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SENSITIVITY OF A PHYSICALLY-BASED CLOUD PACKAGE
IN THE NCAR CCM2

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1. INTRODUCTION

Based upon our earlier investigation on the performance of the National Center for Atmospheric Research (NCAR) Community Climate Model Version 2 (CCM2), we have incorporated into this model a physically-based cloud package which includes the Arakawa-Schubert (AS) scheme for convective cumulus clouds, and the Sundqvist (SUN) scheme for non-convective layered clouds (hereafter referred to as the SUNAS cloud package). This package allows for the prognostic computation of cloud liquid water which is advected using the semi-Lagrangian transport scheme of CCM2 the formation of anvil clouds from deep convective systems, and the coupling of physically based cloud optical properties to the CCM2's shortwave and longwave radiation treatment. A multi-year simulation spanning the period from 1980 to 1988 is conducted using the NCAR CCM2 with the SUNAS cloud package. In this paper, the effect of the cloud package is assessed by comparing the January results of the simulation to model output from a control run over the same period using the original version of CCM2 (Kao et al., 1996). The model results are also compared to data from the global reanalysis for the same period conducted by the National Center for Experimental Prediction (NCEP) and NCAR. In this paper, we place particular emphasis on the cloud package's effect on the climate patterns in the Pacific North American (PNA) Region. The sensitivity of the model performance to the threshold relative humidity for cloud formation in the SUN scheme is also assessed.

2. CCM2

CCM2 is basically a user-friendly, plug compatible, and well-coded GCM. Other climate studies based on CCM2 include Zhang et al. (1994), Lieberman et al. (1994), Kiehl et al. (1994b), and Hahnmann et al. (1995). The detailed description of the version of CCM2 used here has been given in Hack et al. (1993) and Hack et al. (1994). We use the standard resolution of CCM2 which employs T42 horizontal resolution (approximately 2.8° in latitude and longitude) and 18 vertical layers from the surface up to about 3 mb in height with a hybrid vertical coordinate. The model includes both the annual and diurnal cycles of sunlight. The shortwave parameterization uses the 6-Eddington approximation (Briegleb, 1992). The algorithm for cloud/radiation interactions is described in Kiehl (1990). The cloud water paths which were originally specified as functions of height and latitude are calculated according to the cloud water determined by the SUN scheme. The original Slingo's parameterization for fractional cloud coverage is replaced by the SUN parameterization. The "nonlocal" boundary layer parameterization (Holstag and Boville, 1993) diagnoses the boundary layer depth and determines diffusivity profiles and turbulent transport within the boundary layer. The boundary layer parameterization also diagnoses perturbation temperatures and specific humidities within the rising plumes of convective boundary layers. These perturbations are used as cloud-base quantities in the convection scheme. The original cumulus parameterization which was based on a mass flux convection scheme (Hack, 1994) that adjusts the moist static energy over three adjacent layers has been replaced by a version of the Arakawa-Schubert method (Kao and Ogura, 1987).

3. THE CLOUD SCHEMES

The original treatment of layered clouds in CCM2 is highly simplified. Cloud cover is prescribed using the empirical formulation of Slingo (1987). Cloud liquid water is determined using an empirical relationship based on model height and latitude. We have replaced the CCM2 treatment for layered clouds with a package that uses the Sundqvist (1988) method for the prognostic computation of cloud liquid water for stratiform clouds. The Sundqvist method involves a sub-grid scale cloud parameterization which relates the partial cloudiness to the relative humidity and a prescribed threshold relative humidity. Cloud water is computed prognostically based on the available moisture
convergence in a model grid. Cloud water computed from the Sundqvist scheme is treated as a general model constituent in CCM2. Consequently, cloud water is horizontally and vertically advected using the semi-Lagrangian transport built into the CCM2 code. Turbulent diffusion of cloud water is also taken into account. The use of prognostic cloud water in CCM2 allows the clouds to evolve continuously throughout a model simulation based on the physical forcings produced by the model. Cloud optical properties are based on the prognostic computation of cloud water. This is a more realistic situation than setting cloud properties based on some empirical formulation - as in the original CCM2 treatment of layered clouds. Thus, the interaction of clouds and radiation is more physically based.

The AS scheme (Arakawa and Schubert, 1974) employs a one-dimensional steady state entraining cloud model with basic microphysics to represent the clouds. A spectrum of sub-ensembles of clouds are allowed to form simultaneously and modify the environment through compensating downward motion, detrainment, and evaporation of cloud water. Cloud-cloud interaction is considered in a way that the development of one sub-ensemble cloud can affect the growth of other sub-ensembles through its stabilizing effect on the large-scale environment. The exchange processes between the planetary boundary layer and the free atmosphere are also included. The AS scheme uses a quasi-equilibrium approximation to close the parameterization, which requires that clouds stabilize the atmosphere as the large-scale motion generates moist convective instability.

4. RESULTS

Figures 1a, b, and c show a comparison of the January stationary waves at 500 mb for the SUNAS case, the earlier CCM2 results from Kao et al. (1996) (used as our control case), and the NCEP/NCAR reanalysis project which is shown for comparison. Both the SUNAS case and control case reproduce the northern hemisphere major troughs and ridges observed in the NCEP/NCAR reanalysis. For the SUNAS case, the magnitude of the East Asian low pressure trough is in good agreement with NCEP/NCAR, while the control case is too shallow by about 40mb. The strength and position of the high pressure ridge over North America is also somewhat better represented in the SUNAS case. Also, the Siberian high pressure ridge is somewhat better defined than the control case. However, the Icelandic low pressure trough is not as well represented in the SUNAS case. In the Southern Hemisphere, the troughs and ridges have smaller magnitudes than shown for the control case or the NCEP/NCAR data.

Kao et al. (1996) noted that the stationary waves for the PNA sector modeled by CCM2 were better represented for warm decades (i.e., decades characterized by higher than normal SST in the equatorial Pacific) compared to cold decades. We show the January stationary waves for the El Nino years of 1983, 1987, and 1998 (Figures 2), and the La Nina years of 1982, 1984, 1985, and 1986 (Figures 3) for the SUNAS case (Figures 2a and 3a) versus the control case (Figures 2b and 3b) and the NCEP/NCAR reanalysis (Figures 2c and 3c). For the El Nino years, the East Asian low extends somewhat further east for the control case. The high pressure ridge over North America is also slightly better situated than the SUNAS case. Also, the high pressure center over central Asia (Siberian High), and the position and magnitude of the Icelandic low and high pressure ridge over Europe and the Atlantic are somewhat better modeled by the control case. In the southern hemisphere, the pressure

Figure 1. 500 mb departure from the zonally averaged geopotential height for (a) SUNAS, (b) control, and (c) NCEP/NCAR reanalysis.
ridges and troughs are poorly modeled by both SUNAS and the control case. For the La Nina years (Figures 3), the high pressure ridge over North America is better represented by SUNAS compared to the control case. The position and magnitude of the East Asian low are also somewhat better represented than the control case. The Siberian high pressure center is also better represented by the SUNAS case. As in the case of the El Nino year, the troughs and ridges in the southern hemisphere are poorly represented by both models. However, the anomalous high in the Southern Pacific for the control case does not appear in the SUNAS case. Overall, the SUNAS cloud package does not improve the CCM2 performance for the warm years, but appears to yield a moderate improvement of the representation of the PNA sector for cold years. This is somewhat encouraging since Kao et al. (1996) showed that CCM2 tends to perform well during warm years, but suffers from a general westward shift in the circulation patterns in the PNA sector especially during cold years.

Figures 4a, b, and c show the January 200 mb zonal wind averaged over 1980 to 1988 for the SUNAS case, the control case, and the NCEP/NCAR reanalysis. The modeled easterly jets off the east coasts of Asia and North America are fairly situated for both the SUNAS case and control case. However, for the SUNAS case, the East Asian jet is shifted somewhat farther east in better agreement...
direction of wind fields shows a strong dependence on the selection of the threshold relative humidity. To illustrate this dependence, we show a comparison of two runs. The first uses a threshold relative humidity of 85%, while the second uses a threshold relative humidity of 90%. All other factors are the same for each run. Both runs start at 1 October, 1980 and continue through January 1981. Figures 5a and b show the monthly averaged departure from the zonal mean geopotential height for January 1981 for the SUNAS $u_{w0}=0.85$ case, and the SUNAS $u_{w0}=0.90$ case, respectively. For Figure 5a, the East Asian low pressure trough is shifted substantially to the west compared to Figure 5b. The high pressure ridge over the western coast of North America is also shifted westward, and is much less intense compared to case b. The Icelandic low pressure trough in Figure 5a extends well into the North Atlantic, dissecting the high pressure ridge over Europe. The 500 mb pressure ridges and troughs in the southern hemisphere are also quite different for the two cases. This surprising model sensitivity indicates that large scale cloud processes – and their associated effect on the global distribution of heating – play a critical role in the overall global dynamics.

Figure 4. January zonal winds. (a) SUNAS, (b) control, (c) NCEP/NCAR reanalysis.

Figure 5. Departure from the zonally averaged geopotential height for (a) $u_{w0}=0.85$, and (b) $u_{w0}=0.90$

5. SENSITIVITY TESTS ON THRESHOLD RH

Our sensitivity runs show the importance of the selection of the threshold relative humidity for layered cloud formation ($u_{w0}$) on the overall dynamics of the modeled atmosphere. This is especially true in the midlatitudes where the placement of troughs and ridges, and strength and
5. DISCUSSION

The SUNAS cloud package produces significant changes in the performance of CCM2. In this paper, we have illustrated how the overall dynamical features are affected by showing the difference in the 500 mb standing wave patterns and zonal winds for the SUNAS case versus the control case of Kao et al. (1996). The effect of our cloud package is especially evident in the PNA sector where the pattern of standing wave features and high level jets appear to be shifted eastward compared to the study of Kao et al. (1996). This effect is encouraging since CCM2 is known to produce a westward bias for these features in the PNA sector. The sensitivity of the modeled climate patterns to a small change in the threshold relative humidity for the formation of layer clouds also demonstrates the importance of large scale cloud processes in determining the global circulation. This sensitivity also demonstrates that more knowledge may be necessary for choosing this parameter effectively in order to produce reliable simulations of the global climate.

The SUNAS cloud package also produces significant changes in other features such as the overall modeled cloudiness and precipitation patterns. For instance, CCM2's tendency to over-represent the precipitation over areas such as the Amazon basin and the Western Pacific appears to be somewhat alleviated with the SUNAS package. The persistent stratiform cloud decks observed in the eastern ocean basins also appear to be better modeled by the SUNAS package. On the other hand, the modeled low cloud cover in the tropics for SUNAS tends to be overestimated compared to the available data. These features, as well as a more detailed description of the SUNAS performance will be presented later.

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