Use of Surface and Satellite Data to Validate and Improve Climate Models

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Introduction

One of the major obstacles the current climate modeling effort faces is the lack of high-quality observational data to validate the climate models against. This lack has hampered the progress in model improvement needed for climate change studies. With field observations from CEPEX (Central Equatorial Pacific Experiment) and TOGA-COARE (Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment), we are able to address the model validation issue in two critical areas: using surface observations to identify model deficiency and improve model simulation, and exploring a new approach to parameterizing clouds and cloud-radiative interaction in climate models. This study reports on our recent results.

Our work is focused on the following issues closely tied to the major ARM program objectives:

- Understanding the complex interaction between convection, large-scale circulation and surface evaporation
- Using surface observations to identify model deficiencies and improve the simulation of surface climatology by the National Center for Atmospheric Research Community Climate Model (NCAR CCM)
- Developing a strategy to validate cloud parameterization in climate models.

The research by our team of investigators in the first two subjects leads to the implementation of a new penetrative convective parameterization scheme in the NCAR CCM. With this new convection scheme, simulation in surface climatology, particularly precipitation, surface evaporation and surface wind stress over the oceans, has been significantly improved. Our research on treatment of cloud-radiative interactions in general circulation models (GCM) has yielded new insights into cloud parameterization in GCMs. The remainder of this study will address these issues in greater detail, with a summary presented at the end.

Validation and improvement of NCAR CCM

Coupling of Convection and Surface Evaporation

Surface evaporation is one of the major components in the surface heat budget over the oceans. It also affects the atmospheric hydrological cycle on both regional and global scales. However, because of the lack of high-quality observational data, climatological estimates of surface evaporation over the oceans are apt to have large uncertainties. Recently, the international TOGA program provided a very valuable dataset from the moored buoy array deployed in the equatorial Pacific. Using the buoy data, we computed the surface evaporation in the equatorial Pacific, including the western Pacific warm pool (Zhang and McPhaden 1995). Together with the satellite data, we find that (Zhang et al. 1995):

- Surface evaporation in the western Pacific warm pool is about 100 W/m^2, relatively low compared to the central equatorial Pacific and the subtropics, where the sea surface temperature is lower.
- The low evaporation in the warm pool is largely controlled by the weak surface flow associated with the large-scale circulation, which in turn is largely driven by the latent heat release from atmospheric convection in the warm pool.

The identification of the coupling between convection and surface evaporation through large-scale circulation explains the observed low evaporation in the western Pacific warm pool. It also helped us to isolate convective parameterization as the primary factor that could have tremendous impact on model improvement of surface climatology and led us to a successful implementation of a new penetrative convective parameterization scheme in the NCAR CCM.

Implementation of Zhang and McFarlane's Convection Scheme in NCAR CCM

The NCAR CCM2 simulates the global climate reasonably well (Hack et al. 1994). However, there are a number of obvious deficiencies. Among them are the too strong surface evaporation in the tropical oceans, especially in the western Pacific warm pool where surface evaporation exceeds climatological values by 50 to 60 W/m^2, and the poor simulation of the Indian summer monsoon and the Central American summer monsoon. The simulated surface wind stress over the tropical oceans is also too large. All these prohibit the coupling of the atmospheric and ocean general circulation models.

Our observational studies on surface evaporation and its interaction with convection made us believe that the convective parameterization was at least partly responsible for the above model deficiencies in the NCAR CCM2. As a result, we implemented a penetrative convective parameterization scheme developed by Zhang and McFarlane (1995). In CCM2, Hack's (1994) scheme was used to parameterize convection. Although it is a mass flux scheme, many of its features are similar to those of moist convective adjustment. In particular, its imposed depth of penetration (three layers) by convective plumes seriously limited the ability of convection to transport heat and moisture from the lower levels to the upper troposphere. This makes the atmosphere more unstable, leading to stronger Hadley and Walker circulations (Hack et al. 1994). On the other hand, in the Zhang and McFarlane scheme, convection can transport heat and moisture directly from the boundary layer to the upper troposphere. It also emphasizes the stabilization of the boundary layer by convective downdrafts through cooling and drying.

In the new configuration of the NCAR CCM (CCM3), in addition to the new convection scheme, Hack's scheme is retained to represent shallow convection and possible mid-level convection. CCM3 has been used to re-run the AMIP (Atmospheric Model Intercomparison Project) simulation from 1985-1989. Compared with the CCM2 simulation, CCM3 simulates a much better climatology in tropical precipitation, surface evaporation and wind stress over the tropical oceans, particularly in the western Pacific warm pool. As an example, Figure 1 shows the 5-yr mean surface evaporation (latent heat flux) for July from CCM3 (Figure 1a), CCM2 (Figure 1b), and their difference (Figure 1c). Clearly, the CCM3 simulation of surface evaporation over the tropical oceans is significantly lower than that of the CCM2, with differences as large as 50 W/m^2 in the western Pacific warm pool, where the simulated evaporation in CCM3 is much closer to the observed values (Zhang and McPhaden 1995, Ramanathan et al. 1995) and climatology (Oberhuber 1988). A minimum evaporation zone over the equatorial Pacific sandwiched by high evaporation regions in the subtropics associated with the strong trade winds is well simulated in CCM3, but not in CCM2. Similar changes from CCM2 to CCM3 are seen for a January simulation as well (not shown).

Satellite Based Approach to Parameterizing Clouds in Climate Models

Another critical area of climate models that needs improvement for the purpose of climate change studies is the parameterization of clouds and their interaction with radiation. We developed an approach for using satellite radiance data to parameterize clouds in climate models, especially for cloud-radiative interactions (Boer and Ramanathan 1996). The approach consists of three steps:

- First, we select the cloud systems, for it is safe to assume that one scheme may not satisfy all cloud types. The example we choose is the convective-stratiform cloud systems over the western and central tropical Pacific Ocean, including the warm pool. We adopt the hourly Japanese geostationary meteorological satellite (GMS) window channel radiance in the visible and IR window region for cloud classification and characterization.

- Second, we sort the individually identified clouds by cloud type, cloud area, number of clouds in each area bin, and the contribution to the total cloudy albedo and OLR by each cloud area bin. This information can be objectively used to identify the fraction of clouds that should be resolved by the model (depending on its spatial resolution). This fraction, referred to as the resolvable fraction, does not require a subgrid-scale cloud cover parameterization scheme. For the remaining subgrid-scale cloud fraction, a parameterization scheme has to be devised. The cloud sorting process requires a scheme for identifying individual clouds and their cloud edges, which in turn necessitates a method for identifying clear pixels. A detect-and-spread algorithm is proposed for this purpose.

- The third step requires scale-dependent satellite cloud properties for model validation. A distinction has to be made in terms of resolvable and subgrid scales. For the resolvable scale, the critical parameters obtained from the data are life times of cloud systems as a function of their

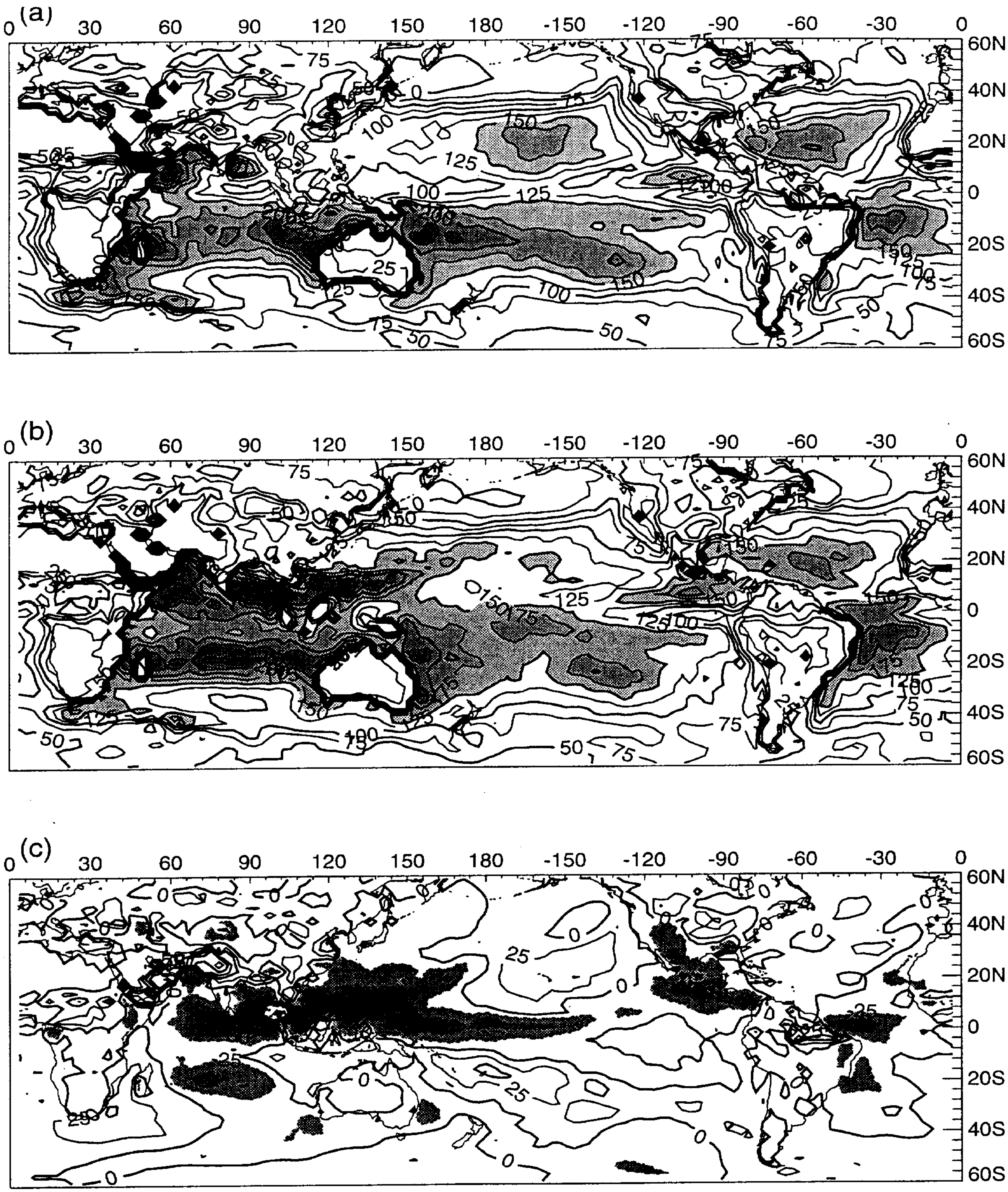

Figure 1. Global distribution of surface evaporation (from 60°N to 60°S) for July 1985-89 as simulated by (a) CCM3, (b) CCM2 of the NCAR climate model, and (c) their difference (CCM3-CCM2). Contours are at every 25 w/m^2 intervals. Contours greater than 150 W/m^2 in (a) and (b), and less than -25 W/m^2 in (c) are shaded.

spatial scales and radiative properties such as albedo and cloud top temperature as a function of the cloud spatial scale. The scale dependent parameters are obtained from the detect-and-spread algorithm.

To illustrate our approach, Figure 2 shows the cumulative contribution of each cloud type to the total percent cloud cover as a function of the cloud area in the region from 20°N to 20°S and 120°E to 160°W over the CEPEX period from March 7 to April 7, 1993. The following features are seen:

- More than 95% of the deep convective cloud contribution to the total area covered by deep convective clouds is from clouds with area greater than 10^4 km^2.

- The reverse is true for low warm clouds. About 80% of the contribution to fractional cover is due to small scale clouds (area <10^4 km^2).

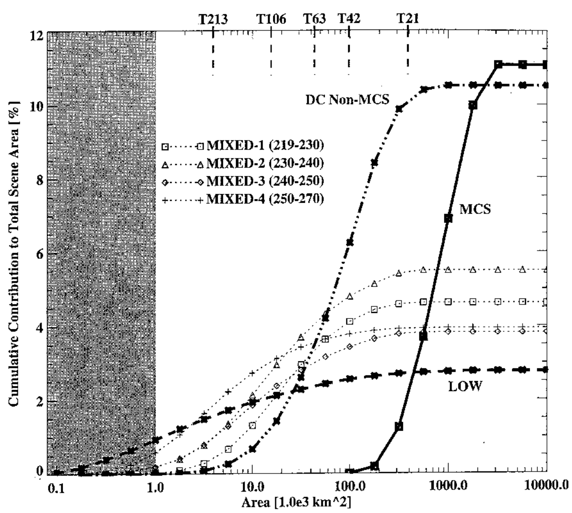

Figure 2. Cumulative contribution of each cloud type to the total percent cloud cover as a function of the cloud area in the region from 20° N to 20° S and 120° E to 160° W over CEPEX period (March 7 to April 7, 1993). The thick solid line is for mesoscale convective systems (MCS), the dash-dotted line is for non-MCS deep convective clouds, and the dashed line is for low clouds. The other lines are for various mixed cloud types (cloud top temperature range given in parentheses). Values in the gray area are expected to have large uncertainties. The symbols on the top, T21, T42,......, denote the spatial resolution, i.e., area of a grid at the equator, of GCMs with triangular truncation.

- The other mixed cloud types fall in between the convective and the low clouds.

For convective-stratiform cloud systems in the tropical Pacific, GCMs with a horizontal resolution of 50 km can resolve 90% of the radiatively important clouds while a GCM with a resolution of 250 km can resolve only 50%. The low clouds that are unattached to convective-stratiform systems are mostly unresolvable by current GCMs. For convective-anvil clouds with areas larger than 10^5 km^2, our statistics reveal that the area increases with the cloud lifetime, which suggests the need to explicitly account for the transport of cloud liquid/ice water in GCMs.

Summary

We presented results in two areas of climate model validation and improvement, one of the main objectives of ARM program. Our work is observationally based and motivated. We implemented a new convective parameterization scheme that has resulted in a much improved NCAR CCM. In particular, the simulation of surface climatology of evaporation, precipitation and wind stress over the tropical oceans is in much closer agreement with the available observations. We also explored a new approach to parameterizing clouds and cloud-radiative interaction in climate models. Using satellite data during CEPEX, we found that clouds with area greater than 10^4 km^2 contribute more than 95% to the total cloud area cover. For convective-stratiform cloud systems in the tropical Pacific, GCMs with a horizontal resolution of 50 km can resolve 90% of the radiatively important clouds, while a GCM with 250-km resolution can only resolve 50%. This and other results (for details see Boer and Ramanathan 1996) suggest that validation of GCMs following the approach we developed can lead to important new insights into GCM cloud parameterization. Our next step is to apply the scale-dependent approach to GCM simulations and to develop a cloud parameterization that is based on the observations.

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