A Strategy for Testing the Impact of Clouds on the Shortwave Radiation Budget of General Circulation Models: A Prototype for the Atmospheric Radiation Measurement Program

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Cloud-climate interactions are one of the greatest uncertainties in contemporary general circulation models (GCMs) (Cess et al. 1989, 1990), and the present study has focused on one aspect of this. Specifically, combined satellite and near-surface shortwave (SW) flux measurements have been used to test the impact of clouds on the SW radiation budget of two GCMs. Concentration is initially on SW rather than longwave (LW) radiation because, as will be discussed shortly, in one of the GCMs used in this study an SW radiation inconsistency causes, at least in part, a LW inconsistency. Thus, there is no logic in testing the LW cloud interactions until the SW problem has been rectified.

The surface data consist of near-surface insolation measured by the upward facing pyranometer at the Boulder Atmospheric Observatory (BAO) tower located approximately 25 km north of Denver. The tower is surrounded by dry-plains agricultural land typical of the adjoining several hundred square kilometers ranging to the east (Cess et al. 1991). These insolation measurements are provided as hourly means. The satellite data consist of top of the atmosphere (TOA) albedo data, collocated with the tower location, as determined from the Geostationary Operational Environmental Satellite (GOES) SW spin-scan radiometer. Although this is an uncalibrated and filtered (i.e., narrow band) instrument, simultaneous calibration and unfiltering were achieved through collocation of GOES and Earth Radiation Budget Experiment (ERBE) pixels. The advantage of using GOES measurements is its high sampling rate. Measurements, collocated with the tower, are made every half hour, with hourly means taken by averaging successive measurements. The combined data are for a 21-day period encompassing 28 June through 18 July 1987 and consist of 202 combined albedo/insolation measurements.

For current purposes, the tower insolation has been normalized by the cosine of the solar zenith, μ, so as to minimize the dependence on solar zenith angle. Although this dependance remains as a secondary effect, the primary variability is caused by cloudiness variability; low albedo and high insolation/μ correspond to clear days, with the reverse coinciding with heavily overcast conditions.

Two GCMs have initially been adopted for comparison with the GOES/tower data; Version 2 of the NCAR Community Climate Model (CCM2) and Cycle 33 of the European Centre for Medium-Range Weather Forecasts (ECMWF). The CCM2 results are for a spectral truncation of T42 and for a perpetual July, and T106 and a seasonal July for ECMWF. For both GCMs, output was selected for a single grid point coinciding with the location of the BAO tower.

In Figure 1, GCM-produced monthly-mean albedos and insolation/μ are compared with the 21-day means from GOES and the BAO tower. That CCM2 underestimates the albedo is consistent with its overestimate of insolation/μ; the model either underestimates cloud cover or cloud brightness. The situation is reversed for ECMWF, although the differences are far more modest. If we were to stop right here, it would be concluded that ECMWF is the better model. But the data provide far more information.

The albedo histograms in Figure 1 amply demonstrate this. Progressing from left to right corresponds to increasing

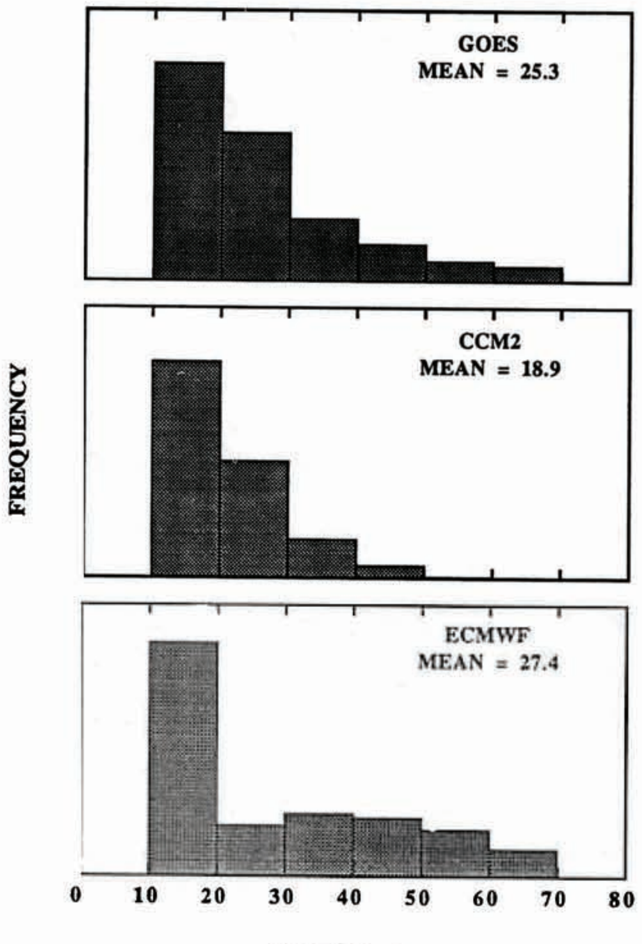

Figure 1. Top of the atmosphere albedos as measured by GOES and from CCM2 and the ECMWF GCM.

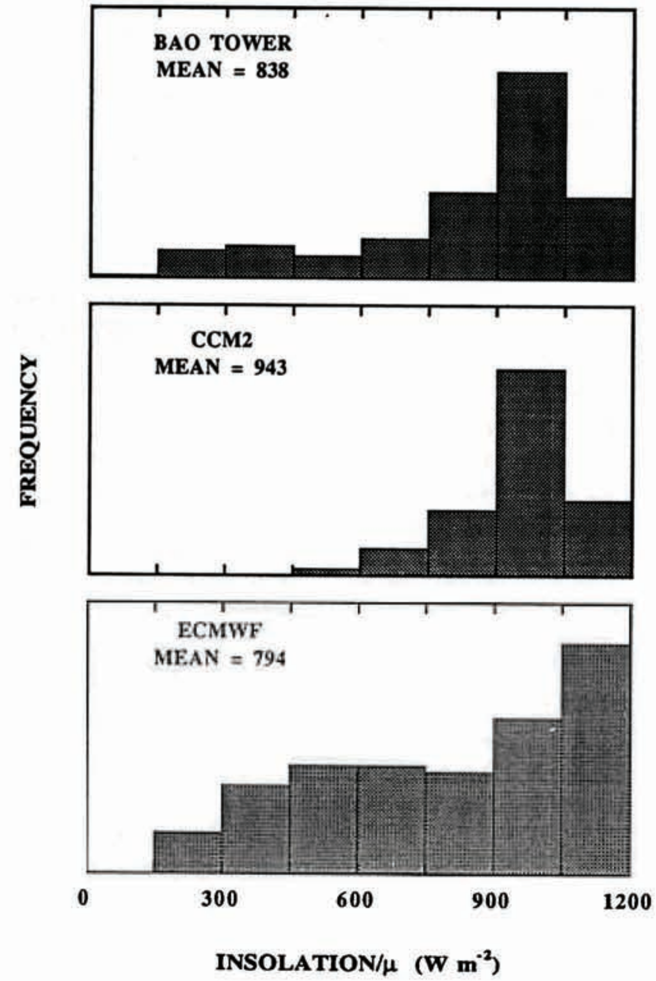

Figure 2. Summary of insolation/μ as measured at the BAO tower and from CCM2 and the ECMWF GCM.

cloudiness. The problem with CCM2 is not that it underpredicts cloud cover (its mean cloud-cover fraction at this location is 0.60), but rather that it underpredicts a small population of optically thick clouds in the 50% to 70% albedo range. The large GOES population in the 20% to 30% albedo range indicates a substantial amount of optically thin clouds, and CCM2 is quite consistent with this. Its mean cloud-cover fraction for this range of albedos is 0.77, so this model has a large amount of optically thin clouds, consistent with the GOES data, while it is underpredicting a small amount of optically thick clouds. For ECMWF, on the other hand, the situation is reversed; this model is overpredicting optically thick clouds while underpredicting optically thin clouds. These overpredictions and underpredictions, however, tend to be compensatory, so that the model produces a reasonable mean albedo.

Histograms of insolation/μ (Figure 2) provide similar information. Here increased cloudiness reduces insolation/μ and so corresponds to a progression from right to left.

The large 900-1050 Wm^{-2} insolation/μ population for both the tower data and CCM2 is again indicative of large amounts of optically thin clouds, while the minimal populations for CCM2 below 600 Wm^{-2} again demonstrate an underpopulation of optically thick clouds. And again, the ECMWF GCM is clearly underpredicting optically thin clouds and overpredicting optically thick clouds.

While the two datasets individually provide useful information, collectively they add a further dimension to SW cloud interactions in GCMs. To demonstrate this, scatter plots of albedo versus insolation/μ are shown in Figure 3. Points clustering to the right denote clear-sky conditions while increased cloudiness corresponds to a leftward progression.

Although CCM2 and the ECMWF GCM appear to be quite different models with respect to Figures 1 and 2, they produce virtually identical slopes (Figure 3) which differ from that produced by the GOES/tower data. To better understand this difference, the albedo slopes may, to an excellent approximation, be expressed as

$$\text{Slope} = \frac{\text{Std. Dev. of Albedo}}{\text{Std. Dev. of Insolation}/\mu}$$

The above standard deviations, normalized to those evaluated from the GOES and tower measurements, are shown in Figure 4. Perfect agreement with the measurements would consist of a normalized standard deviation of unity.

The results in Figure 4 add a further perspective: both models underestimate the increase in SW absorption by the atmospheric column associated with an increase in cloudiness because this increased absorption affects the albedo and insolation/ standard deviations in opposite ways. An increase in cloud SW absorption would reduce cloud albedo and, in turn, the albedo standard deviation. But, simultaneously, this increased absorption by the atmospheric column would reduce surface insolation and thus increase the insolation/ standard deviation. This combination would thus lead to a slope reduction and, as far as this specific aspect is concerned, would provide better agreement of the GCMs with the GOES/tower data (Figure 3). There are several possibilities for implementing such an improvement. But the important issue here is that

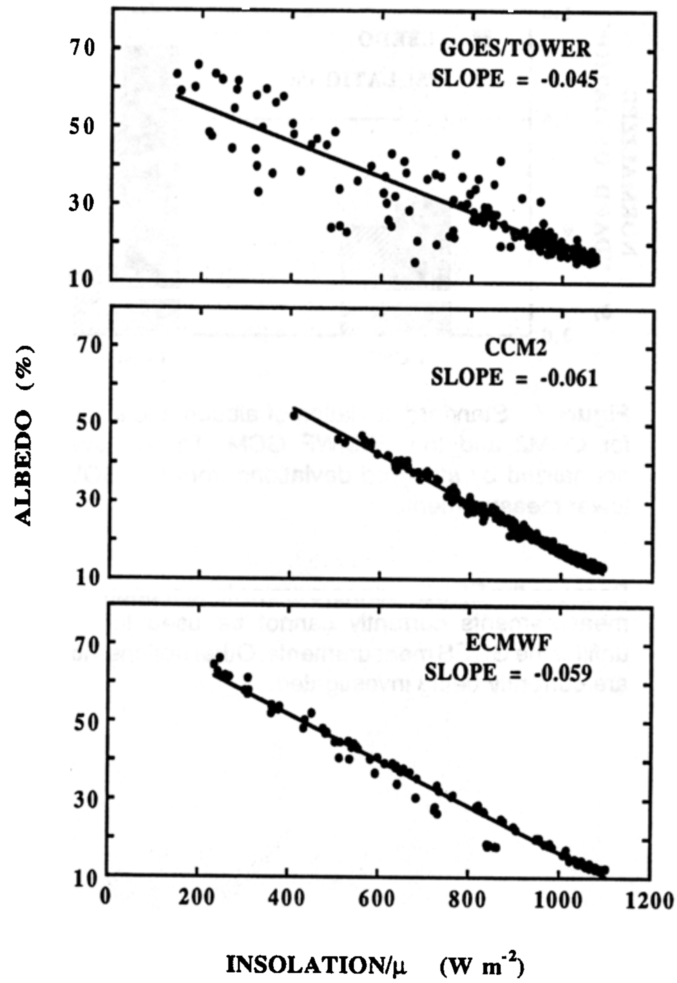

Figure 3. Top of the atmosphere albedo as a function of surface insolation divided by μ. These refer to the combined GOES/tower data, CCM2 and the ECMWF GCM.

the GOES/surface data, both individually and collectively, serve as an extremely useful vehicle for testing cloud SW radiative interactions in GCMs.

The collocated GOES and BAO tower data serve as a useful prototype for demonstrating what can be done, and in an extended fashion, at ARM sites. The recent addition of Dr. Patrick Minnis to the ARM Program means that GOES measurements will be collocated with ARM sites.

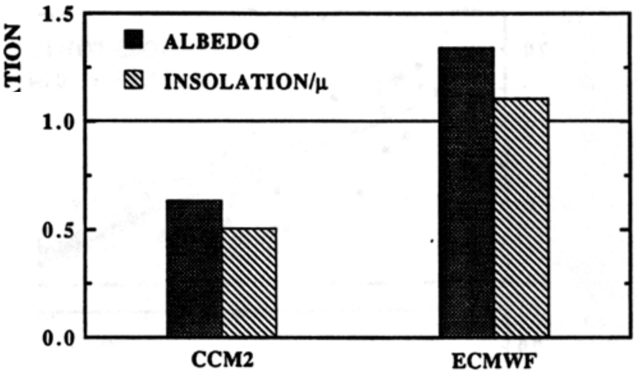

Figure 4. Standard deviation of albedo and insolation/μ for CCM2 and the ECMWF GCM. These have been normalized by standard deviations from the GOES and tower measurements.

Because the ERBE scanners are no longer operative, their measurements currently cannot be used to calibrate/unfilter the GOES measurements. Other options, however, are currently being investigated.

It is thus proposed to pursue the same research at ARM sites as they become operative. What will be advantageous here is that other data, for example cloud optical depth, will be available at these sites. These data will allow a much more comprehensive means of testing and interpreting GCMs than the current research has provided.

References

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