high latitude variability in these models has low potential predictability, at least on the continental scale. However, analysis on smaller spatial scales, currently underway, may reveal that important regional snow cover fluctuations are predictable. For example, in the MPI model, snow mass in western Canada exhibits some dependence on tropical Pacific sea surface temperatures (K. Arpe, per. commun.). Further analysis of model results under AMIP, and potentially AMIP II, will clarify whether snow cover extent and/or snow mass in certain regions exhibit behavior that can be simulated and predicted by GCMs.

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