An analysis of cloud cover in multiscale modeling framework global climate model simulations using 4 and 1 km horizontal grids

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Over the past few years, a new type of global climate model (GCM) has emerged in which a two-dimensional or small three-dimensional cloud resolving model is embedded into each grid cell of a GCM. This approach is frequently called the multiscale modeling framework (MMF) but is also known as a cloud-resolving convection parameterization or a superparameterization. In this article, we compare joint histograms of cloud top height and optical depth from the MMF with those being produced by the International Satellite Cloud Climatology Project (ISCCP) and from the Multiangle Imaging Spectroradiometer (MISR). While the form of the ISCCP and MISR data sets is conceptually similar, the satellite sensors and the algorithms differ, with the result that the joint histograms can differ quite significantly even when viewing exactly the same clouds. The analysis takes advantage of the strengths of each data set, as well as the differences in these data (which, for example, allow one to characterize the amount of some multilayer clouds). MMF simulation runs with three different resolutions are analyzed. One simulation is run using a 4 km horizontal grid with 26 vertical levels (on a stretched grid), a second simulation is run with a 1 km horizontal grid and the same 26 vertical levels, and a third simulation is run with a 1 km horizontal grid and 52 vertical levels. The analysis shows that the MMF reproduces the broad pattern of tropical convergence zones, subtropical belts, and midlatitude storm tracks as observed by ISCCP and MISR. However, the model has several significant shortcomings. Perhaps most seriously, it significantly underpredicts the amount of low-level cloud in most regions. The simulation with a 1 km horizontal grid and 52 vertical layers is found to improve modestly several aspect of the MMF low-level cloud cover. The model output is obtained using ISCCP and MISR instrument simulators and the role of horizontal resolution in the instrument simulators is examined.


1. Introduction

Over the past few years, a new type of global climate model (GCM) has emerged in which a two-dimensional or small three-dimensional cloud resolving model (CRM) is embedded into each grid cell of a GCM. This approach is frequently called the multiscale modeling framework (MMF) but is also known as a cloud-resolving convection parameterization or a superparameterization [Grabowski, 2001; Randall et al., 2003]. The MMF has been the focus of several evaluation studies including Khairoutdinov et al. [2008] and Marchand et al. [2009], both of whom found that the MMF has difficulty representing boundary layer clouds with total low cloud amounts well below observed values and cloud top heights, which are generally too low in altitude. Because of the large computational burden associated with the MMF approach, the CRM in the MMF has been run using an undesirably coarse grid. The MMF simulations in the above-referenced studies used a horizontal grid spacing of 4 km and 26 vertical levels (on a stretched grid). A model with a 4 km horizontal grid or coarse vertical resolution will struggle to resolve the formation of boundary layer clouds (which are often observed to have horizontal spatial scales of one km or less), and consequently, it is not surprising that the MMF is unable to represent boundary layer clouds well.

This is particularly troubling in light of recent studies by Bony and Dufresne [2005] and Bony et al. [2006], who examined tropical cloud radiative forcing response to changes in sea surface temperature in 15 coupled (atmosphere and ocean) climate models. These authors found that, in regimes of large-scale subsidence (where cloud radiative forcing is dominated by low clouds), model results (1) differ the most in climate change response and (2) disagree the
Table 1. Summary of MMF Simulations Analyzed

<table>
<thead>
<tr>
<th>Name</th>
<th>Configuration</th>
<th>Time Period Analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4KL26</td>
<td>64 columns, 4 km horizontal grid spacing, 26 vertical levels</td>
<td>section 3: Dec 2000 to Nov 2001; section 4: Nov 2006</td>
</tr>
<tr>
<td>1KL26</td>
<td>64 columns, 1 km horizontal grid spacing, 26 vertical levels</td>
<td>Nov 2006</td>
</tr>
<tr>
<td>1KL52</td>
<td>64 columns, 1 km horizontal grid spacing, 52 vertical levels</td>
<td>Nov 2006</td>
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most with observations of the current climate. The MMF has a relatively low climate sensitivity as compared to other climate models due in large part to an increase in low cloud fraction and liquid water in tropical regions with increasing sea surface temperatures [Wyant et al., 2006].

The two main objectives of this paper are (1) to present a more detailed evaluation of cloud fields produced by the MMF and (2) to provide an initial assessment on the dependence of simulated low clouds to CRM resolution. The analysis is based on a comparison of model output with joint histograms of cloud top height (CTH) and optical depth (OD) produced by the International Satellite Cloud Climatology Project (ISCCP) and the Multispectral Imaging Spectroradiometer (MISR) mission. While ISCCP data are frequently used in GCM analysis, MISR data are relatively new, and a secondary objective of this paper is to demonstrate how model analysis can benefit from the complementary nature of these data. A detailed examination of the ISCCP and MISR data sets, including several case studies comparing these data for commonly viewed cloud scenes, is given in a companion paper to this article [Marchand et al., 2010].

The organization of this paper is as follows. In section 2, we provide a brief description of the MMF model and simulations analyzed in this study. In section 3, we address the first objective, comparing ISCCP and MISR data sets with MMF output. This analysis is based on MMF simulation runs with the typical 4 km horizontal grid and 26 vertical layers. We examine the model performance globally, followed by a more in-depth comparison using several select regions in the tropics, subtropics, and extratropics. In section 4, we address objective 2, comparing the results of the MMF simulation runs with finer horizontal grid spacing (1 km) to the baseline (4 km) results. The results in section 4 focus on changes in model low-level clouds.

Comparisons between ISCCP observations and climate model output are often (and arguably best) accomplished using the ISCCP instrument simulator [Klein and Jakob, 1999; Webb et al., 2001]. The instrument simulator is a simple program, which converts model output into a form that is very similar to observational data, essentially approximating what a satellite would retrieve if it were flown over the model cloud field. The advantage of the simulator approach is that it allows one to account for some limitations in satellite retrievals. For example, in spite of the fact that clouds sometimes occur in multiple layers, most satellite retrievals assume that clouds are single layered. Often this is for the simple reason that the satellite observations do not provide sufficient information to determine robustly whether or not the cloud field has two layers. The model output, on the other hand, can unambiguously specify the vertical properties of the cloud layer, including the number of layers. Thus, one can often use the greater information available in the model to reproduce what a satellite would produce for the model cloud and so improve comparisons of model output with observational data by reducing the impact of some uncertainties and assumptions in the satellite retrievals. In a similar vein, we have constructed a simple MISR instrument simulator to facilitate comparison between climate model output and MISR retrievals. Details of the MISR simulator are given in Appendix A.

All of the model output in sections 3 and 4 is obtained using ISCCP and MISR simulators. These simulators are applied directly to the MMF cloud resolving model (CRM) output, treating each vertical column in the CRM independently, that is treating each column as if it were a satellite pixel. As a result of this treatment, all cloud boundaries naturally align perfectly with the “simulated pixels,” and there are no subpixels in the cloud. In section 5, we modify the MISR simulator such that the edges of the “simulated pixels” are randomly positioned with respect to CRM columns. Finally, section 6 summarizes the results of the previous sections and discusses likely directions of our future research with the MMF approach.

2. The Multiscale Modeling Framework

This study uses the MMF as developed by Marat Khairoutdinov (State University of New York, Stony Brook) and David Randall (Colorado State University). It consists of the National Center for Atmospheric Research (NCAR) Community Atmospheric Model (CAM) and an embedded two-dimensional cloud resolving model. The details of the MMF configuration are given by Khairoutdinov and Randall [2001] and Khairoutdinov et al. [2005] and are only briefly described here. The NCAR Community Atmosphere Model (CAM 3.0) is the atmospheric component of the Community Climate System Model (CCSM). In our version of the MMF, CAM is run with the finite volume dynamical core and a horizontal resolution of 2° latitude and 2.5° longitude. The dynamical time step of the CAM is 20 min.

In this study, we examine the MMF run in three different configurations, as summarized in Table 1. The 26-vertical-layer (stretched) grid is the default used by the CAM model, while the 52-layer grid was custom designed to have a vertical spacing of about 100 m from the surface to 1.6 km, 200 m from 1.6 to 2 km, 250 m from 2 to 3 km, 500 m from 3 to 10 km, 1 km from 10 to 21 km, and three levels above 21 km. Each analysis period was preceded by 2 months of simulation in order to allow the model to fully spin-up. The CRM domain is aligned in the east–west direction with cyclic lateral boundary conditions and runs continuously with its own 15–20 s dynamical time step. Radiation calculations using the CAM radiative transfer code and optical parameterizations are performed on each CRM column every 10 min. The CRM predicts the total nonprecipitating
water (vapor + liquid + ice) and total precipitating water (rain + snow + graupel).

3. Evaluation of Baseline (4 km) MMF Output

[10] Global maps of total cloud cover over ocean from ISCCP, MISR, and our original baseline MMF simulations are shown in Figure 1. Figure 1 shows that MISR generally produces slightly larger estimates of total cloud cover than ISCCP, most notably in the tropics and subtropics. This occurs primarily because MISR detects more broken boundary layer cloud [Marchand et al., 2010]. The difference between the two observational data sets is small (relative to the difference between the model and either observational data set), which provides confidence that limitations in the ISCCP and MISR retrievals of total cloud cover (including difficulties related to satellite resolution) are not significant for this comparison. We will examine resolution effects on the model output in more detail in section 5.

[11] Globally averaged for 2001, the MMF significantly underestimates total oceanic cloud cover, with ISCCP finding the total cloud cover over ocean to be 67.5%, MISR at 70%, and the MMF producing only 55.5% cloud cover. The MISR and MMF values include only clouds with optical depths larger than 0.3 and are weighted by the cosine of the latitude to account for the change in surface area per degree latitude (but does not account for changes in the fraction of land with latitude). A consistent optical thickness threshold of 0.3 is applied to both observations and simulations in order to make a fair comparison. This is the lowest threshold that can be reasonably applied because ISCCP and MISR have difficulty detecting clouds with optical depths less than about 0.3.

Figure 1. Oceanic cloud cover for 2001. Retrievals from (top left) ISCCP and (top right) MISR. (bottom right) Simulated MMF output (model run uses 4 km horizontal grid and 26 vertical layers). (bottom left) Zonal averages, with global (cosine weighted) average values given above the frame. Only cloudy columns with an optical depth of 0.3 or larger are considered cloudy for MISR and MMF. A consistent optical thickness threshold of 0.3 is applied to both observations and simulations in order to make a fair comparison.
cover (Figure 1) is primarily due to underestimating the amount of low cloud (Figure 3). The situation is particularly striking off the west coasts of North America, South America, and Africa, which are regions well known for their persistent stratocumulus. The model, at best, weakly captures these features. Only at the highest latitudes does the model produce low cloud fractions that compare well with (or exceed) observed values.

In the remainder of this section, we examine joint histograms of cloud top height and optical depth from several oceanic regions. It is important for climate models to capture correctly these distributions, because these properties are closely tied to the cloud’s effect on the radiation budget. That is, outgoing longwave radiation is modulated strongly by cloud top height and likewise outgoing shortwave radiation is modulated by cloud reflectance with optically thicker clouds reflecting more shortwave radiation to space.

3.1. Tropics

Figure 4 shows observed and simulated cloud top height and optical depth joint histograms for the tropical western Pacific (defined here as 10°N–10°S, 130°E–170°W). Figures 4a and 4b show the observed and simulated MISR histograms, while Figures 4d and 4e show observed and simulated ISCCP histograms. Figures 4c and 4f compare profiles of cloud fraction with height including only clouds with optical depths greater than 0.3. The profiles are obtained by summing the values in the joint histograms in the right-most six (optical depth) columns along each (cloud top height) row. (In the case of ISCCP observations, the first optical depth column contains all detections with an optical depth less than 1.3, and so some clouds with optical depths less than 0.3 are included in the height profile. However, validation studies have shown that ISCCP detects few clouds with optical depths less that 0.3, and the contribution of such cloud to this profile is expected to be small.)

Comparing the observed and simulated MISR histograms (top row), we see that the MMF produces too much cloud with cloud tops above 9 km (as already noted above in connection with Figure 2), while producing too little cloud with cloud tops below 9 km. Of particular interest is the peak in cloud fraction observed by MISR between 5 and 7 km. This altitude range typically includes the tropical freezing level, where a cloud layer has long been noted to preferentially form [Johnson et al., 1999] and is frequently captured in ground-based cloud radar observations [Hollars et al., 2004] and more recently by CloudSat [Marchand et al., 2009]. Figure 4 clearly demonstrates that the MMF, unfortunately, does not capture this freezing-level cloud.
At first glance, the ISCCP comparison (middle row) would seem to tell a somewhat different story. The ISCCP comparison suggests that the model produces too much high cloud, but only in the highest-altitude, lowest-pressure bin (cloud top pressure less than 180 hPa). Below this level, the ISCCP data suggest the model underpredicts the cloud fraction except near the surface where the ISCCP comparison indicates that the model overpredicts cloud amount (the opposite of what the MISR comparison shows for low clouds). The ISCCP observational data show no sign of a midlevel cloud peak.

A resolution of these apparent differences lies in understanding the difference between the retrieval algorithms used to produce the MISR and ISCCP data sets. The MISR retrieval of cloud top height is based on a stereo-imaging technique. This technique tends to return the altitude at which contrast in the observed scene occurs, which is not always the same as the top of the highest cloud. In particular, the MISR algorithm will often “see” through thin, high-level cloud and return the height of bright, lower-altitude cloud (especially broken clouds) in multilayer cases. A comparison of MISR cloud top height retrievals with ground-based radar and lidar data indicate that this typically occurs when the optical depth of the upper-level clouds is less than 1–2 [Marchand et al., 2007]. Because of this effect, the MISR data set will show smaller amounts of optically thin, high-altitude cloud and larger amounts of low cloud. The MISR low cloud fractions can also be expected to be larger because MISR detects more trade cumulus than ISCCP [Marchand et al., 2010]. We stress that the tendency of MISR to “see” through thin cloud is included in the MISR simulator (see Appendix A).

ISCCP, on the other hand, retrieves cloud top pressure by converting observations of infrared brightness temperature in combination with thermodynamic profiles of pressure and temperature. Many high clouds are sufficiently thin that they do not radiate like thermal black bodies and the observed infrared temperatures are increased by emissions from the surface or lower clouds. As a result, ISCCP retrievals of cloud top height for high-level clouds are sometimes biased into midlevels. For very thin clouds, on the other hand, ISCCP is sometimes able to detect a cloud but is unable to determine the cloud altitude. In this situation, ISCCP assigns the cloud top height to the lowest-pressure bin. Many, if not most, of the clouds appearing in the ISCCP highest-altitude and lowest–optical depth bin, the upper left corner of the histogram in Figure 4d, have been assigned to this altitude and may in fact be lower in altitude (see Marchand et al. [2010] for examples and further discussion on these topics). Thus, one should be cautious in comparing separately the distribution of ISCCP high-level and midlevel clouds with model output, and we generally recommend comparing the total amount of ISCCP high-level and midlevel clouds with the total model high-level and midlevel cloud amounts, as for example is done in Figure 4h.

Figure 3. Same as in Figure 2 except for low (L) clouds (cloud top heights less than 3 km).
Figures 4g and 4h plot the change in cloud fraction with optical depth. These plots are obtained in a similar fashion to the height profiles shown in Figures 4c and 4f, except by summing the values in the joint histograms along each column rather than along each row. Figure 4h includes only clouds with cloud top heights either above 3 km in altitude (MISR bins 8–17) or below 680 hPa in pressure (ISCCP bins 3–7). The legend gives the total (high + mid level) cloud fraction (again counting only clouds with an optical depth greater than 0.3). As one would expect from the previous discussion, this frame shows that MISR and ISCCP see very similar amounts of optically thick high-level and midlevel cloud, but ISCCP sees a great deal more optically thin cloud. We can take advantage of the differences between

Figure 4. Observed and simulated histograms of cloud top height and optical depth for the tropical western Pacific in 2001. (a) MISR and (d) ISCCP data and (b and e) equivalent MMF output (obtained via MISR and ISCCP instrument simulators). The cloud fraction (CF) for all clouds with an optical depth (tau) greater than 0.3 is listed at the top of each frame. Comparison of observed (retrieved) profiles of cloud fraction with cloud top height (for clouds with column optical depth greater than 0.3) with model output for (c) MISR and (f) ISCCP. (h) Comparison of the observed cloud fraction with optical depth for high-level and midlevel clouds (i.e., clouds above 3 km in the MISR data/simulator or below 680 hPa in the ISCCP data/simulator). The cloud fraction (high + mid) is given in the frame legend. The difference between ISCCP (high + mid) and MISR (high + mid) cloud fractions provides a rough estimate of the amount of multilayer cloud (in which the upper cloud is optically thin) and is given at the bottom of the frame (see text for more details). (g) Similar to Figure 4h, except for low clouds. The frame legend gives the observed low cloud fraction and an estimate for the true low cloud fraction, assuming that high-level and midlevel clouds randomly overlap low-level clouds (see text).
the two observational data sets to characterize the amount of such multilayer cloud. Subtracting the MISR (high + mid level) cloud fraction from the ISCCP (high level + midlevel) cloud amount yields a rough estimate of the amount of multilayer cloud. For the TWP, we therefore estimate the “thin multilayer cloud” amount at about 19% (which is also listed in Figure 4h). This estimate includes only multilayer clouds where the upper cloud is optically thin enough for MISR to “see” through it (optical depth less than ~1–2) and also thick enough for ISCCP to detect (optical depth greater than about 0.3). This estimate is based on a number of assumptions discussed in detail by Marchand et al. [2010] and is likely only accurate to a few percent.

[20] Comparison of the MMF MISR and ISCCP simulators with the observations in Figure 4h shows that the model produces too much optically thick cloud with cloud tops at high and mid levels. Perhaps coincidentally, the comparison of MISR observations with model simulated MISR output in the TWP shows that the model overestimate in high cloud is (almost completely) balanced by the under prediction of midlevel cloud such that the total amount of simulated high-level + midlevel cloud (~44%) is close to the observed MISR value (~40%). Examination of the ISCCP observations and simulations in Figure 4h similarly show that the model produces too much optically thick (optical depth > 10) high-level + midlevel cloud and, in addition, suggests the model also produces too little optically thin (0.3 < optical depth < 10) high-level + midlevel cloud. Not surprisingly, the amount of thin multilayer cloud produced by the model (~6.8%) is much smaller than the observed value (~19%). These same basic trends were found by McFarlane et al. [2007], when comparing MMF output with ARM cloud radar observations at Manus Island in the tropical western Pacific, with the exception of multilayer cloud amounts which were not examined in that study.

[21] Although both the MISR and ISCCP simulators show that the MMF produces too much high-altitude cloud, the MISR simulation indicates that the upper-level clouds are at about the right altitude while the ISCCP simulation indicates that the clouds are too high in altitude. While it is possible that most of this difference reflects the tendency of ISCCP to assign the optically thinnest cloud to the lowest-pressure bin, we note this assignment only occurs for optically thin clouds and the ISCCP comparison shows that model clouds are too high even for optically thick clouds. Rather, in the model, it appears that most high clouds have an extended region (near the top) with low ice crystal concentrations (and low optical thickness), such that, while the bulk of the cloud ice is near the correct altitude, true cloud top is too high. The MISR simulator “sees” through the thin upper cloud to the level where the cloud optical depth reaches a value of about 1–2 (Appendix A), whereas the ISCCP simulator is affected by this thin overlying cloud ice. Inspection of the CRM condensate fields shows that the MMF simulations commonly generated large amounts of extremely high-altitude, very low optical depth cloud (optical depth < 0.3) throughout the tropics. Zhang et al. [2008] reached this same conclusion when examining output from this same model using an 11 μm brightness temperature simulator.

[22] Comparison of observed and simulated low clouds is complicated by the fact that the ISCCP algorithm does not detect small boundary layer clouds as well as MISR and because the ISCCP algorithm sometimes locates low-level clouds too high in altitude [Marchand et al., 2010]. Therefore, we concentrate our analysis of the model low clouds using only MISR observations. Comparing MISR observations and simulator output in Figures 4c and 4g shows that the model produces too little low cloud and the cloud that is produced is too low in altitude and too optically thick.

[23] Because the model overpredicts the amount of optically thick, high-level cloud, one might expect the MISR simulator (which reports the location of the highest cloud top that MISR would observe) to show less low (and midlevel) cloud than it would if the model correctly predicted the amount of high-level cloud, and this might explain the apparent lack of model low cloud. However, if we assume that high-level and midlevel clouds randomly overlap low-level clouds, we can approximately account for the difference in the amount of high-level and midlevel clouds and estimate the true low-level cloud fraction. The legend in Figure 4h lists both the observed or simulated low-level cloud fraction and the estimated true value for each observation and model simulation. We see that, even correcting for differences in the high-level and midlevel cloud fraction, MISR observations indicate more low-level cloud (41%) than is produced by the model (29%).

[24] In summary, based on this analysis, we conclude, for the tropical western Pacific, the following:

[25] 1. The MMF produces too much high-altitude cloud with optical depths greater than about 10 and too little with optical depths between about 0.3 and 3.6. The data also suggest that the MMF may have too much cloud with very low optical depths (less than about 0.3). This very optically thin cloud may be too high (on average).

[26] 2. The MMF underestimates the amount and altitude of low cloud, which is also too optically thick.

[27] 3. The MMF underestimates the amount of multilayer cloud where the top layer is optically thin (with an optical depth greater than about 0.3 so that ISCCP can detect it but less than 1–2 so that MISR locates the underlying cloud).

[28] 4. The MMF does not adequately capture the formation of midlevel cloud near the freezing level. The midlevel cloud that is produced is too optically thick.

[29] We find these same trends occurring throughout the annual cycle and over most of the tropical ocean. Perhaps the only significant exception is in the Tropical Atlantic where (at least in 2001) the model appears to have underestimated, rather than overestimated, the amount of high-altitude cloud. The high cloud that was produced, however, remained too optically thick.

3.2. Subtropics

[30] In the subtropics, we examine the Hawaiian trade cumulus zone (defined here as 15°N–35°N and 140°W–160°E), the California stratocumulus zone (15°N–35°N and 110°W–140°W), and the South American stratocumulus zone (0°S–30°S and 70°W–100°W).

[31] The situation in the Hawaiian trade cumulus zone (Figure 5) is much like that found in the tropics. The model overpredicts the amount of cloud with cloud top heights above 9 km and underpredicts the amount of low cloud.
Model clouds (especially low clouds) are too optically thick, and the low cloud tops are too low in altitude. The situation at midlevels, however, differs from that found in the tropics. In the subtropics, the MISR retrievals show no midlevel cloud peak and the model total cloud fraction is in good agreement with the MISR observations between 3 and 9 km. The ISCCP retrievals, on the other hand, continue to show more midlevel cloud tops than are simulated by the model. This is likely an artifact in the ISCCP retrieval, which often misplaces cloud top at midlevels in multilayer cloud situations.

Figure 6 shows the observed and simulated histograms of cloud top height and optical depth for the California stratocumulus region. For high-altitude and midlevel clouds, the results are characteristically similar to what was observed in the Hawaiian trade cumulus zone, although the total amount of high-level and midlevel cloud is much less. For low-level clouds, the ISCCP and MISR observations both show larger cloud amounts and larger cloud optical depths (on average) than in the Hawaiian trade cumulus zone. (Note: different scales are used in frames g and h in Figures 5 and 6). While the model does show an increase in the amount of low cloud relative to that predicted in the Hawaiian trade cumulus zone, it nonetheless continues to significantly underestimate the cloud amount and overestimate the cloud optical depth relative to the observations.

MISR observations also show that low cloud tops are lower in altitude (on average) in the California stratocumulus zone than in the Hawaiian trade cumulus zone. This is not true of the ISCCP observations, which show low cloud tops that are higher in altitude (on average), with a larger fraction of tops in the 680–800 hPa pressure bin rather than the pressure bin closest to the surface (cloud top pressure greater than 800 hPa). A small percentage of the ISCCP low clouds even appear to be in the 680–560 hPa bin. Almost all of the low cloud observed by MISR is found to have a cloud top below 2 km (most is actually below 1.5 km), which if converted into equivalent cloud top pressure would appear
in the ISCCP pressure bin closest to the surface. It has long been recognized that ISCCP retrievals in stratocumulus regions tend to be biased high (in altitude) due to difficulties in converting observed IR temperatures to pressure in regions with strong temperature inversions [Wang et al., 1999] (see also examples, discussion, and additional references in the work of Marchand et al. [2010]). The ISCCP simulator cannot easily account for this bias in the observations, because the simulator has perfect information about the model's temperature profile, while the ISCCP retrievals use erroneous soundings and analyses without sharp inversions. Because of this high bias, along with the increased MISR's sensitivity to small broken clouds, we recommend that MISR retrievals be used (in combination with a MISR simulator) for the analysis of climate model low clouds, especially in stratocumulus or transition regions.

[34] Overall, the MISR data show that the model clouds (which are slightly too low in altitude in the Hawaiian trade cumulus zone) are much too low in altitude in the California stratocumulus zone. Visual examination of the MMF CRM output shows that much of the model cloud occurs in the lowest model vertical layer, as would be expected of fog. We observe characteristically similar results for the stratocumulus zones off the west coast of South American, Australia, and Africa. All of these stratocumulus zones have a significant seasonal cycle in both the amount of cloud cover and in the distribution of cloud horizontal size [Klein and Hartmann, 1993; Jensen et al., 2008]. Overall, we find the model does capture the seasonal cycle, if weakly. Figure 7 compares the seasonal cycle of MISR observed and modeled cloud top height and optical depth histograms for the South American stratocumulus zone. The MISR observations show low-altitude cloud fractions (for 2001) which are about 80% averaged over the 3 month period June, July, and August (JJA), as well as September, October, and November (SON), and lower (about 65%) in December, January, and February (DJF) and March, April, and May (MAM). The MISR observations also show that cloud
top altitudes are lower (on average) in JJA and SON than in DJF and MAM. The MMF captures the overall trends rather weakly. Although the model cloud top height is too low throughout the year, it is lower on average in JJA and SON. Also, while the model cloud fractions are too small throughout the year, the cloud fractions do increase from a low of about 43% in MAM to more than 49% in JJA and SON.

**Figure 7.** Seasonal cycle in observed and simulated MISR histograms of cloud top height and optical depth for the South American stratocumulus region. (left) MISR observations for 3 month intervals starting with December, January, and February (DJF) in the top row, and ending with September, October and November (SON) in the bottom row. (middle) The equivalent model output for the same period. (right) Comparison of profiles of cloud fraction with cloud top height for clouds with optical depths greater than 0.3.
3.3. Extratropics

Throughout the annual cycle, MISR cloud top height and optical depth histograms for the North Pacific (30°N–60°N, 140°W–160°E) show a bimodal structure, with a large optical depth and high-altitude cloud mode and a low optical depth and low-altitude mode (Figure 8a). The MMF output (Figure 8b) shows a large optical depth and high-altitude mode in rough agreement with the observations, but with somewhat larger optical depths and in slightly larger amounts than are observed (Figures 8c and 8g). MISR data show that high-altitude clouds are lower in altitude than in the tropics or subtropics, which is captured in the model, except during the summer season when model clouds generally appear to be too high (not shown). As in the tropical and subtropical regions, the model low clouds in the North Pacific are optically thicker and lower in altitude than observed. However, the total amount of low cloud in the North Pacific compares much more favorably with the observations than in the tropics or subtropics. The estimated true low cloud cover is about 65%–70% for ISCCP and MISR observational, data respectively, and only about 10% less than this value in the model.

Like MISR, the ISCCP joint histogram (Figure 8d) shows significant amounts of large optical depth and high-altitude cloud. Unlike MISR, the ISCCP data also shows large amounts of midlevel cloud, mostly at optical depths below 10. As in other regions, the presence of such midlevel clouds in the ISCCP observations and the lack of such midlevel clouds in the MISR observations are characteristic of multilayer clouds. The difference in the MISR and ISCCP observations suggests multilayer clouds with an optically thin upper cloud occur about 15% of the time in the North Pacific. In spite of the fact that the model is producing a large amount of low cloud, the model does not produce enough multilayer cloud. This may well be because (as in the other regions we have examined) the model does not
produce enough high-level cloud with optical depths between about 0.3 and 3.6. This should be interpreted to mean that the optical depth of most model high cloud is too large because the total amount of high cloud already slightly exceeds that observed.

[37] Comparisons of observations and MMF output for the North Atlantic and Southern oceans are similar to that shown here for the North Pacific. At higher latitudes (above 60° north or south), observations show that high-altitude clouds are lower in altitude and less abundant and low-altitude clouds are more abundant (though we note that the observations and analysis are limited to those times of year when sunlight is present and sea ice is not). The model captures these broad trends and may even overestimate the low cloud amount in some regions (not shown).

4. Sensitivity of the MMF to CRM Resolution

[38] The choice of 26 vertical layers for the original or baseline simulations was a natural starting point, since this is the vertical resolution used by the CAM, which forms the model’s outer grid. The 4 km horizontal grid, on the other hand, reflects a compromise between the large computational burden associated with running many thousands of CRMs for one or more years (of simulation time) and the higher resolution more typically used for cloud resolving or large-eddy simulations. While long duration simulations (e.g., more than 1 year) with higher horizontal and vertical resolution remain computationally prohibitive, it is reasonable to run simulations for a few months with modest increases in the resolution. In this section, we briefly compare the results of two short, 3 month sensitivity tests, in which the MMF was run with a 1 km horizontal grid, against the original MMF configuration, which has a 4 km horizontal grid. In the first run, the model vertical grid is kept the same, 26 vertical layers on a stretched grid (which we will hereafter call simulation 1KL26), while in the second run, the model vertical grid is increased to 52 layers (hereafter 1KL52). Here we examine the results of the third month of these simulations (November 2006), concentrating specifically on low clouds.

[39] Figure 9 compares the global change in low cloud amount simulated by the three model configurations with the low cloud amount observed by MISR. The MISR observations used here are an average of MISR data for November 2001 and 2007, which were the only 2 years of data available at the time this evaluation was initiated. At the large regional to global scale used in this analysis, the differences between the MISR data for these 2 years is small relative to the differences between the observations and model simulations. In all three simulations, the amount of low cloud remains significantly below the observed amount. Perhaps surprisingly, the amount of low cloud decreases rather than increases as the horizontal grid spacing of the model is decreased from 4 to 1 km and the vertical grid held fixed at 26 levels. The reduction in low cloud amount is not quite as severe as Figure 9 makes it appear because both 1 km simulations produce somewhat more high cloud than the 4 km simulation (not shown). Nonetheless, even if one accounts for the increase in high cloud, the result remains qualitatively similar with the 1KL26 simulation producing less total low cloud. The 1KL52 simulation produces a low cloud amount that is remarkably similar to the original configuration. However, the zonal plot of low cloud amount (Figure 9e) shows that the 1KL52 simulation produces slightly more cloud at some latitudes. This is primarily due to improved cloud properties in stratocumulus dominated regions.

[40] We examine the changes more closely in Figure 10, which compares cloud top height and optical depth histograms for the three model configurations with MISR observations for the South American stratocumulus region. The simulation with a 4 km horizontal grid frequently produces clouds that occupy the model layer closest to the surface in stratocumulus-dominated regions (see Figures 6 and 7). In the South American stratocumulus region, Figure 10b shows this same basic result for November. Figures 10e and 10f show the simulation results for 1KL26. These two frames, as well as the profile of cloud fraction with height in Figure 10d, indicate that, in this simulation, the clouds in the lowest model layer have largely dissipated, which lowers the total amount of cloud, increases the average cloud top height, and decreases the average cloud optical depth (see Figure 10g). In the 1KL52 simulation, Figures 10h and 10i, on the other hand, we see that although the total low cloud amount remains much below observed values, the low cloud amount increases above the amount in the 4 km simulation. The distribution of cloud top height is also in much better agreement with the MISR observations (Figure 10d), as is the distribution of cloud optical depth (see Figure 10g).

5. Sensitivity of the MISR Simulator to Resolution

[41] All of the model output depicted in sections 3 and 4 was processed using an ISCCP or MISR simulator. These simulators are applied to the MMF cloud resolving model (CRM) output, treating each vertical column in the CRM independently, that is, treating each column as if it is equivalent to a satellite pixel. As a result of this treatment, all cloud boundaries naturally align perfectly with the “simulated pixels” and there are no subpixel clouds or partially filled pixels. Here we examine the impact of these assumptions by modifying the MISR simulator so that the edges of the “simulated pixels” are randomly positioned with respect to CRM columns. This is accomplished by generating a uniform random variable from 0 to 1 (each time the simulator is called) and offsetting the edge of the simulated pixel from the CRM column by this fraction. The simulator then linearly combines the optical extinction (which is calculated on each of the original CRM columns) from two neighboring columns as depicted in the example in Figure 11.

[42] Figures 12 and 13 examine the effect of offsetting the instrument simulator pixels from the CRM grid for low clouds. Figures 12 and 13 compare the highest resolution simulation (1KL52) using the MISR simulator without any offset (labeled “baseline” in Figures 12 and 13) with two independent simulations using a random offset. In the first
of these two simulation, we use a random offset and retain the full 1 km horizontal resolution of the CRM (labeled “1 km rand”), while in the second simulation, the CRM grid is randomly offset and then averaged down to 4 km resolution (labeled “4 km rand”). The “1 km rand” approach emulates what a 1 km imager would do (roughly the nadir resolution of MISR), whereas “4 km rand” approach shows the nominal effect for a 4 km imager (similar to what might be expected for ISCCP near nadir).

[43] Offsetting the instrument simulator grid from the CRM grid increases the simulated low cloud fraction (Figure 12). Increasing the pixel size from 1 to 4 km further increases the apparent low cloud fraction. In spite of these increases, the model cloud amount remains too low. The largest increases in model cloud fraction occur in trade cumulus regions. We examine the situation more closely by comparing the cloud top height and optical depth histograms for the Hawaiian trade cumulus region (Figure 13). Figure 13
Figure 10. Observed and simulated histograms of cloud top height and optical depth for the South American stratocumulus region in November. (a) MISR observational data. (b, e, and h) Equivalent MMF output obtained using three different model resolutions (see text/Figure 9). (c, d, and i) The difference between the MISR data and the simulation in the frame to its left. Figure 10d shows a comparison of the observed profile of cloud fraction with cloud top height (for clouds with column optical depth greater than 0.3) with model output for all three simulations. The cloud fraction (CF) with an optical depth for (g) low clouds and (j) high-level and midlevel clouds, with the total cloud fraction (for clouds with optical depth greater than 0.3) given in the legend.
Figure 11. Example of offset between cloud resolving model (CRM) columns and simulated pixels. The example depicts two CRM columns with shaded areas representing cloud filled volumes. The left CRM section has a total optical depth of 5, and the right section has a total optical depth of 11. In this example, the simulated pixel is offset from the CRM columns by 2/3 of a CRM column. The simulated pixel has a total optical depth of 9, with \((10 \times 2/3 =) 6.67\) of the total in the upper level and the remainder in the lower vertical level.

(e especially Figure 13g) shows that the primary effect of the random offset and increased pixel size is to increase the amount of low cloud with optical depths less than about 10. There is no significant change in the amount of high-level or midlevel cloud nor is there much change in the amount of optically thick low-level cloud. The reason for this consistency is simply that model high-level and midlevel clouds, as well as optically thick model low-level clouds, tend to occur on spatial scales which are significantly larger than 4 km, such that increases in the amount of cloud which might come from partially filled edge pixels are small. The opposite is true of the optically thin low-level clouds, which tend to be horizontally smaller (more broken).

6. Summary and Future Directions

[44] Overall, we find that MMF simulations using a cloud resolving model with a 4 km horizontal grid and 26 vertical layers reproduce the broad pattern of tropical convergence zones, subtropical belts, and midlatitude storm tracks as observed by ISCCP and MISR. The model also captures seasonal trends in cloud amount, though often weakly, as the model frequently underpredicts the total cloud cover relative to observations (retrievals) by both ISCCP and MISR. The underprediction in total cloud cover is due primarily to an underprediction in the amount of low-altitude cloud and is particularly large in stratuscumulus dominated regions. The total amount of high-level cloud is overestimated in most regions (especially in the tropical western Pacific and Indian Ocean) but is about right in the North Pacific and North Atlantic. However, the model significantly overpredicts cloud optical depth at all altitudes and in all regions. The overprediction of cloud optical depth largely compensates for underprediction in the total cloud cover such that the model is able to generate a top-of-atmosphere outgoing shortwave flux that is comparable to observations on a global basis [see Khairoutdinov et al., 2008].

[45] We also find that the MMF (1) produces too much high-altitude cloud with optical depths greater than about 10, too little with optical depths between about 0.3 and 3.6, and too much cloud with very low optical depths (less than about 0.3); (2) underestimates the amount and altitude of low cloud in most regions, particularly in stratocumulus dominated areas; (3) does not capture the formation of midlevel cloud near the freezing level in the tropics; and (4) underestimates the amount of multilayer cloud where the top layer is optically thin (optical depth greater than about 0.3), so that ISCCP can detect it, but less than 1–2, so that MISR locates the underlying cloud. The underestimate is particularly noteworthy in the extratropics and tropics, where the observed thin multilayer cloud cover is typically observed to be 15% or larger.

[46] The response of model low clouds to modest increases in the resolution of the MMF cloud resolving model was examined. Model simulations with a 1 km horizontal grid and 26 vertical levels (1KL26) were found to dissipate much of the lowest-altitude model cloud. There was generally little change in the amount of low cloud with optical depths of less than about 10 and a net reduction in the total amount low cloud. Model simulations with a 1 km horizontal grid and 52 vertical levels (1KL52), on the other hand, were found to result in an increase in the total amount of low-level cloud. This increase was clearly associated with an increase in the amount of cloud with optical depths less than 10, bringing the model results into better agreement with MISR observational data. Nonetheless, the total amount of model low cloud remained much too low and there was still too much low cloud with large optical depths (greater than 23). The 1KL52 simulation also showed a significant improvement in the distribution of cloud top heights for low clouds in all regions, including the South American and California stratocumulus zones.

[47] Our analysis made synergistic use of MISR and ISCCP observations, taking advantage of the strengths of each data set, for example, the accuracy of MISR stereo heights for low clouds heights and clouds near the freezing level in the tropics and the greater sensitivity of ISCCP to optically thin, high-altitude clouds. The combination was also used to examine the occurrence of multilayer clouds and single-layer low clouds.

[48] Comparison with model output was facilitated using simple instrument simulators. We examined the effect of alignment between the MMF cloud resolving model grid and the MISR instrument simulator, as well as the role of the resolution used in the instrument simulators. This evaluation used the highest-resolution MMF simulation we have performed to date with a 1 km horizontal grid and 52 vertical levels. We found that a random offset between the model grid and the simulated “satellite pixels” increased the apparent cloud fraction of low cloud, primarily those with optical depths less than about 10, while generating no significant change in the amount of high-level or midlevel cloud. The amount of change was not large enough in this case to qualitatively alter any of the conclusions reached in the earlier analysis. The MISR and ISCCP instrument simulators are quite simple codes that primarily account for the effects of cloud overlap and treating clouds as uniform, single layers. The retrievals have other limitations and the results of this analysis, in particular, suggest that the effect of cloud element size on MISR and ISCCP cloud fractions is
another factor that may need to be incorporated into MISR and ISCCP instrument simulators in the future.

The improvement in model low clouds, as well as the need to further characterize the role of resolution in the instrument simulators, suggests that additional sensitivity simulations with somewhat higher horizontal resolution should be undertaken. MMF simulations run with higher horizontal resolution seem likely to generate smaller clouds and may well be able to reproduce the MISR observed distribution of cloud optical depth in trade cumulus-dominated regions, where the effect of broken clouds is largest. However, sufficiently increasing the vertical resolution in order to capture the formation of inversion-topped stratocumulus will be difficult. Accurate simulation of the cloud water content for stratocumulus clouds requires vertical grid spacing of perhaps 10 m or less [Bretherton et al., 1999; Stevens et al., 2002, 2003]. One potential solution to this problem is to use a model with an adaptive vertical grid (that is, a model that is able to add vertical layers where and when needed) rather than trying to use a fixed grid with high vertical resolution throughout the boundary layer. We are currently modifying the cloud resolving model used in the MMF to support an

Figure 12. Comparison of low-altitude cloud fraction (cloud top height less than 3 km) for November retrieved by MISR and simulated by the MMF model using simulator pixels offset from the CRM grid (see text). The “baseline” simulation uses 1 km horizontal resolution and 52 vertical layers. Frames same as Figure 9.
Figure 13. Comparison of cloud top height and optical depth histograms for the Hawaiian trade cumulus simulated by the MMF model using simulator pixels offset from the CRM grid (see text). The “baseline” simulation uses 1 km horizontal resolution and 52 vertical layers. Frames same as Figure 10.
adaptive vertical grid and initial results appear quite promising. We hope to test the adaptive grid as part of MMF simulations in the near future.

**Appendix A: Description of MISR CTH-OD Simulator**

The MISR CTH-OD simulator is a simple FORTRAN subroutine that estimates where MISR would likely retrieve the stereo height of a given model cloud field. The cloud field is defined by a matrix of visible wavelength extinction where, as is customary, the total column visible optical depth is given by the sum of the extinction in the column. The extinction values should be determined from the model cloud condensate in a fashion consistent with the model shortwave radiation code (which will vary from model to model). The structure of the MISR simulator subroutine call is nearly identical to that of the well-known ISCCP simulator [Klein and Jakob, 1999], except that one must input the physical height of model layers (in meters) rather than the layer pressures. As with the ISCCP simulator, the input cloud field can be obtained directly from a cloud resolving model (as we have done in this paper with the MMF) or using a domain profile average in conjunction with a sub-grid column generator [Klein and Jakob, 1999; Webb et al., 2001].

The MISR simulator estimates the stereo height using a set of simple rules obtained from comparison of the MISR stereo height retrieval with ground based radar and lidar systems [Marchand et al., 2007]. Strictly speaking, the tool described here might be termed an emulator rather than a simulator, since we do not use two- or three-dimensional radiative transfer to calculate multangle images from the model clouds and then use such as input to a MISR-like stereo height retrieval code. Rather we use a simple rule-based approach because (1) climate models (even the MMF) do not produce cloud fields with sufficient resolution to realistically simulate observed angular radiances [e.g., see Marchand and Ackerman, 2004; Ovchinnikov and Marchand, 2007] and (2) even if they did, the calculations would be far too computationally expensive. The key rules used in estimating the MISR stereo height from the model cloud field are as follows:

1. For columns with an optical depth greater than 0.3 but less than about 0.5, the simulated height is set to “NR” (no retrieval), because the MISR cloud mask would generally detect the cloud but the stereo height algorithm would usually not successfully locate a cloud top. (A possible exception to this rule would be to set the simulated height to the same height as neighboring pixels if the cloud is adjacent to a successful height retrieval. This would mimic the effective resolution of the MISR pattern matcher (~6 MISR pixels). We have not yet implemented (or examined the impact) of this exception clause. We mention it here because it is a likely expansion in later versions of the MISR simulator. In general, this extension could only be invoked if the resolution of the simulated cloud field is ~2 km or less). 

2. For single-layer clouds with optical depths greater than 0.5 and less than 1, the simulated height is set to true cloud top.

3. For single-layer clouds with an optical depth greater than 1, the simulated height is set to the altitude where the optical depth reaches 1 (as measured downward from true cloud top).

4. In multilayer cloud conditions involving a water layer OR a physically thick cloud with a mixture of ice and liquid water, if the level where liquid water exists is encountered before the optical depth (as measured from the true top of the cloud to the water level) reaches 2, than the simulated height is set to the altitude of the water layer. Otherwise the simulated height is located at the optical depth 1 level.

5. In multilayer cloud conditions involving only ice layers, the simulated height is set to the optical depth 1 level, in the first cloud encountered with a total optical depth greater than 1. If the total optical depth is larger than 0.5 but no cloud exceeds optical depth 1, the simulated height is set to top of the first cloud layer.

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