NSF 2005 CPT Report

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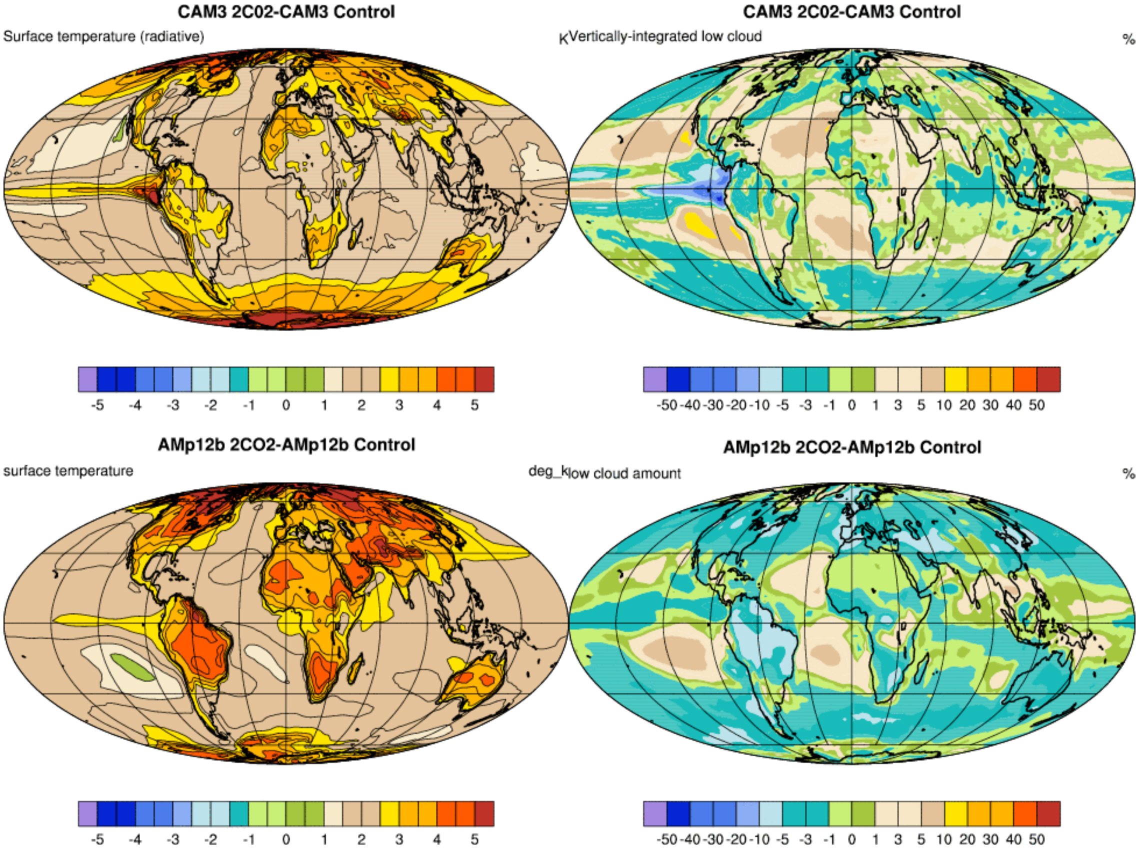
Introduction:

The focus of our research is on the role of low tropical clouds in affecting climate sensitivity. Comparison of climate simulations between the Community Atmosphere Model (CAM3) and the GFDL Atmospheric Model (AM2) indicates that these models have a very different response to a warming due to increased carbon dioxide. Figure 1 shows the change in surface temperature due to a doubling of carbon dioxide and the accompanying change in low cloud fraction. These results are from atmospheric models coupled to slab ocean models and are run to equilibrium solutions.



CAM3 2C02-CAM3 Control

CAM3 2C02-CAM3 Control

AMp12b 2CO2-AMp12b Control

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Figure 1. Change in surface temperature (°C) due to a doubling of carbon dioxide from the CAM3 and AM2 models on the left, change in low cloud amount (%) due to a doubling of carbon dioxide from the CAM3 and AM2 models on the right.

One can see a remarkable anti-correlation between the local surface temperature warming and the local change in cloud amount. For example, over the Amazon, the AM2 model shows significant warming compared to the CAM3 model, and the AM2 model shows a large decrease in Amazonian low cloud amount, while the CAM3 model shows less of a decrease in low cloud. A reduction of low cloud allows more shortwave radiation to reach the surface, which adds to increased warming. Thus, a larger decrease in low cloud amount creates more surface warming or larger climate sensitivity. Indeed, the AM2 model's climate sensitivity is larger than the CAM3 sensitivity. These results and consideration of other regions where the low cloud response differs between the two models indicates that low cloud processes are a major contributor to the overall climate sensitivity of these two models.

Low clouds in regions off the west coast of tropical continents play a particularly important role in modulating sea surface temperatures in these regions. Stratus and stratiform cloud cover off the coasts of southern California, northern South America, north and south Africa reduce shortwave radiation reaching the sea surface by order 50 to 80 Wm^{-2}. An underestimate of cloud amount in these regions leads to a severe overestimate of shortwave heating of the sea surface, which, in turn, leads to excessively warm waters off the coasts in these regions. These biases in sea surface temperature in these regions can affect the climate of the entire tropical regions. Large and Danabasoglu at NCAR have carried out simulations of the coupled Community Climate System Model (CCSM3) where they have fixed the sea surface temperatures in these regions to match observations. When they eliminate the local SST biases along coastal regions, the entire tropical circulation reorganizes towards an improved simulation of the climate system. For example, the inter-tropical convergence zones look more realistic. They also carried out simulations where they replaced the model surface shortwave radiative fluxes with data for these regions. Their findings indicate that the correct shortwave flux in these regions explains roughly half of the SST bias. Thus, it is very important that atmospheric models accurately simulate low cloud properties in these coastal regions, not only for the local climatology, but for the climatology of the whole tropics.

The motivation for looking at low clouds in coastal regions is thus two-fold: 1) these clouds play a major role in determining the climate response to warming, 2) these clouds also play a major role in determining the present state of the coupled climate system.

We are carrying out a systematic investigation of clouds in these coastal regions by employing observations, reanalysis and a hierarchy of climate models. The first stage of this project has focused on documenting and classifying the existing biases in model cloud properties for the CAM3 and AM2 simulations for the present day climate. We also have explored the major large-scale factors that determine the low cloud amount in the coastal regions.

Methodology:

We chose the boxed regions shown in figure 2 to explore in detail. These are regions where extensive persistent low cloud forms over the oceans. The stability of the low cloud in this region is a result of both atmospheric and oceanic conditions, where in the atmosphere large scale subsiding air occurs, while in the ocean upwelling of cold water takes place. Thus, the large scale conditions are of warm air above a cold sea surface, leading to a stable moist atmospheric boundary layer.

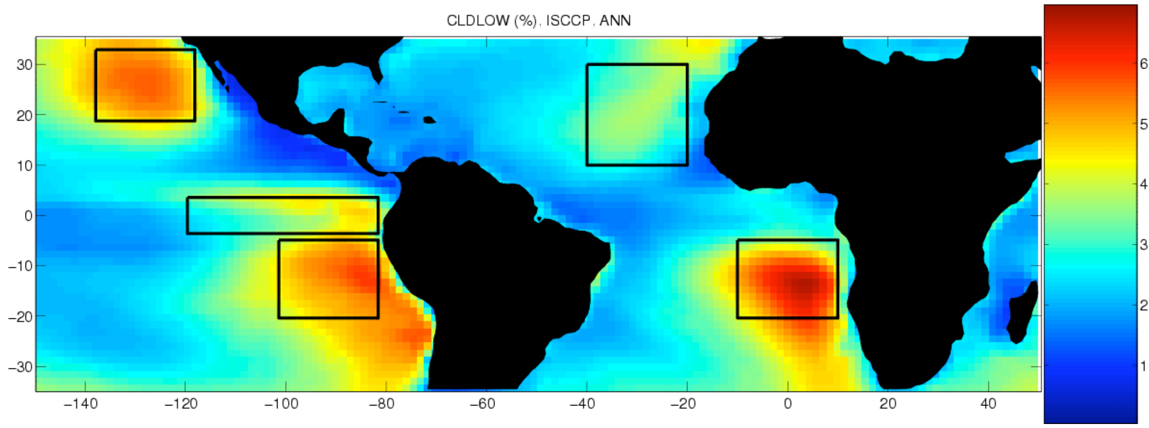

Figure 2. Boxed regions are those considered in the present study of tropical low cloud. Shading indicates the annual mean ISCCP low cloud amount (%).

The dominant processes that operate under these conditions are shown in figure 3. Large scale subsiding air warms as it descends, thus the potential temperature at 700 mb is larger than at the surface. A measure of the static stability in this region, defined by Klein and Hartmann (19xx), is the difference in the potential temperate at 700mb and the surface, SS = θ_{700} - θ_s. Turbulent eddies form in the mixed layer and maintain its structure. A measure of this activity is the buoyancy surface flux, which includes both moist and dry processes. Clouds form under the boundary layer, where there is a jump in the potential temperature. The vertical resolution in climate models is too course to resolve this jump, so the static stability is viewed as a qualitative measure of this jump in θ.

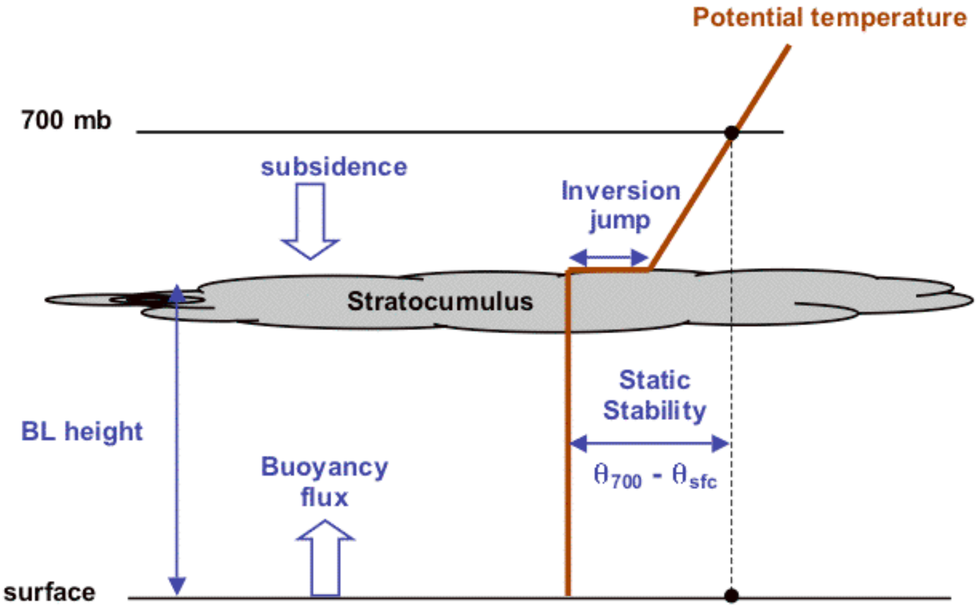

Figure 3. Processes operating in regions where stratocumulus cloud clouds form in coastal regions.

We have carried out extensive analysis of the cloud properties and large-scale properties in terms of the annual mean, monthly mean and spatial and temporal variability within the boxes shown in figure 2. We explore the observational data and model simulations using probability density functions, correlation analysis and standard mean statistics. We briefly summarize our findings in this report.

Data and Model Simulations:

To carry out a comprehensive analysis of the clouds in these regions, we spent considerable effort in collecting a large array of data for both cloud properties and meteorological variables. Cloud fraction is obtained from the 1983-1999 ISCCP satellite dataset and the Warren and Hahn surface cloud climatology. Cloud water path is obtained from the 1987-2000 SSM/I microwave satellite sensor. The top-of-atmosphere radiation fluxes are obtained from the 1985-1989 ERBE dataset. Sea surface temperatures are from the HadISST data from 1979-1999. The meteorological fields of vertical velocity, thermal structure, and surface fluxes were obtained from the EMWF ERA-40 reanalysis, which covers the years 1979 to 1999.

The model simulations were based on AMIP integrations, which employ observed monthly mean sea surface temperatures. For the CAM3, the horizontal resolution is T85, or ~1.4° by 1.4°. For the GFDL AM2 model the horizontal resolution is 2° by 2.5°.

Results:

If we first consider the annual mean cloud fraction for the tropical Pacific region, figure 4, we see that for the CAM3 the clouds are too close to the coastal regions and that the cloud cover is over predicted in general. For the AM2 model the cloud cover is generally under estimated and the clouds are too far from the coastal regions.

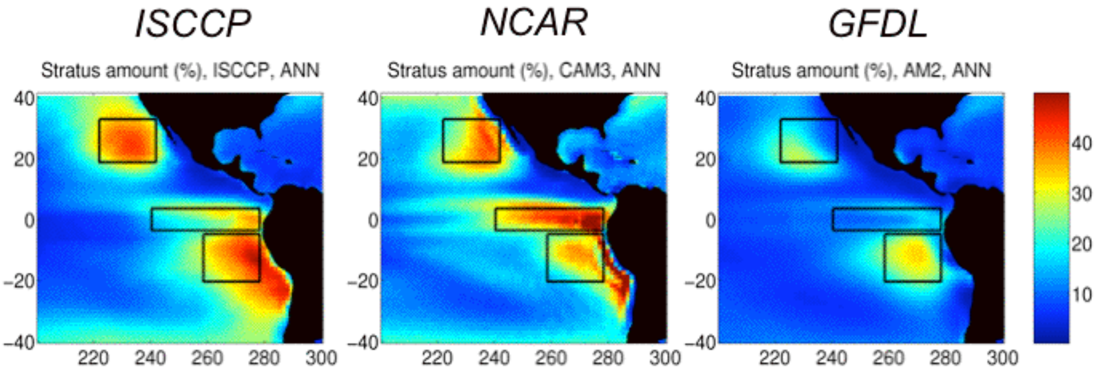

Figure 4. Annual mean low cloud amount (%) for the Eastern Equatorial Pacific region from the ISCCP observations, the CAM3 and the AM2 models.

These biases in cloud amount have a significant impact on the surface shortwave energy budgets for these models.

In order to discover which large scale meteorological variables correlate best with the low cloud amount, we have carried out statistical correlations of the static stability, vertical pressure velocity, boundary layer mean relative humidity, and surface buoyancy fluxes for each of the boxes in figure 2. We have also considered correlations with other fields, e.g. cloud radiative forcing, cloud liquid water path. These correlations have been carried out with fields within each box and for the box averages. We have also looked at the correlation on various time scales from the monthly mean up to annual mean time scales. We have found significant dependences on space and time scales that are relevant for the parameterization of these clouds for climate models. The probability density functions for the Eastern Equatorial boxes are shown in figure 5.

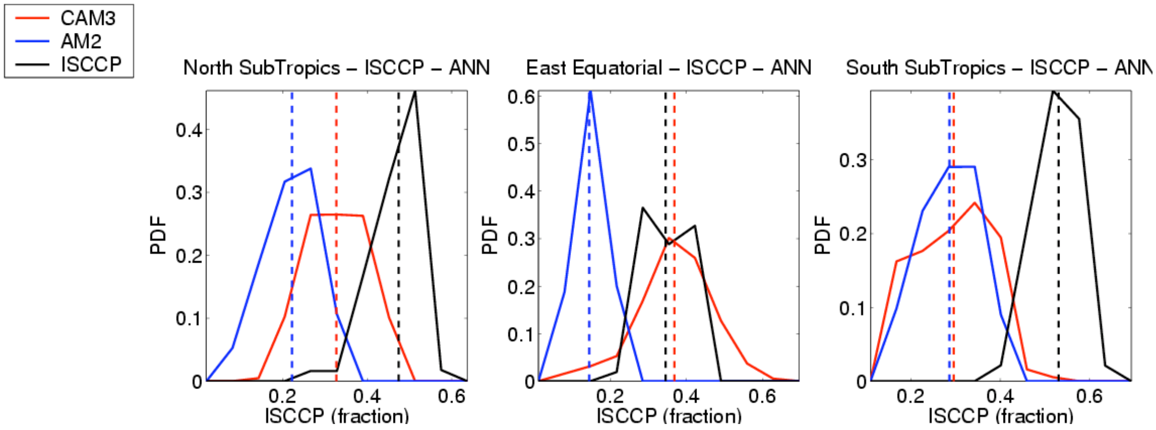

Figure 5. Probability density functions (PDFs) of low cloud amount (fraction) for the three boxes in the Eastern Equatorial region. PDFs are shown for the ISCCP observations (___), the CAM3 (___) and the AM2 (____) models.

These results indicate that statistical structure, in terms of the shape of the distribution of the cloud amount from both models does not compare well with the observations. Thus, the models may represent the mean cloud cover for a region, see CAM3 in the East Equatorial region, but may not capture the higher moments of this field.

Going beyond an annual mean analysis allows us to consider cloud variations given a large seasonal forcing in solar insolation, or range in surface forcing. Thus, we can correlate the annual cycle of low cloud amount to the annual cycle in subsidence, static stability, buoyancy flux and other variables. We have created matrices of the correlation coefficient to see which variables are most promising predictors of cloud amount. Figure 6 shows results for the Eastern Equatorial Pacific regions in terms of the annual cycle of cloud amount, shortwave cloud forcing, and cloud liquid water path. The CAM3 predicts a reasonable cycle in cloud amount for the box in the northern equatorial region, while in the other regions is performs more poorly. There is significant variation in the cloud liquid water simulated in the two models, despite similarities in the cloud prognostic water formulation in these models.

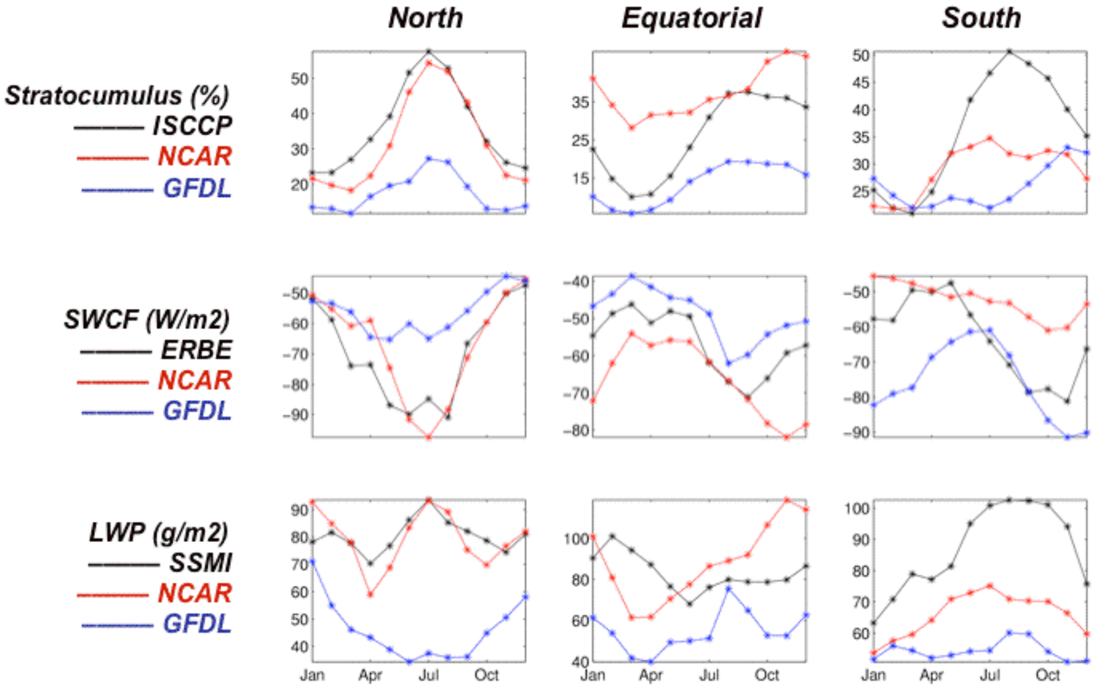

Figure 6. Annual cycle in cloud amount, shortwave cloud forcing (SWCF), and cloud liquid water path (LWP) for the three Eastern Equatorial Pacific regions. Data sources as noted in legend.

The annual cycle in cloud amount is compared to large-scale meteorological variables in figure 7. For all three regions, the correlation between cloud amount and static stability is highest, supporting the finding of Klein and Hartmann (19xx). The CAM3 does a good job in capturing the annual cycle of the buoyancy flux for the equatorial and southern region, while the AM2 does a better in simulating this flux for the northern region. A finding of our work is that the region off of the coast of California has characteristics that do not match with the other regions. We are currently investigating why this region is unique in its properties. Both models seem to simulate the annual cycle in the large scale subsidence, with the largest errors in the northern region.

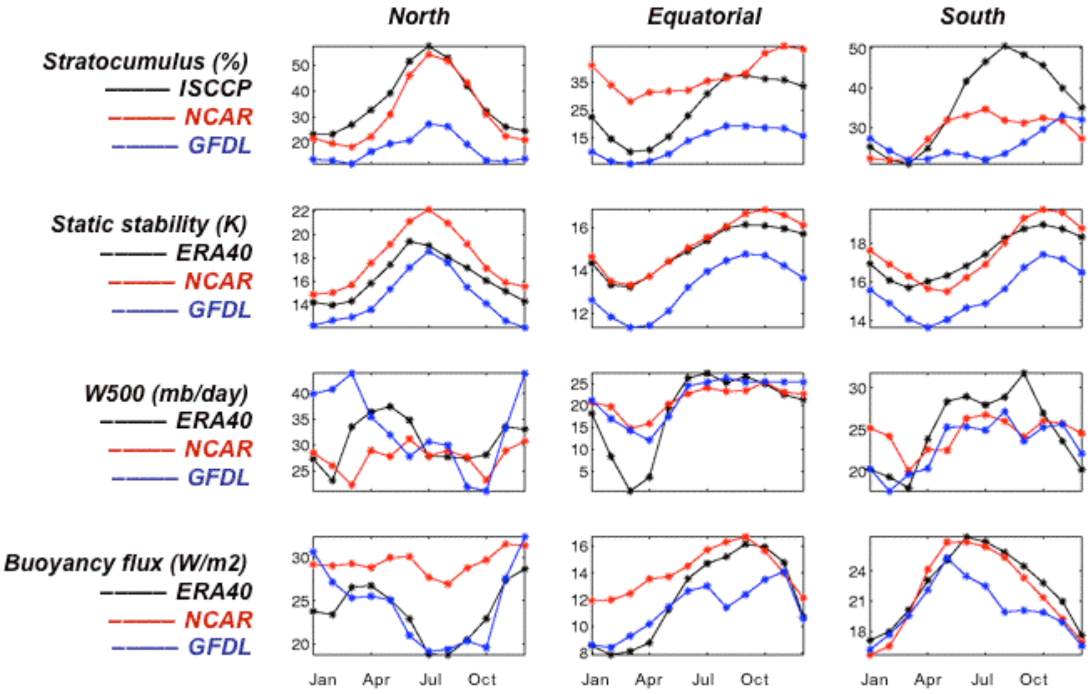

Figure 7. Annual cycle in cloud amount (%), static stability (°C), vertical pressure velocity (mb day^{-1}), and buoyancy flux (Wm^{-2}). Data sources as noted in legend.

We have found the correlation of static stability and low cloud fraction is very high on the seasonal and annual time scales. However, we have also discovered that this correlation breaks down for smaller spatial scales, ~200 km, and for monthly and shorter time scales. This implies that for climate model parameterization of low cloud, a more physically based approach is required than what is currently used in CAM3, where the cloud amount is explicitly linked to static stability. This is especially important when applying this type of approach to a climate change scenario, such as increased warming due to increased greenhouse gases.

Other Current Work:

In addition to our research of low cloud properties in observations and models, we have also participated in a number of other activities related to cloud processes.

Project: GCSS Pacific Cross-section Intercomparison (GPCI)
Joao Teixeira (UCAR/VSP, NRL, Monterey, now at NATO Undersea Research Centre, Italy)

Weather and climate prediction models are analyzed along a cross-section in the Pacific Ocean, from California to the Equator. The cross-section over the Pacific Ocean encompasses several fundamental cloud regimes such as stratocumulus, shallow cumulus and deep cumulus, as well as the transitions between them. The CAM3 model output was collected every 3 hours (JJA 1998 and 2003), which allows for a better understanding of issues associated with the diurnal cycle of clouds and cloud related processes in the tropics and subtropics. Presently, GPCI has collected output from 6 models from GFDL, NCAR, UKMO, MétéoFrance, JMA and KNMI.

Project: CPT Columns: comparison between the GFDL model and NCAR model:

see: http://www.cgd.ucar.edu/ccr/CPT/columns.html
Brian Mapes (University of Miami) and Richard Neale (CDC)
Robert Pincus (CDC) and Crispian Batstone(CDC)

Implementation of the Monte Carlo Independent Column Approximation (McICA)
Collaborators: Robert Pincus, Bill Collins.

We are implementing a new radiative scheme called the Monte Carlo Independent Column Approximation (McICA). The McICA is a method developed to improve the treatment of cloud variability in climate models. This method is essentially a sampling strategy that yields unbiased estimates of heating rate profiles with respect to the full ICA, but that speeds the calculation up compared to the full ICA. Implementing McICA requires a way to build subcolumns in the model. Our 'subcolumn generator' will include flexible overlap rules (i.e. maximum-random overlap, exponential overlap, etc) and it will able to generate subcolumns for various cloud distributions (i.e. using the homogeneous cloud assumption, or a beta distribution of cloud condensate assumption).

CAPT simulations for the year 2001

Collaborators: Dave Williamson, Jerry Olson, Steve Klein (LLNL), Jim Boyle (LLNL)

In the CAPT protocol, we realistically initialize CAM3 with NWP analyses, and we then run the model in forecast mode to determine the drift from the NWP analyses and/or from available field data. This method allows us to diagnose model parameterization deficiencies. This project is a collaboration with the LLNL and it will include:

- Comparison with the fields data (DYCOMS, EPIC, ARM sites, ISCCP global fields)
- Tests of Chris Bretherton's atmospheric boundary layer scheme
- Sharing the data with the CPT scientists