Diagnosing Sources of Error in the Cloud Parameterizations of the NCAR Climate Community Model*

Jonathan L. Vigh

SOARS Protégé
Pennsylvania State University, College of Earth and Mineral Sciences
State College, Pennsylvania

Research Mentor:
Joel Norris
Advanced Study Program
National Center for Atmospheric Research
Boulder, Colorado

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* A CD-ROM supplement is available that contains observational and model data and plots, as well as the scripts used to produce them.

ABSTRACT

The goal of this study is to find biases related to incorrectly parameterized cloud processes in CCM3 and prototype versions of CCM4, the atmospheric component of the NCAR Climate System Model, version 1. The variables of low, mid, and high cloudiness, cloud radiative forcing, and precipitation are investigated through the use of seasonal climatologies. The frequency distribution of cloudiness over cloud top pressure and cloud optical thickness is also investigated for conditions of ascent and descent in the North Pacific during July 1988. Biases include too much low cloudiness over winter land and too little over winter oceans, the misplacement of deep convection, poor stratocumulus representation, and missing tropical and subtropical middle cloudiness. Several of these deficiencies may be related to moisture transport in and above the boundary layer, while others probably result from the lack of a correct physical parameterization of important small scale processes.

1. Introduction

Clouds are one of the primary regulators of earth's radiation budget (Fouquart et al., 1990). Due to their complex thermodynamical and microphysical interactions, they are also recognized to be one of the most sensitive components of the climate system (Schneider 1972). In order to correctly portray the climate system, climate models must accurately represent the processes by which clouds form and dissipate as wells as their radiative and microphysical properties. There are many challenges to be overcome before clouds are properly simulated by climate models. Since clouds commonly exist on a subgrid scale of hundreds of meters, the greatest challenge of current GCMs is their low resolution (typically 100 km in the horizontal and 1000 m in the vertical). Thus cloud processes and effects must be parameterized in the model code. As a result, these parameterizations are usually severely simplified and often do not represent actual physical processes. This results in poor model performance [Zhang et al. (1994); Cess et al. (1987)]. If model simulations of past or future climates are to be believed with confidence, the cloud parameterizations need to be improved.

The goal of this paper is to identify and diagnose sources of error in the cloud parameterizations of the National Center for Atmospheric Research (NCAR) Climate Community Model, version 3 (CCM3) and proposed modifications to the cloud parameterizations that may be incorporated in version 4 (CCM4). To accomplish this goal, five-year June-July-August (JJA) and December-January-February (DJF) climatologies of the CCM run over climatological seasonal cycle sea surface temperature (SST) are compared to observational climatologies. The parameters investigated include shortwave and longwave cloud radiative forcing, cloud amount at low, mid, and high levels, and precipitation. In order to

evaluate the connection between synoptic processes and cloudiness, the frequency distribution of cloud top pressure and cloud optical thickness is compared for ascent and subsidence regimes over the North Pacific during July.

2. Data

a. Observational Data

Climatologies of low, mid, high, and total cloud amount were obtained from the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer, 1991). Data based on satellite observations are advantageous because they offer high spatial resolution, global coverage, and quantitative radiative information. The recently released level D2 data **(Doutriaux-Boucher and Sèze, 1998)** are used, but some important calibration issues remain. Limb-viewing effects are still present in the climatologies, particularly over the Indian Ocean. Because polar data are more uncertain, this study focuses primarily on the tropics and midlatitudes. The climatological monthly means for low, mid, high, and total cloud amount for the period 1983-93 are averaged into seasonal DJF and JJA climatologies with a spatial resolution of 2.5° x 2.5°. Since a satellite will not see low clouds obscured by higher clouds, a random overlap assumption is used to estimate the actual amount of low and mid clouds.

Data from the Earth Radiation Budget Experiment (ERBE) [Barkstrom (1984); Barkstrom et al. (1989)], covering a period from 1985-89, are used to construct DJF and JJA climatologies of the top-of-atmosphere (TOA) longwave, shortwave, and net cloud radiative forcing. The data have a spatial resolution of 2.5° x 2.5°. Possible errors in the data may result from difficulty in distinguishing clouds from snow as well as resolving clouds that are smaller

than the 2.5 km resolution of the satellites.

A surface observational dataset of low cloudiness over the oceans is used to mitigate the uncertainty caused by inability to measure obscured low clouds in ISCCP. This dataset was compiled from the Extended Edited Cloud Report Archive (EECRA) based on Hahn et al. (1996). The EECRA is a collection of 60 million synoptic ship reports taken from 1954-92, primarily by Volunteer Observing Ships (VOS). These were compiled into a climatologies of synoptic low cloud types with nominal resolution of 2.5° x 2.5° by Norris (1998). The advantage of using surface observations is that human observers classified clouds by morphology which provides a substantive link between a cloud type and the process by which it formed, whereas ISCCP only classifies the cloud by cloud top pressure and cloud optical thickness.

The Global Precipitation Climatology Project (GPCP), version C dataset [Huffman et al. (1995); Huffman et al. (1997)], is used to construct DJF and JJA climatologies from monthly data spanning the years 1987-98. The version C rain gauge product data used undergoes substantial algorithmic processing to provide a best estimate on global precipitation based on satellite rain estimates and ground-based meteorological rain gauge reports. Precipitation climatologies are especially useful for diagnosing the location and intensity of the areas of deep convection that occur in the climate system.

b. Model Output

Three five-year model runs of CCM were studied in this paper. The first run is the standard CCM3, CCM3527, which contains a diagnostic cloud water scheme. The second run,

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CLIMSST3, contains a new prognostic cloud water scheme. The third run, TCN03A, also contains the prognostic cloud water scheme as well as convective triggers. Each model version ran with seasonal cycle climatological SSTs and an interactive land surface model at T42 horizontal resolution (transform 2.8° x 2.8°) and a vertical resolution of 18 levels. All three runs were allowed to spin up for several years until a stable climate was observed. Below is a description of the distinctive features of each model version. This information is summarized in Table 1.

The model physics and other aspects of standard CCM3 are well documented by Kiehl et al. (1996). The cloud amount and associated optical properties of CCM3527 are computed via a diagnostic method. Clouds are formed in the model as a function of the relative humidity, vertical velocity, atmospheric stability, and the convective mass flux associated with parameterized moist convection. Moisture and heat are transported, then the amount of cloud water condensate content is diagnosed as an exponentially decreasing function of height scaled by integrated water vapor. The effective droplet radius for warm clouds over land and ocean is fixed, the ice fraction varies linearly with temperature, and the radiatively active ice effective radius increases linearly with pressure. The albedo, absorptivities, and emissivities of the clouds are based on the amount of diagnosed condensate, effective radius of cloud particles, and ice fraction. Surface albedos, snow cover, and heat and moisture fluxes are predicted by a coupled land-surface model.

CLIMSST3 contains a new prognostic cloud water scheme to predict the water and ice content of model clouds (Rasch and Kristjánsson, 1997). Instead of merely diagnosing the water content of clouds, the new scheme predicts the amount of condensate based on local physical

processes. The cloud parameterizations in CLIMSST3 were updated to use this new scheme, with each process contributing a separate amount of cloud condensate. This facilitates the isolation of the role of different processes in producing clouds. The convective, effective radius, and ice fraction parameterizations were left unchanged. The parameterization of tropical trade cumulus was removed and the stratocumulus parameterization was updated.

TCN03A includes the same predicted cloud condensate scheme as used in CLIMSST3, with the addition of convective triggers to help improve the simulation of deep convection. The old convection scheme produced convection whenever there was convective available potential energy (CAPE). This resulted in unrealistically persistent areas of convection in certain regions of the tropics. The convective triggers provide inhibition, only allowing deep convection to proceed after overcoming a certain threshold.

3. Methodology

a. Geographical climatologies

The first method used in this study compares the model's geographical climatology of cloud radiative forcing, cloud amount, and precipitation to observations. Since low clouds tend to have a significant negative shortwave forcing (except over snow) and high clouds tend to produce a positive longwave forcing, the long and shortwave cloud forcing give key information about the model's energy budget as well as information on the amount and type of clouds present. Seasonal latitude-longitude plots of total cloud amount help reveal general cloudiness biases. Since much of tropical precipitation results from convection, the distribution of precipitation allows inference of the distribution of convection. The inference is not direct

however because of differences in the efficiency of precipitation processes related to the geographical variance in the size distribution of cloud condensation nuclei (McCollum et al. 1999).

In order to diagnose errors in the cloud parameterizations, a closer look at the clouds themselves is needed, since total cloud cover could hide compensating biases between low and high clouds. The traditional method of using zonal averages works well for distinguishing seasonal biases, but is inadequate for the specific study of clouds because such a method misses compensating meridional biases. To get around these potential pitfalls, the geographical climatologies of low, mid, high, and total cloud cover are used, supplemented by long and shortwave forcing and precipitation climatologies. Taken together, these climatologies reveal regional biases for certain cloud types, which facilitates the inference as to which cloud parameterization might be responsible for a particular bias.

b. Frequency distributions over synoptic conditions

Clouds are parameterized under the assumption that cloudiness is related to synoptic scale variables such as vertical velocity, relative humidity, etc. Geographical climatologies are helpful in identifying biases in cloud type, but an average over time however cannot specify what contribution a certain parameterization makes to the observed seasonal cloud amount. This is especially true for the extratropical storm tracks over the midlatitude oceans where large changes in synoptic conditions occur with the passage of cyclones and fronts. Thus, this study uses a second method of analysis to identify model biases for specific cloud processes.

Three hour daytime cloud type frequencies from ISCCP are used in conjunction with

reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) model for July 1988 over the North Pacific to construct a observational frequency distribution of cloudiness over cloud top pressure versus cloud optical thickness. ISCCP uses seven levels of cloud top pressure and six bins for cloud optical thickness to classify clouds (Fig. 1), resulting in 42 generic cloud types. Thus, the frequency distribution identifies the amount of time each of the 42 cloud types occurred during July 1988. This is done for all cases of omega (vertical velocity in pressure coordinates), just for negative omega (upward vertical motion), and just for positive omega (downward vertical motion). Vertical velocity is an important factor in the formation of certain cloud types over midlatitude oceans, especially for stratocumulus under subsidence conditions, and frontal cloud shields under conditions of ascent. This method of analysis is effective in evaluating the contribution of cloud parameterizations that are affected by vertical velocity.

In order to compare the model to ISCCP, one month of three hourly instantaneous cloud output from a July run of CCM is transformed by a program so that the number of frequency samples of CCM output is comparable to the number of samples for ISCCP. The program breaks each model gridbox into one hundred subcolumns and distributes cloudiness among subcolumns in a manner consistent with the model's overlap assumption. Each subcolumn is assigned a cloud type based on cloud top pressure and cloud optical thickness following the ISCCP algorithm. The cloud top pressure is not the highest model level with cloud but rather a value based on the radiative method ISCCP uses to determine cloud top pressure. Averaging is done for conditions of positive and negative omega.

4. Results

a. Low cloud problems related to boundary layer processes

Several biases in cloud type and amount are discussed that may be related to the errors in the model's cloud and boundary layer parameterizations. The first and perhaps most noticeable bias is the overestimate of winter low clouds over midlatitude land with an accompanying and a likely related underestimate of winter low clouds over the midlatitude oceans. This can be seen by comparing DJF and JJA low cloud cover for ISCCP observations (Figs. 2a and 3a), surface observations from ships (Figs. 2b and 3b), and CCM3527 (Figs. 2c and 3c). This is most pronounced in the northern hemisphere with the model overestimating low clouds by as much as 70% and in general 30-60% over Siberia and northern Canada and Alaska. There is also a noticeable overestimate in the mid level cloud cover in these same regions for DJF, which can be seen by comparing the DJF and JJA ISCCP observed mid cloud cover (Figs. 4a and 5a) to CCM3527 (Figs. 4b and 5b). Some of this discrepancy might be explained by an underestimate in the satellite observations due to the fact that these regions are largely snow covered during the winter. In contrast to land, winter low clouds are underestimated by 20-50% over parts of the North Pacific and North Atlantic Oceans for DJF. This underestimation is further highlighted by looking at plots of total cloud cover for DJF (Fig. 6) and JJA (Fig. 7). Off the east coasts of Asia and North America, there are drastic differences between the observations and models. Due to the lack of surface observations in the Antarctic region, it is difficult to tell if this bias exists for the southern oceans. The CLIMSST3, with a predicted condensate scheme, had a slightly better low cloud distribution over Siberia than the standard CCM3 (compare Fig. 8 to Fig. 2 for DJF), although the underestimate over winter oceans is worse than CCM3527.

The overestimate of low clouds over winter land has little effect on shortwave forcing in DJF (Fig. 9) because the snow-covered land and clouds have a similar albedo. There is a general overestimate in DJF longwave forcing (Fig. 10) however over land. The underestimate over the ocean causes a noticeable underestimate of shortwave cloud forcing of about 10-20 W/m^2.

This bias likely results from problems with the way moisture is transported into the free troposphere from the boundary layer. Since the amount of low cloudiness is often related to the amount of moisture present in the layer, an erroneous boundary layer moisture transport scheme would have a large effect on low clouds in or just above the boundary layer. Winter over land usually features a stable atmosphere, whereas over the oceans, intense wintertime sensible and latent heat fluxes cause instability and rapid convection. It seems that over the winter land, CCM has too much moisture in the lower layers, probably caused by not transporting moisture up out of the boundary layer fast enough. The underestimate over the oceans may reflect a failure of the cumulus parameterization, or it might be caused by moisture being transported too rapidly upward from the lower levels.

Another bias of low clouds likely related to the boundary layer is a general shortage of tropical and subtropical oceanic low clouds (Figs. 2 and 3), especially when compared to the surface observations over the subtropical oceanic deserts. The discrepancy between ISCCP and the surface observations might be partially explained by the fact that trade cumulus are often smaller than the resolution of a pixel, so ISCCP will tend to underestimate these clouds. The radiative forcing effects of this underestimation are hard to quantify because the models seem to have an overestimate of shortwave cloud forcing for DJF (Fig. 9) and JJA (Fig. 11), despite the shortage of low clouds. The low clouds are simply too bright. This has been a common problem

in GCMs. In CCM, the problem has been alleviated somewhat by not allowing clouds to form in the lowest model layer (Kiehl et al., 1998). This points to a problem with the parameterization of low cloud radiative effects. The underestimate in tropical low cloudiness in CLIMSST3 results because the trade cumulus parameterization has been removed. The process by which trade cumulus form is not well understood and has not yet been accurately included in the model.

Finally, a third bias of low clouds involves the underestimation of low clouds over winter time subtropical continents such as southern Asia, the Arabian peninsula, and the Sahara (Fig. 2). The model have virtually no clouds in these regions, while observations have about 15-30% cloud cover. Perhaps this bias is related to the boundary layer and moisture transport over the deserts.

b. Deep convection mislocated

Convection is perhaps the most problematic model variables to parameterize correctly, with many model biases occurring as a result of poor simulation. In general, the three model versions misplace convection and make it too intense. This can be easily seen by comparing DJF and JJA plots of longwave cloud forcing (Figs. 10 and 12) and precipitation (Figs. 13 and 14). In the DJF precipitation over Southern Asia and western Melanesia, the models' maxima seem to coincide with the observed precipitation minima. The models also produce too much precipitation north of the equator in a double ITCZ feature. Over land, the models produce unrealistically large values over South America and the Caribbean as well as southern Africa. The northern hemisphere winter storm tracks seem to be well represented, however. In the

geographical precipitation distribution for JJA (Fig. 14), several glaring biases appear. The most noticeable is perhaps the 10 mm day^{-1} overestimate in the Caribbean and another large overestimate stretching from central Africa over to Singapore. Another conspicuous region is the Central Pacific between Hawaii and Japan where the models generally produce twice the precipitation that is estimated in the observations. This bias is also reflected in an overestimation of total cloud cover in this area. Further south and west near the Philippines, there is an underestimate of precipitation. The models do not seem to pick up on the summer monsoon in North America. Finally, the models seem to underestimate the precipitation in the thin ITCZ regions off the coast of Africa and Central America.

Compared to observations, the longwave cloud forcing is overestimated in the convectively active tropical regions by about 10 W m^{-2} (Figs. 10 and 12). The predicted condensate scheme has somewhat higher values for longwave cloud forcing than the standard CCM3. TCN03A, with its convective triggers, has produced a distribution of precipitation (Figs. 15 and 16) and longwave forcing (plots not shown) much closer to the observations over southern Asia and the Caribbean. In some areas like Central Africa, however, it reduces the amount of precipitation too much.

The causes of these biases in convection could be related to many factors including a misrepresented tropical boundary layer, lack of proper convective inhibition, lack of discrete propagation of convection triggered by outflow boundaries, the misplacement of large scale convergence zones such as the ITCZ, the poor spectral topographical terrain representation in the model, and the lack of consistency between the parameterized local convective mass fluxes and the general gridbox mass flux. Some of these potential causes are related to the fact that subgrid

phenomena are difficult or impossible to parameterize with the current horizontal resolution. The spectral representation of islands and their topography may be responsible for the misplacement of precipitation maxima in the island archipelagos of southern Asia. The tropical boundary layer, convective inhibition, and inconsistent convective mass fluxes on the other hand are primarily vertical problems. Together with better theory and a higher vertical resolution, the convection problem may be helped. The addition of convective triggers seems to be a step in the right direction.

c. Stratocumulus cloud decks under subsidence regimes

The geographical distribution of stratocumulus in CCM is close to observations in terms of location, but the model has too few stratocumulus and the clouds that it does have are too bright. This is reflected in the plots of summertime low cloudiness (Figs. 2 and 3), total cloudiness (Figs. 6 and 7), and shortwave cloud forcing (Figs. 9 and 11) for the stratocumulus regions off the west coasts of North America, South America, and Africa. CLIMSST3, with a predicted cloud condensate scheme and updated stratocumulus cloud amount parameterization, tends to be even brighter than CCM3527 [compare JJA plots of low clouds (Fig. 17) and shortwave cloud forcing (Fig. 18) for CLIMSST3 to Figs. 3 and 9 for CCM3527].

The frequency distributions for the month of July 1986 in the North Pacific reveal a more subtle bias. During times which omega was positive (downward motion), the model has a recognizable peak frequency in the mid-latitude stratocumulus area of the cloud top pressure vs. cloud optical thickness plots (Fig. 19), but the model's clouds are both too low and too optically thick. Observations indicate that under downward motion there is much less clear sky than the

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model indicates. The observed distribution also has a broader range of cloud types, which may be partly explained by the uncertainty in the ECMWF model's omega. The amount of clear sky for subsidence regimes is 45% in the CCM3527, 36% in CLIMSST3, and 16% according to ISCCP. For the times when omega was negative (upward motion, Fig. 20), the model has a similar amount of clear sky (7-8%) compared to the observations (9%). But once again the model's clouds, mostly high, are concentrated in a maxima that is too optically thick and not as diverse as what actually occurs. CLIMSST3 with its predicted cloud water scheme shows a remarkably similar pattern to CCM3527, so plots are not shown.

The cause of this stratocumulus bias in the subtropics might be related to biases in the model's omega, or the spectral terrain (which causes hills in the oceans near mountainous coasts like the Andes), but it is likely primarily related to the fact that small scale processes are not well represented in CCM. These clouds form in the regions where the subtropical high advects marine air equatorward over increasingly warm water. The surface moisture flux moistens the air, forming low, bright clouds. The strong radiational cooling at the cloud top causes air parcels to become denser and sink, entraining dry air from above the cloud. This mixes air in the cloud, decreasing the relative humidity. So stratocumulus exist as an energy balance between release of latent heat from condensation and radiational cooling and a mass balance between moist convection from below and dry entrainment from above. These processes occur on a scale of meters, while the model's vertical resolution is hundreds to thousands of meters. Empirical relationships relating large scale variables to stratocumulus cloud amount exist, but the processes are not well understood. To accurately represent these clouds, the small scale cloud top processes need to be effectively parameterized using representative physics.

d. Subtropical middle cloud underestimates

CCM3 lacks sufficient tropical and subtropical mid-level clouds compared to observations (Figs. 4 and 5). Observations indicate that most of the tropical middle clouds occur in conjunction with the ITCZ and other areas of convection. It is difficult to see the effect of missing mid-level clouds in the short and longwave forcing plots (Figs. 9-12), and there is probably little net radiative forcing caused by this bias. Hack et al. (1998) have recognized that the models do not have enough tropical moisture. This bias is likely the result of insufficient horizontal detrainment of moisture from deep convection.

5. Conclusions

The goal of this paper was to investigate model biases in the climatological coverage of low, mid, high, and convective cloud in order to determine how these biases are related to the model's cloud parameterizations. While no cause can be assigned with certainty, several of the biases are likely caused by a poor representation of the transport of moisture in the boundary layer. Such biases include large errors in wintertime low clouds resulting from poor vertical moisture transport, and a lack of tropical middle level clouds resulting from insuffient detrainment from deep convection. Other problems such as the underestimate of stratocumulus are probably caused by the lack of a physical parameterization of critical small scale processes. Many model biases are at least partially caused by the model's inability to resolve cloud processes that occur on small vertical and horizontal scales. In general, CCM generates too much low and high cloudiness that is too optically bright, while missing many other types of

clouds. This is probably a function of the parameterization of radiative effects.   Some general

conclusions that can also be drawn from comparing the different model runs to each other. For

one, the model runs, although containing different cloud parameterizations, still agree better

among themselves than with the observations. This indicates that there are some robust errors in

the model, possibly unrelated to the cloud parameterizations. Also, the addition of a predicted

condensate and convective trigger scheme did improve the overall simulation, pointing to the

fact that the addition of parameterizations based on real physical processes should improve the

model if the physical interactions are correctly understood and implemented.

The significance of these biases are not completely known due to the complicated

feedback processes in the climate system. Deep convection has a significant impact on the large

scale dynamics of the atmosphere through the release of latent heat and longwave cloud radiative

forcing. Biases in the distribution of convection will likely result in a poor CCM ENSO

simulation. The regional biases in CCM are also significant. For example, the North American

monsoon is practically nonexistent. Thus users of model output, especially for regional studies

should use caution.

Further research should be conducted to determine the precise contribution of each cloud

parameterization to the model's overall cloudiness, both by region and known cloud processes.

Careful study should be given to determine which cloud types need the most improvement, so

that parameterizations can be developed based on the physical processes that form and dissipate

those specific cloud types. Also, it would be prudent to conduct studies using high resolution

cloud resolving models to determine the sensitivity of the various cloud types to small scale

processes. Another effort should focus on the how unphysical terrain (caused by poor horizontal

resolution and spectral representation) affects variables like convection and omega. Finally, the

feedback processes between clouds and other components of the climate system such as the

atmosphere's general circulation should be studied to determine if there are links between model

biases in cloud amount and other related variables.

ACKNOWLEDGMENTS

LIST OF FIGURES

Figure 1: The International Satellite Cloud Climatology Project (ISSCP) cloud classification scheme: ISCCP uses cloud top pressure (hPa) and cloud optical thickness to classify clouds. There are 42 generic cloud tops that can further be classified as low, middle, and high, or by the commonly used name, such as stratocumulus. The latter classification is somewhat arbitrary.

Figure 2: DJF low cloud cover (%) for (a) ISCCP for 1983-93, random overlap assumed, (b) synoptic surface reports from ships for 1954-92, and (c) model run CCM3527, years 6-10.

Figure 3: Same as in Fig. 2, but for JJA.

Figure 4: DJF middle cloud cover (%) for (a) ISCCP for 1983-93, random overlap assumed and (b) model run CCM3527, years 6-10.

Figure 5: Same as in Fig. 4, but for JJA.

Figure 6: DJF total cloud cover (%) for (a) ISCCP for 1983-93 and (b) model run CCM3527, years 6-10.

Figure 7: Same as in Fig. 6, but for JJA.

Figure 8: DJF low cloud cover (%) for (a) ISCCP for 1983-93, random overlap assumed and (b) synoptic surface reports from ships for 1954-92, and (c) model run CLIMSST3, years 31-35.

Figure 9: DJF shortwave cloud radiative forcing (W m^{-2}) at the top-of-atmosphere (TOA) for (a) the Earth Radiation Budget Experiment (ERBE) for 1985-89 and (b) model run CCM3527, years 6-10.

Figure 10: DJF longwave cloud radiative forcing (W m^{-2}) at TOA for (a) ERBE for 1985-89 and (b) model run CCM3527, years 6-10.

Figure 11: Same as in Fig. 9, but for JJA.

Figure 12: Same as in Fig. 10, but for JJA.

Figure 13: DJF precipitation (mm day^{-1}) for (a) Global Precipitation Climatology Project (GPCP) for 1987-98 and (b) model run CCM3527, years 6-10.

Figure 14: Same as in Fig. 13, but for JJA.

Figure 15: DJF precipitation (mm day^{-1}) for (a) GPCP for 1987-98 and (b) model run TCN03A, years 1-5.

Figure 16: Same as in Fig. 15, but for JJA.

Figure 17: Same as in Fig. 8, but for JJA.

Figure 18: JJA shortwave cloud radiative forcing (W m^{-2}) at TOA for (a) ERBE for 1985-89 and (b) model run CLIMSST3, years 31-35.

Figure 19: July 1986 frequency distribution of cloudiness by cloud top pressure (hPa) and cloud optical thickness for only positive omega over the North Pacific for (a) ISCCP and ECMWF reanalysis observations and (b) the standard CCM3527, run oldjulA.

Figure 20: Same as in Fig. 19, but for only negative omega cases.

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Table 1: Comparison of the Three CCM Model Runs

	CCM3527	CLIMSST3	TCN03A
Condensate scheme	Diagnostic	Prognostic	Prognostic
Convective triggers	No	No	Yes
Trade cumulus	Yes	No	No

Table 1: Different aspects of the CCM model runs used in this study are compared over three categories relating to cloud parameterizations: the type of condensate scheme used to predict the amount of liquid and ice water present in a cloud, whether convective triggers were used, and whether a trade cumulus parameterization was used in the model.