6.3 TESTING AGCM-PREDICTED CLOUD AND RADIATION PROPERTIES WITH ARM DATA: THE SUPER-PARAMETERIZATION APPROACH

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1. INTRODUCTION*

The sophistication of global climate models (GCMs) has increased dramatically over the last several decades naturally raising both the prospect and expectations of greater accuracy for their predictions. For the potential of latest advances to be fully realized, however, model development must go hand-in-hand with appropriate expansion of validation procedures to include more quantitative and strict tests of model performance. Such tests require the detailed observations of the evolving atmospheric state. Much of the recent success in this area can be attributed to continuous improvements in satellite remote sensing. These improvements include expansion of the fleet of satellites collecting observations from various instruments at multiple wavelengths and angles at high spatial resolution as well as development of more accurate retrieval algorithms. Despite the progress in remote sensing, application of the satellite-based approach to global model validation has important limitations, many of which are related to space-time sampling.

Instruments on sunsynchronous platforms make observations at high horizontal resolutions (down to under 100 m in some cases) and have the benefit of the global or near global coverage. However, depending on the swath of the instrument, it can take anywhere from one day to a few weeks to image the entire Earth. Consequently, it is impossible to observe the evolution of individual clouds with characteristic time scales of minutes and hours.

Currently geostationary satellites, on the other hand, do sample any point within their viewing area frequently but at much coarser spatial resolution and provide little information content on cloud vertical structure.

Ground-based observations represent a complementary alternative to the satellite approach by delivering much more detailed and complete measurements, albeit only at a few selected locations. The importance of comprehensive long-term local observations for climate studies has been long recognized and was largely behind the Atmospheric Radiation Measurement (ARM) program initiated by the US Department of Energy (DOE) in 1991. Since then, ARM has instrumented several operational sites worldwide and compiled an unprecedented archive of cloud, radiation as well as general meteorological observations. Most ground observations provide time series of a parameter or, at best, a vertical profile of the parameter measured at a specific location and usually averaged over some short period. These observations may come from instruments with a variety of fields of view that range from extremely narrow beams to hemispherical. In any case, the measurement differs from the model. The model output may well contain time series of parameters that are similarly averaged in time (although often over larger intervals) but in addition are subjected to implicit spatial averaging over gridcells with horizontal dimensions reaching hundreds kilometers on a side. Therefore, there is again an enormous discrepancy in time-space sampling that generally prevents direct model-to-observation comparison. Ergodicity, i.e., assuming that time-average and space- (or ensemble) average are equivalent, can be used sometimes (at least for mean values) but as with any other assumption must be carefully tested.

For the reasons stated above, the traditional parametric approach of diagnosing gridcell mean cloud and radiation properties from large-scale model fields is not well suited for comparison with observed time series at selected locations (Fig. 1). Another recently emerged approach called the super parameterization has shown promise to bridge the gap. Super parameterization (SP) consists of a two-dimensional cloud-resolving model (CRM) embedded into each grid of the NCAR Community Atmospheric Model (CAM) (Khairoutdinov and Randall, 2001). The approach provides for the first time an opportunity to more directly evaluate treatment of clouds and radiation in GCMs using long-term ARM observations. In this study, we explore this opportunity by comparing observations from two ARM sites to the

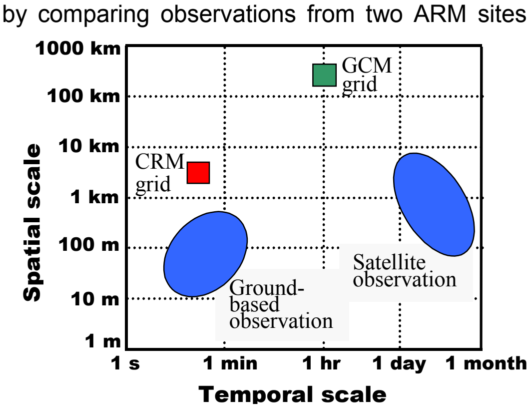

Fig. 1. *Characteristic temporal and spatial scales resolved by models and observations.*

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model output from both the CAM run and the run using super parameterization approach (CAM-SP).

The rest of the paper is organized as follows. Section 2 describes observations and model outputs used in the study. Sections 3, 4, and 5 present analysis of the cloud fraction, precipitation, and downwelling solar radiation flux at the surface, respectively. Finally, the results are summarized in section 6.

2. STATISTICAL APPROACH AND ANALYSIS METHODOLOGY.

The CAM-SP model setup is described in detail by Khairoutdinov and Randall (2001) and only briefly summarized here. The CAM has 26 layers in vertical (stretched grid) and T42 horizontal (spectral) resolution, which corresponds to grid size of 2.8º x 2.8º. Thus, each gridcell represents area of approximately 300 x 300 km^2 in the tropics. The CRM has 64 columns at 4 km spacing and 24 layers in vertical coinciding with the lowest 24 CAM levels. Time steps are 1 hour for CAM and 20 seconds for CRM.

Our choice of the time periods for the comparison is determined largely by the only few years worth of CAM-SP simulations that are presently available. Two sets of model runs are analyzed in this study: one using climatological sea surface temperatures (SSTs) and another using the observed SSTs for the year of 1999. Each set consists of a CAM run with standard cloud and radiation parameterization as well as a CAM-SP run employing the superparameterization. Each simulation covers a period from October to the end of the following year. However, in order to prevent seasonal bias, only one full year worth of data (January through December) is analyzed meaning that the first fall season is excluded from consideration. In this study, we look only at the yearly statistics, although we realize that there are important aspects of seasonal and diurnal variability that need and will be addressed in the future.

Comparison is done for the Tropical Western Pacific (TWP) and Southern Great Plain (SGP) ARM sites. The two TWP sites are located at the island of Nauru (0.521ºS, 166.916ºE) and Manus Island (2.058ºS, 147.425ºE). The model grid cell closest to Nauru's coordinates is centered at (1.395ºS, 165.938ºE) or about 150 km to the southwest of Nauru. SGP Central Facility is located at (97.50ºW, 36.617ºN).

Obviously, comparison of the climatological SST set of runs with the runs for the real SST for the single year does not allow for comprehensive study of the inter-annual variability in model simulations. Nevertheless even this limited analysis can provide an initial assessment of model strengths and weaknesses and identify potential problem areas for future research.

There could be a smaller bias introduced by missing observations. For the Nauru ARM site, we use three years worth of data from November 1, 1998 through October 31, 2001. The total number of days is 1096, or 8768 3-hour periods. Of those, the radar data are available for 5648 periods (about 64%) and broadband solar radiation measurements are available for 8635 periods (including night periods), or about 98.5%.

For the SGP ARM site, we use four years worth of data from September 1, 1998 through August 31, 2002. The total number of days is 1461, or 11688 3-hour periods. Of those, the radar data are available for 9870 periods or 84%, precipitation measurements for 10883 or 93%, broadband solar radiation measurements are available for 1409 days, or about 96%.

In general, we should expect larger extremes and more variability in point measurements than in the SP strip model, which in turn should be more variable than the mean CAM grid-cell properties.

3. CLOUD FRACTION

Cloud fractions analyzed here are determined as follows. For any model column, the CAM cloud fraction (CF) is taken as predicted by the cloud parameterization and averaged over one or three hours, as indicated below. In the CAM-SP simulation all cloud are predicted explicitly and the domain CF at any time is defined as the ratio of the number of cloudy columns to the number of clear columns. Similarly to the CAM CF, the CAM-SP CF used here is averaged over same period. Although time averaging is used in the analysis, both these CFs are instantaneously defined for a prescribed area. In contrast, CF derived from the vertically pointing cloud radar is defined only for a time series as a number of observations with returned signal exceeding specified threshold to the total number of observations over that period. In order to mimic such observations, CF was also computed for a single column of the CAM-SP. These column data are available for the 1999 run only.

3.1 TWP site

Table 1 and Fig. 2 present comparison of model predicted CF from the runs with climatological SSTs with radar derived CF at Nauru. Compared to observations, CAM greatly overpredicts completely overcast conditions, while CAM-SP simulation seems to lacks this regime. Note that the latter discrepancy could be, at least partially, due to the sampling difference discussed earlier, that is one can still have 100% cloud cover at the ARM site without 100% cloud cover over the entire CSRM domain. The CAM statistics on the other hand is clearly unrealistic since an overcast condition over a larger area (as in CAM run) must also be observed at any location within this area. It is certainly ture that the radar doesn't observe all tropical cirrus, but even taking this factor into account the CAM is overpredicting the cloud occurence.

Comparison of cloud fractions for low (below 700 mb), middle (between 700 and 400 mb), and high (above 400 mb) level clouds reveals that the overcast conditions in the CAM run are primarily due to high-level (cirrus) clouds. This known shortcoming of the traditional cloud scheme is corrected, and perhaps overcorrected in the CAM-SP run, in which overcast conditions are extremely rare in any 3-hour period.

Table 1. Parameters of total cloud fraction distributions for the TWP.

	Nauru obs	CAM-SP	CAM
Mean	0.55	0.30	0.84
Median	0.53	0.27	0.99
Std Deviation	0.33	0.21	0.27
Variance	0.11	0.04	0.07

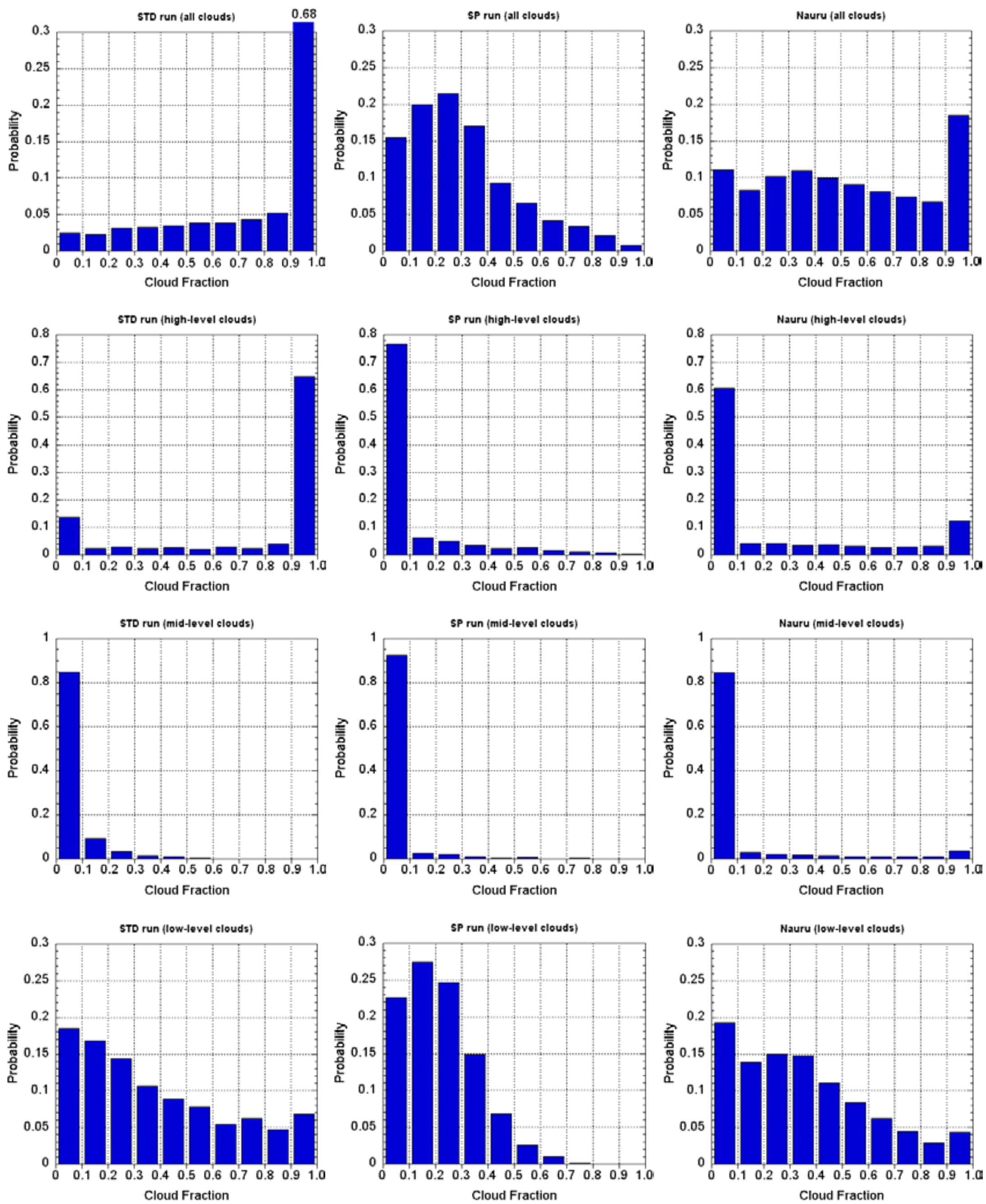

Fig. 2. *Histograms of cloud fractions from CAM (left column) and CAM-SP (middle column) runs and from Nauru cloud radar (right column). Four rows from top to bottom show cloud fractions for all, high, middle, and low-level clouds. The histograms are constructed by grouping all 3-hour average values into ten cloud fraction intervals. Model cloud fractions are taken at the grid cell covering the Nauru location.*

Table 2. Parameters of total cloud fraction distributions for the SGP site.

	SGP obs	CAM-SP	CAM
Mean	0.48	0.22	0.31
Median	0.43	0	0
Std Deviation	0.43	0.34	0.43

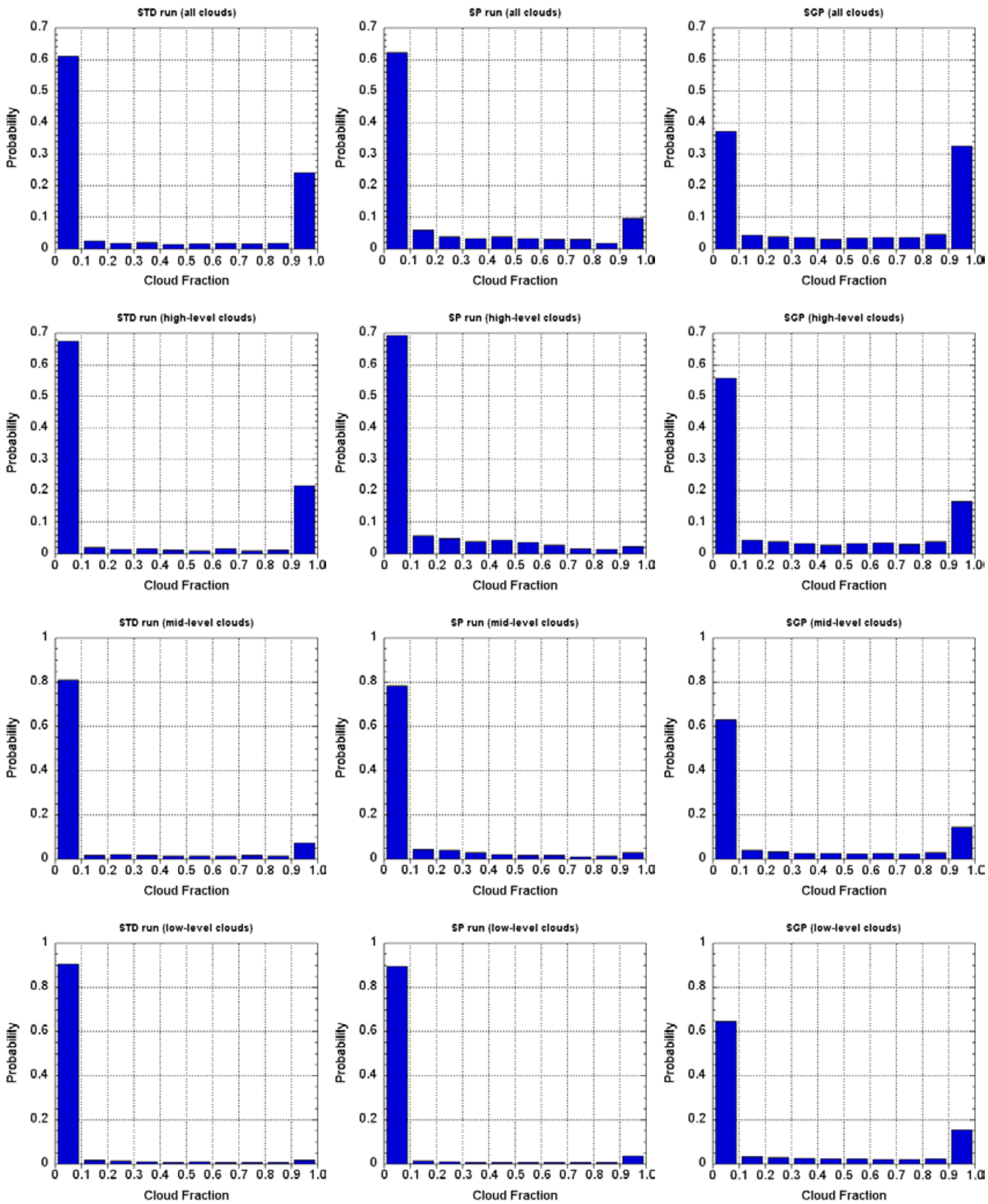

Fig. 3. *Same as Fig. 2 but for the SGP site.*

Comparison of the low-level cloudiness is less conclusive. There are at least two complicating factors. First, small cumulus clouds, which are a prominent feature in the tropics, are not well resolved on the 4-km SP grid. Second, radar derived cloud statistics could be contaminated by the island effect, which will be most pronounced in low-level cloud observations. One recent study has shown that the frequency of cloud occurrence

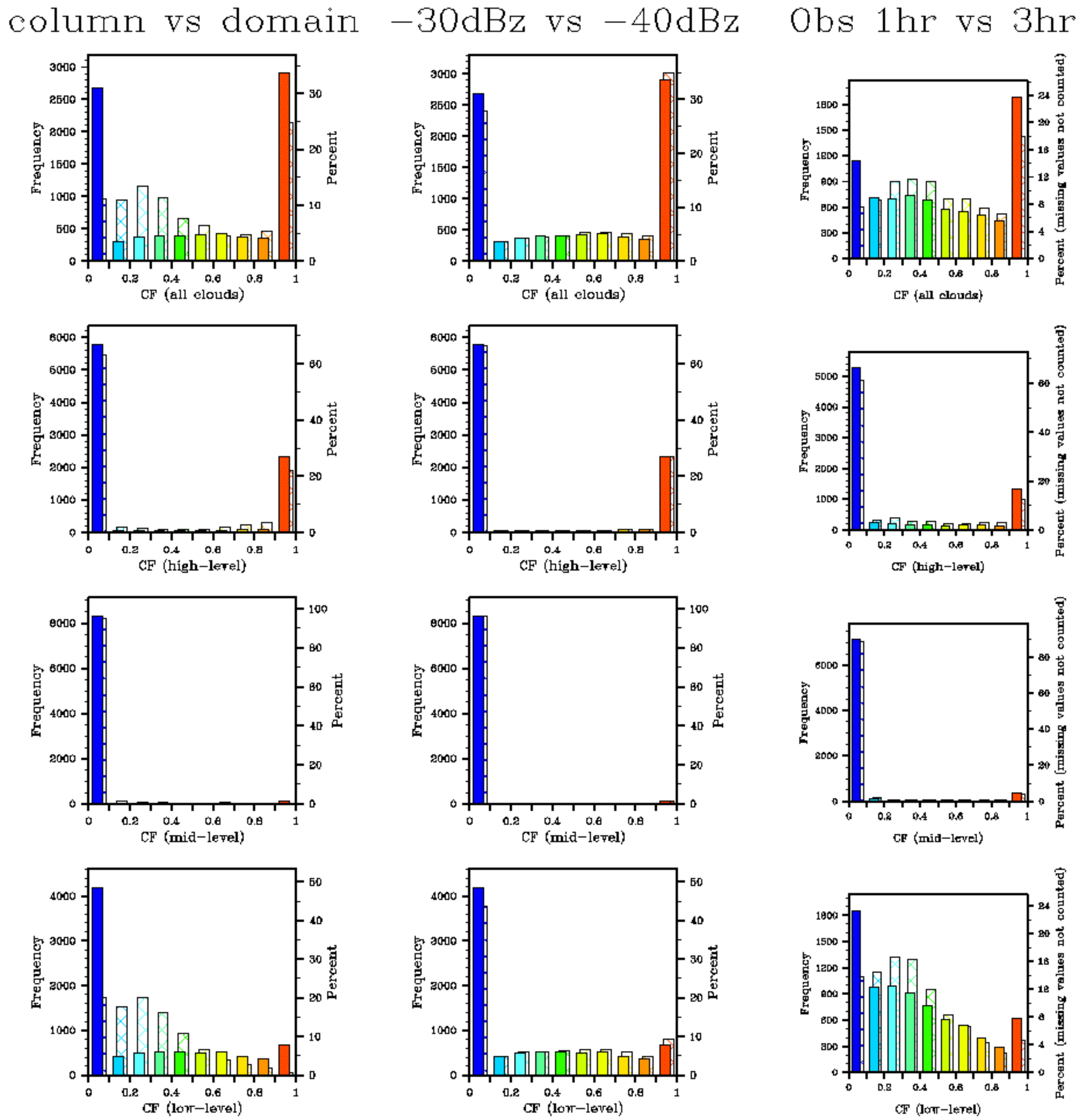

Fig. 4. *Histograms of cloud fraction for 1999 from CAM-SP (left and middle column) and from Nauru cloud radar (right column). Rows from top to bottom show CF for all, high, middle, and low-level clouds. See text for further discussion.*

can be up to 10% higher on the downwind side of the island compared to the upwind side (McFarlane et al., 2003).

3.2 SGP site

Table 2 and Fig. 3 show comparison of model predicted CF from the runs with climatological SSTs with radar derived CF at the SGP site. Both model runs underpredict the total cloud amount.at all levels, the only exception being the overprediction of overcast high-level clouds in the CAM run.

3.3 Sensitivity study

The CAM–SP framework allows us to explore the effects of various definitions of cloud fraction. Fig. 4 illustrates two examples from the 1999 run. Whether CF is calculated spatially for the domain or temporally for the column has very strong effect on the low-level CF while the influence on the mid- and high-level statistics is negligible (Fig. 4, left column). The result is to be expected since horizontal extent of cirrus clouds is usually much larger than that of low-level clouds. Thus, for example, the column contains low-level clouds for the whole hour about 8 percent of the time, while the probability of the domain CF being equal to one is close to zero. Compared to the radar observations in 1999 (Fig. 4, right column), CF from the model column is underpredicting small CF and overpredicting large CF, largely due to 4-km horizontal resolution, which is too coarse to resolve many cumulus clouds.

Second sensitivity test addresses the issue of determining the cloud boundary. For that the CF was computed for the CRM column using two cloud thresholds:

(1) IWC > 0.0165 g m^{-3} or LWC > 0.136 g m^{-3} , and

(2) IWC > 0.0042 g m^{-3} or LWC > 0.038 g m^{-3}.

The first threshold roughly corresponds to ~ -30 dBZ and the second threshold corresponds to ~ -40 dBZ. The effect of this change is small and once again affects primarily low-level clouds.

Finally, we study the effect of the time period used to obtain CF from radar observations. Predictably, the longer time period results in the narrower distribution of CF.

4. PRECIPITATION

Precipitation is one of the major components of the water cycle. Prediction of both the total amount and the distribution of the intensity of precipitation is important. We start with the analysis of the annual precipitation amounts.

In the standard CAM setup, the total precipitation analyzed here includes both convective (subgrid) and stratiform (resolved) components, which are predicted separately. In the tropics, the effect of stratiform precipitation is minimal, while in mid-latitudes both components can be important (Fig. 5). There is no such division in the CAM-SP setting as all precipitation comes from explicitly resolved clouds.

4.1 TWP site

Table 3 summarizes results from two sets of runs and observations from the TWP site: the first set is forced with climatological SST and the second with 1999 SSTs. 1999 was a La Niña year of medium strength according to the Multivariate El Niño/Southern Oscillation (ENSO) Index (MEI) (http://www.cdc.noaa.gov/~kew/MEI/). At Nauru, this ENSO phase usually corresponds to a negative precipitation anomaly during November through March period and near normal precipitation for May through September period. Accordingly, the observed annual precipitation in 1999 is only 358 mm or 55% of the 1998-2002 average of 637 mm.

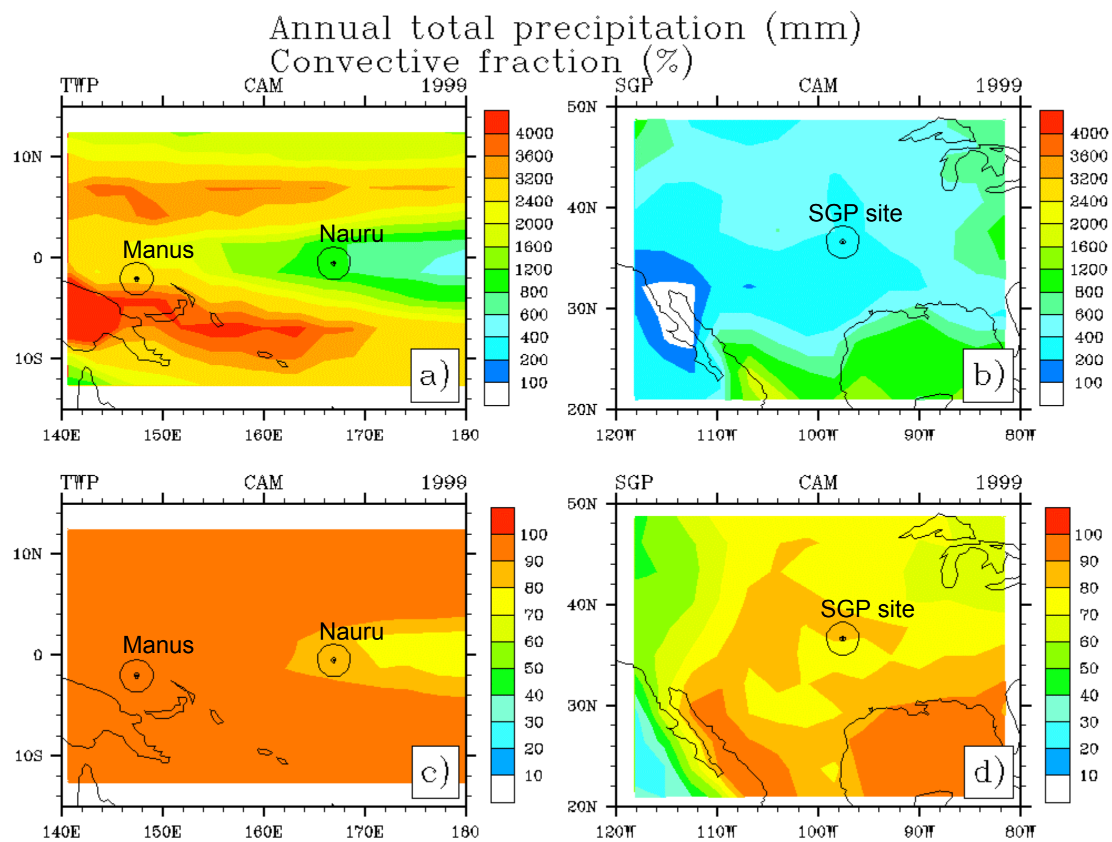

Fig. 5. CAM predicted a*nnual total precipitation amount (top) and its percentage from convective parameterization (bottom)for the TWP (left) and SGP (right) regions. Centers of the open circles indicate locations of the ARM observation sites.*

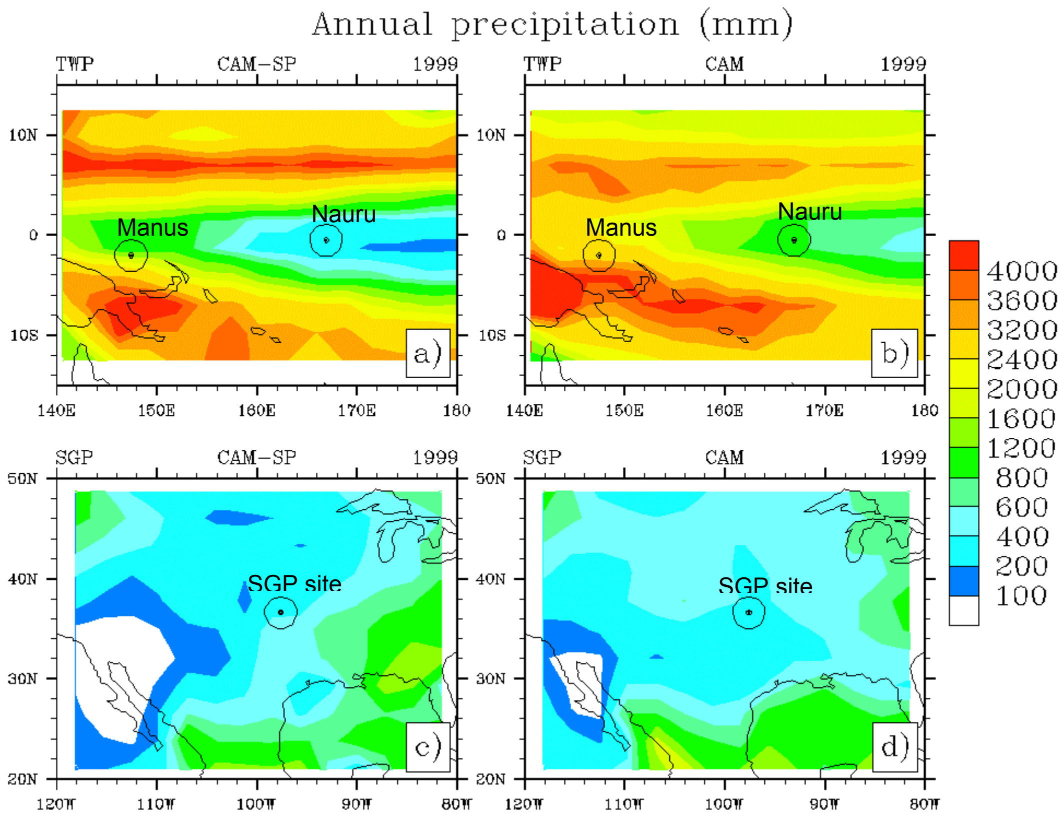

Fig. 6. *Total annual precipitation amount as predicted by CAM-SP (left column) and CAM (right column) for TWP (top row) and SGP (bottom row) regions for 1999.*

Table 3. Total annual precipitation at the ARM TWP Nauru site and at four surrounding model gridpoints in mm.

	CAM		**CAM-SP**		**Nauru** 166.9° E, 0.5° S
	165.9° E, 1.4° N	168.7° E, 1.4° N	165.9° E, 1.4° N	168.7° E, 1.4° N	
	Mean		**Mean**		
	165.9° E, 1.4° S	168.7° E, 1.4° S	165.9° E, 1.4° S	168.7° E, 1.4° S	
Climate	1429	1315	700	613	
	1309		**677**		**637**
	1235	1258	781	615	
Year 1999	906	764	393	308	
	826		**286**		**358**
	884	750	216	227	

Table 4. Total annual precipitation at the ARM SGP CF site and at four surrounding model gridpoints in mm.

	CAM		**CAM-SP**		**SGP** 97.5° W, 36.6° N
	98.4° W, 37.7° N	95.6° W, 37.7° N	98.4° W, 37.7° N	95.6° W, 37.7° N	
	Mean		**Mean**		
	98.4° W, 34.9° N	95.6° W, 34.9° N	98.4° W, 34.9° N	95.6° W, 34.9° N	
Climate	480	520	468	603	
	431		**478**		**878**
	328	397	395	444	
Year 1999	392	390	294	302	
	319		**407**		**1031**
	217	278	510	522	

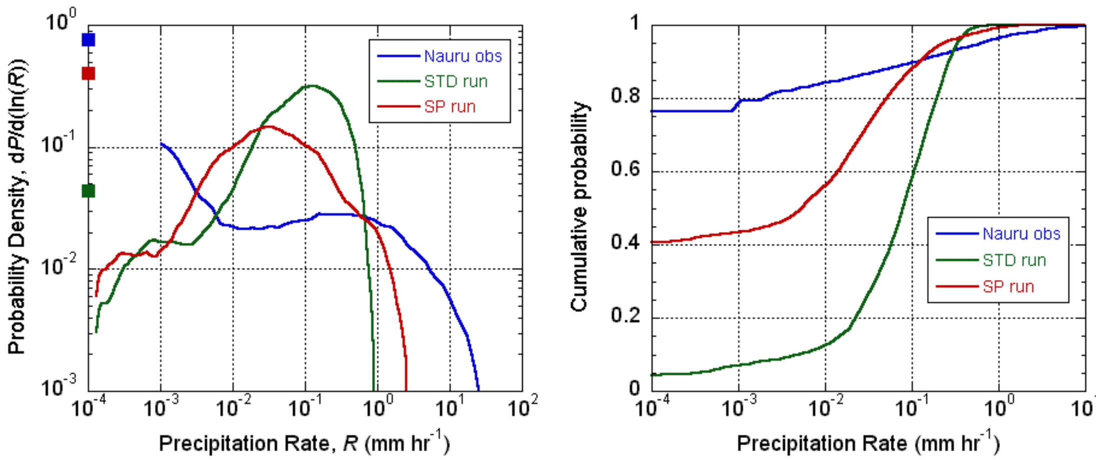

Fig. 7. *Probability distribution functions (a) and cumulative probability distributions (b) of precipitation rate from CAM (green) and CAM-SP (red) runs and from observations at Nauru (blue). Squares on (a) indicate the probability of precipitation rate smaller than 10^{-4} mm hr^{-1}.*

Table 5. Parameters of total precipitation rate distributions.

	Nauru	CAM-SP run	CAM run
Minimum (mm hr^{-1})	0	0	0
Maximum (mm hr^{-1})	35.8	3.1	1.2
Mean (mm hr^{-1})	0.12	0.09	0.17
Median (mm hr^{-1})	0	0.009	0.12
Std Deviation (mm hr^{-1})	0.90	0.27	0.17

Table 6. Parameters of total precipitation rate distributions.

	SGP	CAM-SP run	CAM run
Minimum (mm hr^{-1})	0	0	0
Maximum (mm hr^{-1})	119	3.0	2.2
Mean (mm hr^{-1})	0.11	0.05	0.05
Median (mm hr^{-1})	0	0	0
Std Deviation (mm hr^{-1})	1.37	0.25	0.18

CAM-SP simulation results are in close agreement with observations both in annual precipitation amount and in predicting a relatively dry year in 1999. In the two CAM simulations, the precipitation is overestimated by a factor of two or more although the relative reduction for the year 1999 compared to climatology is still captured.

The CAM-SP 1999 run is characterized by strong north-south gradient at this location. In fact, the mean of the four neighboring points (286 mm) is closer to the observations (358 mm) than is precipitation at the grid point closest to the Nauru (216 mm).

Probability distribution functions of three-hour average precipitation rates from meteorological observations at Nauru and from GCM runs with standard and superparameterization treatment of clouds are shown in Fig. 7.

All data are consistently averaged in time (over a three-hour period), but the spatial averaging is very different. Observations represent point measurements with no spatial averaging, SP statistics correspond to a strip of 64 columns (area 256 x 4 km^2), and standard parameterization provides mean values for the GCM grid (roughly 300 x 300 km^2). In the tropics, with precipitation dominated by convection, it is likely that the precipitation rate at points 100 km apart are statistically independent (or at best weakly correlated), although the precipitation distributions at points 4 km apart (as in the adjacent SP columns) could be highly correlated.

While the probability distributions on Fig. 7 look very different they are not necessarily inconsistent with each other. To illustrate the point, we construct a hypothetical domain containing 2, 4, 8, and 16 statistically independent regions such that distribution within each region is the same as that measured at Nauru. (fig. 8). (Numerically, we construct new time series by averaging the required number of randomly rearranged original (observed) time series, which mathematically represent convolving the original pdf 2, 4, 8, and 16 times, respectively.)

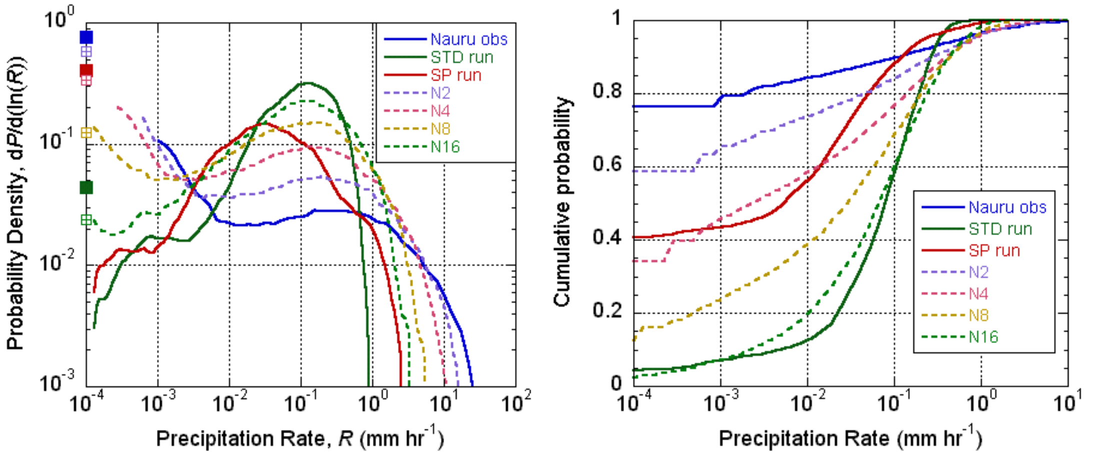

Fig. 8. *Same as Fig. 7 but with added probability distributions of precipitation rate from a hypothetical domain containing 2, 4, 8, and 16 statistically independent regions with identical pdf's.*

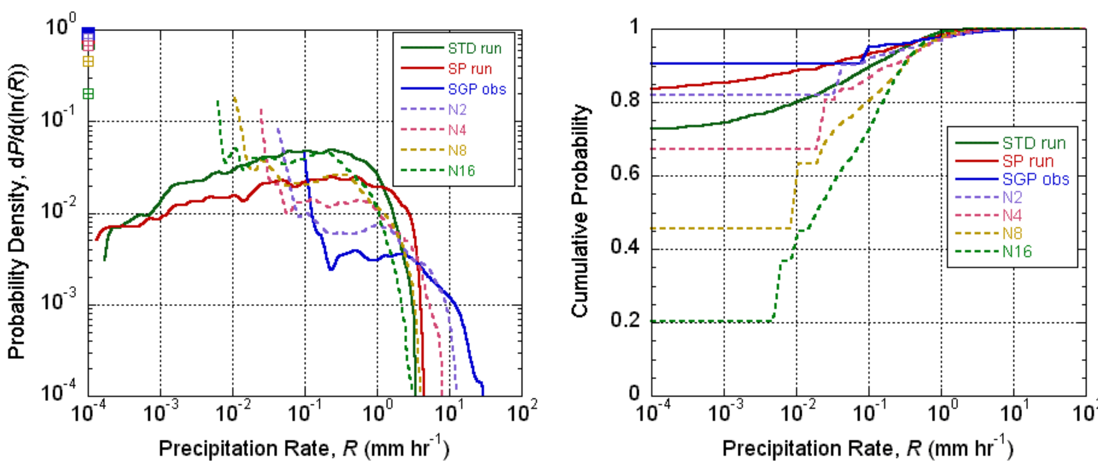

Fig. 9. *Same as Fig. 8 but for SGP site.*

The simplified example above is for illustrative purpose only. In reality, various precipitation events will have different correlation scales in time and space and the result may not be well approximated by a simple averaging of independent samples.

4.2 SGP site

For the northern Oklahoma region, La Niña years generally correlate with drier than normal conditions. In 1999, however, a notable positive precipitation anomaly was observed at the SGP site (Table 6) with total precipitation for the year exceeding the multi-year average by 15%. Verifying that this is not an instrumental artifact, the increased precipitation for the region in 1999 is also confirmed by the three Oklahoma Mesonet stations surrounding the CF. The sites near Medford (20 km to the NW), Blackwell (20 km to the NE), and Breckinridge (30 km to the SW) reported 1199, 1468, and 1255 mm, respectively, well about the normal annual precipitation of about 890 mm for the 1971-2000 period (http://climate.ocs.ou.edu/normals_extremes.html).

The model fails to produce enough precipitation in the area, regardless of the cloud treatment. Both CAM and CAM-SP runs predict only about half of the observed annual precipitation amount in the simulations. Moreover, in contrast to observations, both models show 1999 as the drier year compare to climatology by 20 to 25%.

There are several possible reasons for the apparent lack of improvement in CAM-SP predictions for the SGP region compared to the TWP region. First of all, although the convection is still the primary source of precipitation in the SGP (Fig, 5), the large scale dynamical forcing is much more complicated and important in mid-latitudes compared to the tropics. Exchanges between CAM columns and the surface as well as interactions among these CAM columns are handled on a large scale and are not affected much by the embedded CSRMs. In addition, part of the precipitation in this region falls as snow, which introduces more uncertainty in both simulations and observations.

5. SOLAR RADIATION AT THE SURFACE

Only net solar and longwave radiative fluxes at the surface were saved from the model climatological runs, while the measured quantities are the downwelling fluxes. For comparison purposes, the solar downwelling flux ($\boldsymbol{F}_{\text{down}}$) is converted to the net solar surface flux ($\boldsymbol{F}_{\text{net}}$) using $\boldsymbol{F}_{\text{net}} = (1 - \alpha)\, \boldsymbol{F}_{\text{down}}$, where albedo α was set to 0.07. Because the conversion is rather arbitrary, we focus on the shape rather than the position of the probability distribution. In the future run, we will save the simulated downwelling solar surface flux to make the comparison more quantitative.

The CAM run distribution is broader and has more low-values of flux than either the CAM-SP or observed distributions, which is consistent with CAM run also having largest mean cloud fraction (Table 1). CAM-SP run has narrower distribution than the observed one, again as one would expect from the cloud fraction analysis. Note, that cloud fraction statistics for 3-hour periods around local noon (not shown) are a little noisier (due to shorter time series) but generally differ only slightly from the statistics for all of the periods (Fig. 2).

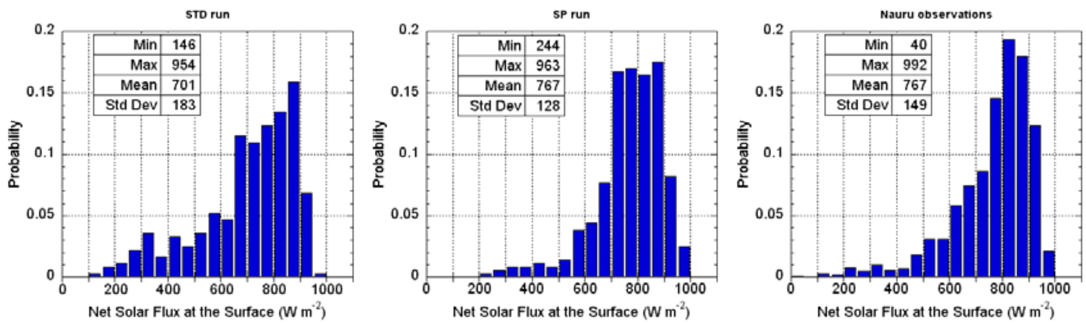

Fig. 11. *Probability distributions of net solar surface flux at Nauru. Flux is averaged over three-hour period around local noon.*

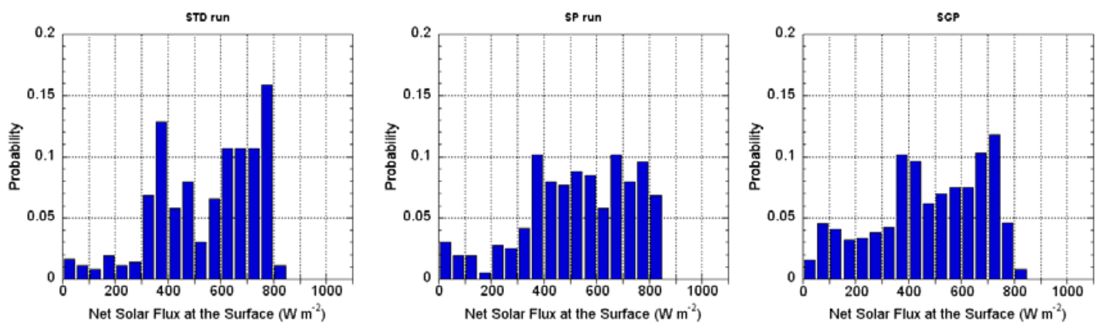

Fig. 12. *Same as Fig. 11 but for SGP site.*

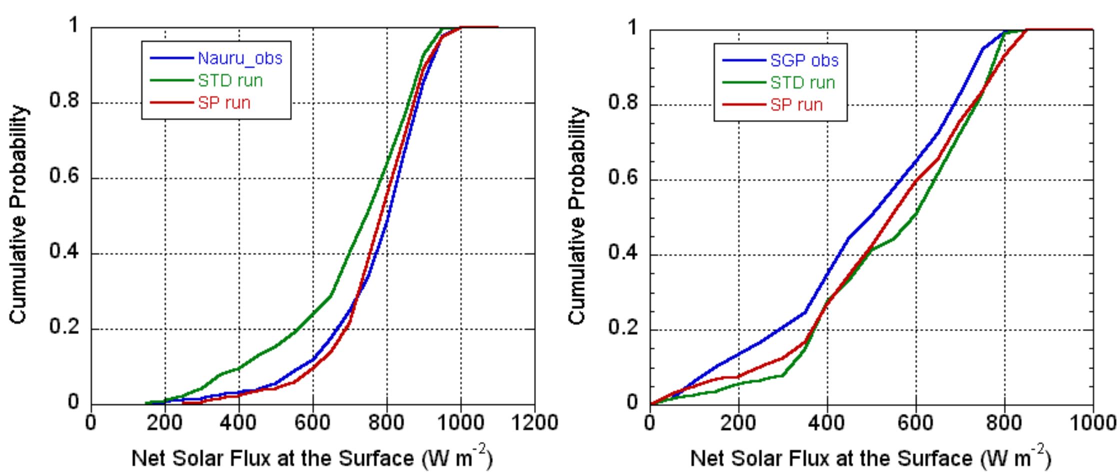

Fig. 13. *Cumulative probability distributions of net solar surface flux at Nauru (left) and SGP (right) site.*

Table 7. Parameters of net solar radiation flux distributions at the surface around local noon at Nauru.

	Nauru	CAM-SP run	CAM run
Minimum ($W\ m^{-2}$)	40	244	146
Maximum ($W\ m^{-2}$)	992	963	954
Mean ($W\ m^{-2}$)	767	767	701
Median ($W\ m^{-2}$)	805	786	745
Std Deviation ($W\ m^{-2}$)	149	128	183

Table 8. Parameters of net solar radiation flux distributions at the surface around local noon at SGP.

	SGP	CAM-SP run	CAM run
Minimum ($W\ m^{-2}$)	5.6	23	19
Maximum ($W\ m^{-2}$)	818	824	803
Mean ($W\ m^{-2}$)	478	529	547
Median ($W\ m^{-2}$)	494	546	591
Std Deviation ($W\ m^{-2}$)	207	204	190

6. DISCUSSION AND CONCLUSIONS

By explicitly resolving clouds, the CAM-SP framework notably improves the prediction of precipitation and cloud amount, as well as the net solar radiation flux in the tropics.

It is important to realize that cloud fraction in traditional GCM parameterizations is an intermediate parameter generated by a cloud scheme and injected into radiation and other parameterizations, which in turn compute the effects of the cloud fields. For the model to perform well, the cloud fraction does not have to be realistic as long as the resulting energetics (e.g., latent heat release, precipitation rate, and cloud radiative forcing) is correct. The latter is the primary driver for the GCM and is often achieved by tuning cloud and radiation parameterizations. We want the cloud fraction to be realistic, however, not only because cloud amount is one of the more easily observable parameters but also because clouds represent a physical link between many thermodynamic, radiative, chemical, and other processes. Thus, it is imperative to test the model ability to represent real cloud fields, not just the effects of the cloud fields. The combination of ARM data and CAM-SP simulations provides a unique framework for such a test. We also note that adjusting GCM parameterizations to obtain the correct fluxes at the top of the atmosphere (as is frequent done) does not guarantee that the distribution of surface fluxes and precipitation will be correct, and in fact the results shown here indicate that the CAM model is having some difficulty with these quantities.

7. REFERENCES

Khairoutdinov, M. F., and D. A. Randall, 2001: A cloud resolving model as a cloud parameterization in the NCAR Community Climate Model: Preliminary results. *Geophys. Res. Lett.,* **28**, 3617-3620.