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Characteristics of Seasonal Snow Cover as Simulated by GFDL Climate Models

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Abstract

Two climate simulations were performed using an atmospheric general circulation model developed at the Geophysical Fluid Dynamics Laboratory. The model employed for these simulations uses the spectral method, in which the horizontal distributions of atmospheric variables are represented by a limited number of spherical harmonics. In this study, the seasonally-varying distribution of insolation at the top of the atmosphere was prescribed, along with the climatological distributions of sea surface temperature and sea ice. The snow cover distributions produced in these simulations were compared with satellite observations. Both versions of the model generate snow cover very similar in extent to the observed snow cover.

A number of studies have suggested that the feedback mechanism involving snow cover, albedo, and temperature is an important factor in climatic change (e.g., Schneider and Dickinson, 1974). Thus, it is reasonable that the realistic treatment of snow cover may be quite important in studies of CO_2-induced climate change using mathematical models of the earth's climate. The most sophisticated of these models, the general circulation models (GCMs), are capable of simulating snow cover and its interactions with the atmospheric circulation. In such models, the proper representation of the snow-albedo-temperature feedback mechanism requires reasonable agreement between the simulated snow cover and realtiy. This study compares the area and distribution of Northern Hemisphere snow cover produced by a GCM with observational data from satellites.

The GCM used in this study was developed by S. Manabe and his collaborators at the Geophysical Fluid Dynamics Laboratory and is similar to that described by Manabe et al. (1979) and Manabe and Hahn (1981). The model is global with realistic geography and topography. Insolation at the top of the atmosphere is prescribed as a function of season, but no diurnal variation is included. Seasonally-varying sea surface temperature and sea ice cover are prescribed based on climatological data from Reynolds (1982), Walsh (1978), Zwally et al. (1983), and Alexander and Mobley (1976). Cloudiness is fixed and depends only on latitude and height. The model uses a hydrologic budget to predict soil moisture based on rainfall, snowmelt, evaporation, and runoff, and computes snow cover based on snowfall, snowmelt, and sublimation.

For its dynamical computations, the model uses the spectral method, in which the horizontal distribution of atmospheric variables is represented by a limited number of spherical harmonics. The model's horizontal resolution is determined by the number of spherical harmonics retained. This study uses GCMs with two different horizontal resolutions; the low resolution version is truncated at wavenumber 15 (corresponding grid size: 4.5° latitude x 7.5° longitude) and the high resolution version at wavenumber 30 (2.25° latitude x 3.75° longitude). Nine finite-difference levels, extending from the surface to approximately 25 mb, are used to represent the vertical distribution of the atmospheric variables.

Both models are started from an initial state consisting of a dry, isothermal atmosphere at rest. A relatively short period of integration is required for the models to reach a quasi-equilibrium climate, since the sea surface temperature distribution is prescribed. The models are further integrated to provide data for analysis. This analysis period is nine model years for the low resolution model and only one year for the high resolution version due to its greater computational requirements.

The most comprehensive set of observations of Northern Hemisphere snow cover available for comparison with the model is the NOAA satellite-derived snow cover data base (Matson and Wiesnet, 1981). A climatology of the seasonal variation of Northern Hemisphere snow cover area based on this data set has been published by Dewey and Heim (1981), and monthly maps of mean Northern Hemisphere snow cover have been constructed by Robock (1980). Both of these studies will be used as sources of observed snow cover data to which the model snow cover distributions can be compared.

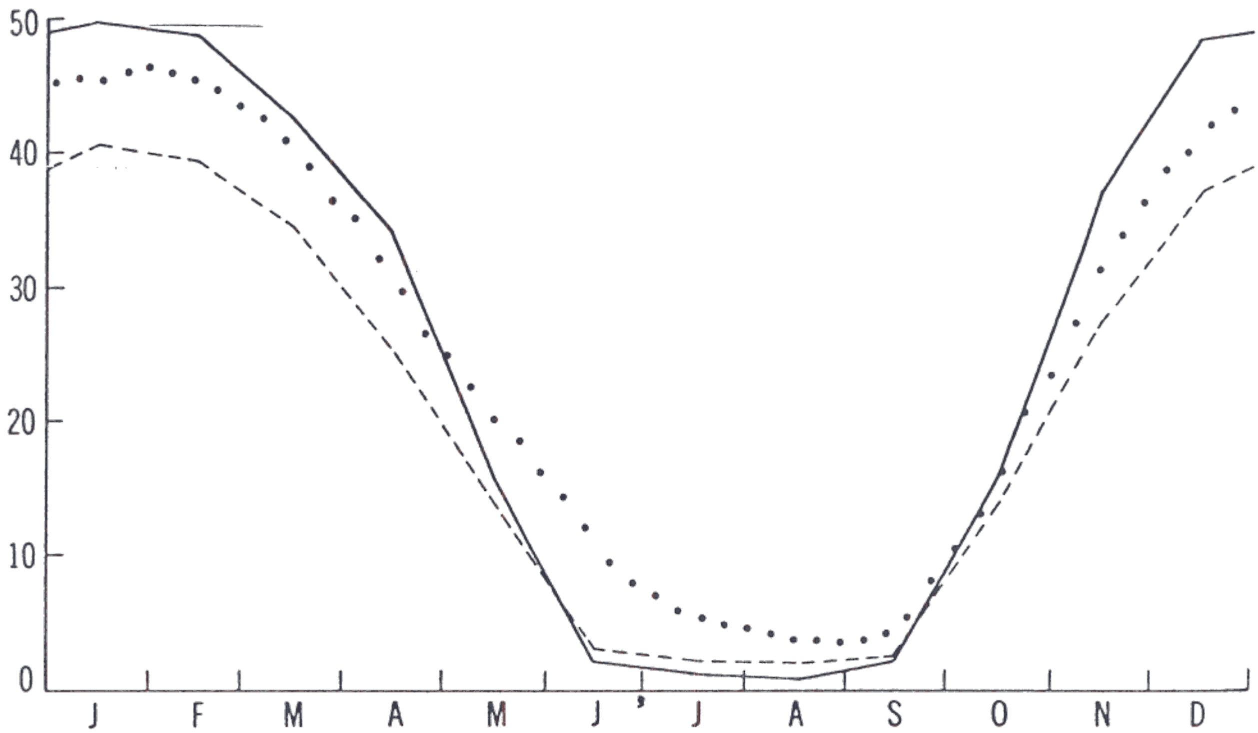
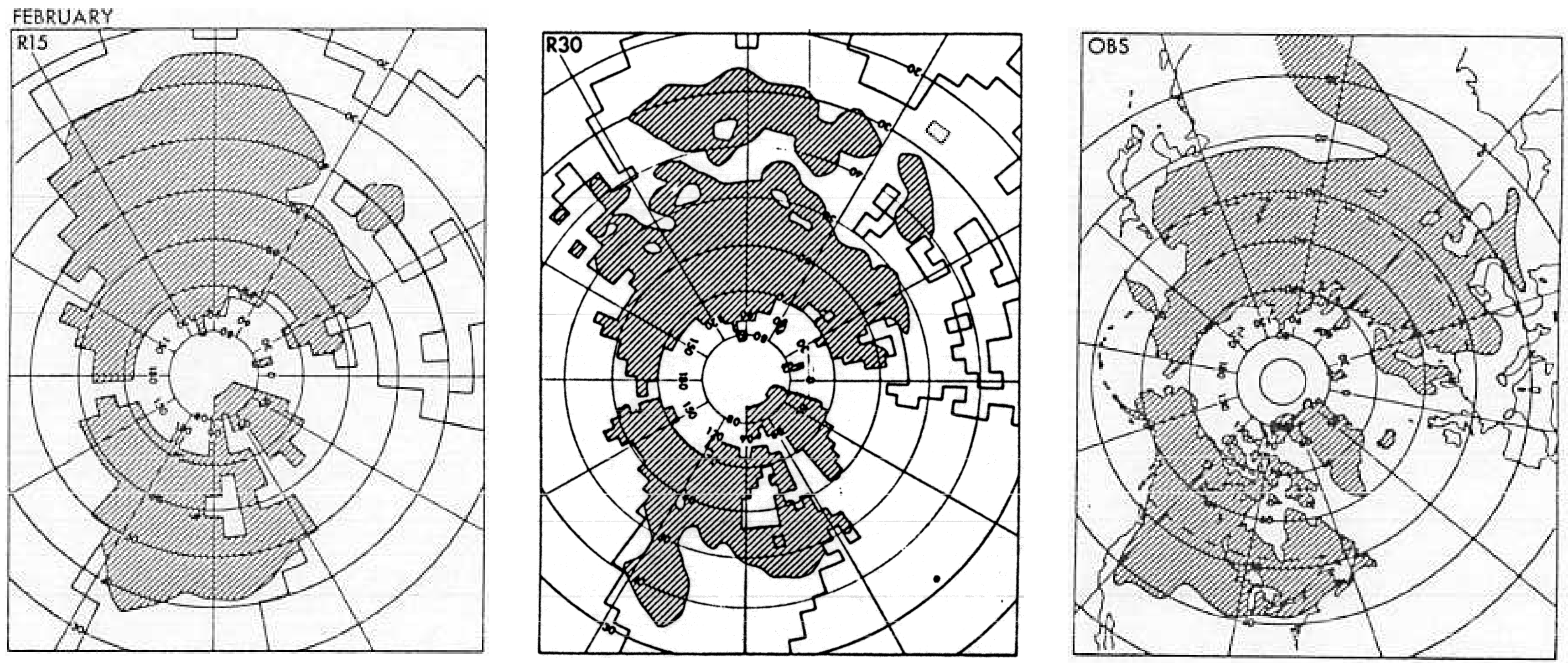


Figure 1. Areal coverage of Northern Hemisphere snow cover ($10^6 km^2$) from the low resolution (solid line) and high resolution climate simulations. The observed snow cover area from the climatology of Dewey and Heim (1981) is indicated by the solid circles.



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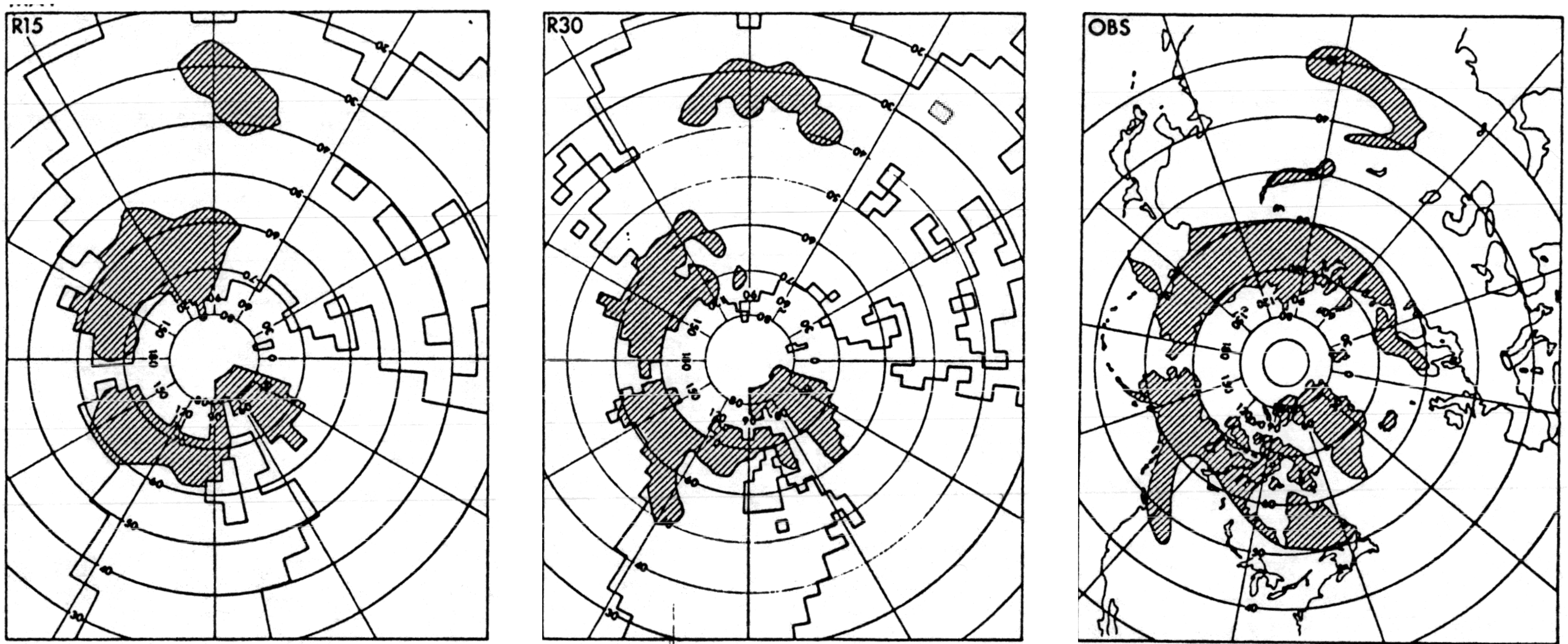

Figure 3. As in Figure except for May

The seasonal variation of snow cover area produced by both models is compared with observed data in Fig. 1. A model gridpoint is considered to be snow-covered if the water equivalent of the snow on the ground averages at least 1 cm. Both the high and low resolution versions of the model simulate a seasonal variation quite similar to that observed. The low resolution model overestimates snow cover from November through April and underestimates it from May through September. In contrast, the high resolution model systematically underestimates snow cover area in practically all seasons. In comparing the two resolutions with each other, the low resolution model has more snow cover in all but summer. Both versions produce a spring retreat of snow cover that is too rapid.

The comparison of the geographical distributions of snow cover produced by each of the GCMs with observations is made at two different times during the seasonal cycle. February is representative of the seasonal maximum of snow cover, and May illustrates the spring retreat phase of the seasonal cycle. Maps of snow cover from both resolution models are compared with the observed snow cover maps of Robock (1980) in Figs. 2 and 3.

During February, the low resolution model simulates snow cover which is slightly too extensive, while the high resolution version has snow cover area well below that observed. Over North America, the low resolution simulation is very close to reality, with the snowline at approximately 40°N. In the

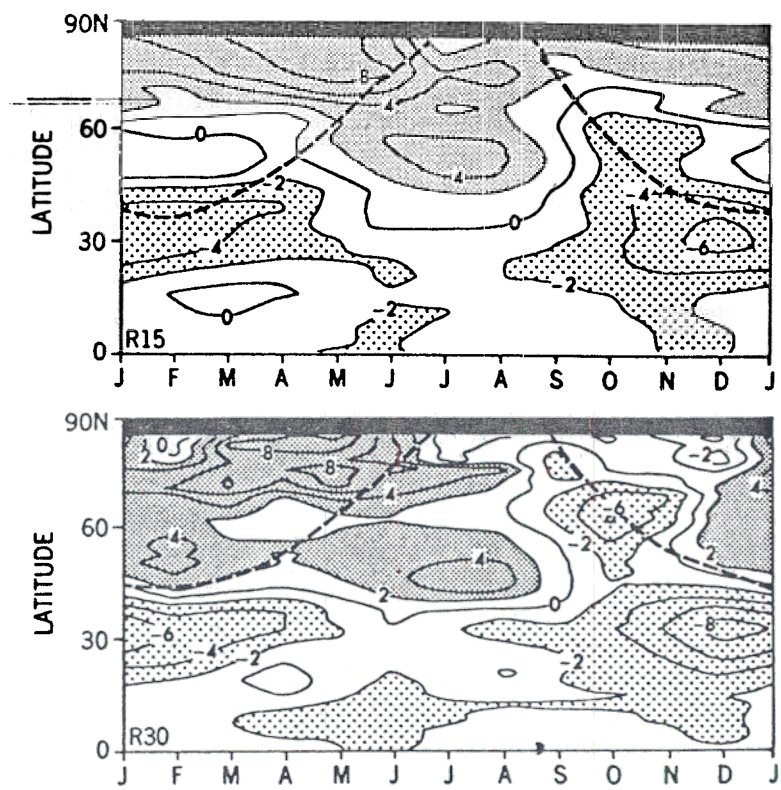

Figure 4. Latitude-time distribution of the difference between the climate model and observed zonal mean surface air temperature (°C): (top) low resolution model; (bottom) high resolution model. The observed data are taken from the climatology of Crutcher and Meserve (1970). The dashed lines represent the approximate southern limit of snow cover from each model simulation.

high resolution model too little snow covers the eastern two-thirds of the continent. In western and central Europe both models are very similar to the observed snow cover, while a slight deficit of snow cover can be noted from eastern Europe to the Caspian Sea region south of 50°N. In Asia an excessive amount of snow covers China between 30-42°N in the low resolution model. This excess snow cover is the primary reason for the model's overestimation of winter snow cover area. In the high resolution simulation, only a slight excess of snow occurs in western China. The more patchy appearance of the snow cover in the high resolution model results from the short averaging period as compared with the low resolution case (one February versus nine Februaries).

Turning to the May maps (Fig. 3), both models can be seen to underestimate snow cover in the spring retreat season. In North America, the area east of Hudson Bay is free of snow in the model simulations in contrast to the snow cover observed in this area. In both models snow cover is also absent from much of high latitude Eurasia from Scandinavia along the coasts of the Barents and Kara Seas, while observations show this area to be snow covered. Better agreement occurs along the Arctic coast of Siberia east of 90°E.

In a model as complicated as a GCM, it can be difficult to ascertain the causes of a particular deficiency in the model's climate simulation because of the complex interactions that take place. In the case of snow cover, sorting out cause and effect can be particularly difficult. Its existence depends on factors such as temperature, precipitation, and solar radiation, but once present snow cover can influence each of these factors. Despite this difficulty, the strong association between temperature and snow cover may allow some insight to be gained into the systematic errors in the simulation of snow cover by studying the temperatures simulated by the model.

Figure 4 is a latitude-time plot of the difference between the simulated and observed zonal mean surface air temperature over land. The observed temperatures are taken from the Northern Hemisphere climatology of Crutcher and Meserve (1970). Both models have a similar error pattern, with temperatures too warm at high latitudes and too cold in middle latitudes. In the high resolution model, the region of excessive warmth extends farther south than it does in the low resolution version. This is consistent with the differences in the snow cover simulated by the two models.

An approximate southern limit of snow cover (excluding regions of elevated terrain) is indicated on each latitude-time plot by the heavy dashed line. During the spring retreat of snow cover, both models are too warm at the latitudes near the mean snow boundary. This is consistent with the too rapid retreat of the snow cover in both models. During the autumn expansion of snow cover, the snow boundary occupies latitudes at which the models' temperatures are close to or slightly cooler than observed. Although cause and effect cannot be distinguished, the consistent behavior of temperature and snow cover suggests that the models treat the interaction between these climatic variables in a reasonably realistic manner.

In summary, both models are quite successful in reproducing the seasonal variation of snow cover area, with the low resolution version producing more snow than the high resolution model. In both model simulations, the spring retreat of snow cover occurs too rapidly. Errors in the simulation of surface air temperature are consistent with those involving snow cover.

Future efforts to validate climate models should continue to consider snow cover by virtue of its importance in the climate system. The availability of the NOAA satellite-derived snow cover data set in digital form should allow more detailed comparisons of observed snow cover frequency and variability with model simulations.

Acknowledgments

I am indebted to Suki Manabe for making his climate model available for this study and providing advice and encouragement. He and Tom Delworth contributed a number of useful suggestions that improved this manuscript. Many thanks to Joyce Kennedy for typing the camera-ready copy, and to John Conner and Phil Tunison and his staff for preparing the illustrations.

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