Addressing Moist Physics Parameterization Errors in Climate Models with a Weather Forecasting Approach: The CAPT Project (2004-2006)

The simulation of many phenomena in climate models is hindered by inaccurate representation of physical processes – particularly those associated with moisture. These representations, called parameterizations, are known to be among the least sound components of a climate model. Consequently, a significant amount of current research aims to improve these parameterizations which strongly impact model simulations of the hydrologic cycle and radiation budget. As part of this research, the CAPT project at PCMDI compares the simulations of climate models when run in weather forecast mode to observations related to moist processes. CAPT is an acronym for the CCPP – ARM Parameterization Testbed (Phillips et al. 2004, http://www-pcmdi.llnl.gov/projects/model_testbed.php), where CCPP is DOE's climate modeling program entitled the Climate Change Prediction Program and ARM is DOE's observational program entitled the Atmospheric Radiation Measurement program. Two central aims of the CAPT project are (a) to assess moist-processes and radiation errors in climate models at the weather time scale by comparison of model simulations to ARM and other observations, and (b) to assess the degree to which new parameterizations reduce these errors. Examining model simulations at the weather time scale is useful because this time scale is closer to that over which moist processes evolve and it permits examination of the errors that may be responsible for the climate drift of the model.

Here developments in the CAPT project for the period May 2004 to May 2006 are reviewed. In brief, the two most important developments are (a) that a new climate model

has been added to the parameterization testbed and (b) that the simulations of climate models for locations other than the ARM Oklahoma site have been examined.

GFDL Climate Model Added to CAPT

The climate model of the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (NOAA/GFDL) has been added to the testbed. The GFDL model, known as AM2 (GFDL GAMDT 2004), is the second model in the testbed and joins the climate model of the National Center for Atmospheric Research (NCAR), known as CAM3 (Collins et al. 2006). The addition of a second model is very valuable to the project as it allows us to compare and contrast model performance and learn something about how models may err in different ways. This also expands the impact of the project by assisting the development of a second major climate model for the United States.

As an example, Figure 1 shows the precipitation simulation of the GFDL climate model over the United States in summer. Both panels show the model precipitation error with the top panel displaying the error in the first day of CAPT weather forecasts initialized with analyses of the European Center for Medium-range Weather Forecasts (ECMWF) for June and July of 1997 and the bottom panel displaying the error in June through August precipitation of the GFDL model when run in climate mode. Both panels show a very significant underestimate of precipitation in the central United States which suggests that a weather forecasting approach might be useful to address this significant error in the model's climate. Analysis of the forecasts indicates that most of the missed precipitation occurs at night as part of convective systems that are initiated at sunset over

the front range of the Rockies and propagate eastward reaching the Great Plains in the middle of the night (Klein et al. 2006). The failure of the model to simulate these systems is the primary cause of a 5K overestimate of summertime surface temperature in the GFDL model's climate. Similar underestimates of nocturnal precipitation and overestimates of surface air temperature occur in other climate models. The simulation of these convective events is very difficult to do in a climate model and will probably require a combination of resolution increases and parameterization improvements. While CAPT does not have a solution of this problem, CAPT has pointed out that simulations of the summertime climate of the central United States will not be improved without a simulation of these propagating convective events.

Arctic Mixed-Phase Clouds

The ARM program maintains sites in the Arctic and Tropics in addition to its major site in Oklahoma. In October 2004, ARM conducted a major field experiment at its site in Barrow, Alaska on the coast of the Arctic Ocean. This experiment, the Mixed-Phase Arctic Cloud Experiment, was designed to measure the physical properties of clouds that contain both liquid and ice. Observations taken by the ARM cloud radar and lidar were analyzed to deduce the occurrence of cloud at different levels of the atmosphere. The ARM observations in Figure 2 show that low and some middle clouds were persistent in the first half of the experiment but that clouds at all levels were variable in the second half of the experiment. CAPT forecasts for this period, which are initialized with analyses from the National Aeronautics and Space Administration's (NASA) Goddard Data Assimilation Office, indicate that the models capture fairly well

the general placement in time and vertical extent of the clouds. The relative success of the model's simulation of cloud occurrence after October 15 is not too surprising in that baroclinic systems which are responsible for the clouds in this period are generally resolved by climate models. However, it is pleasing to see a relatively good simulation of the boundary layer clouds that occurred in the period October 9-14, because these clouds are generally more difficult to simulate in climate models. These boundary layer clouds resulted from the large heat fluxes out of the Arctic Ocean that occurred when cold air from above the sea ice far to the north passed over the relatively warm ice-free ocean forming clouds that then advected over Barrow.

A good simulation of cloud occurrence, however, does not guarantee that the physical properties of the clouds will be correct. Figure 3 shows that there are large differences between models and observations for the vertically integrated amount of cloud liquid and ice, quantities that determine the radiative impact of clouds. For cloud liquid water path, the NCAR model significantly overestimates the ARM observations whereas the GFDL model has a closer correspondence. For the frontal cloud systems, the NCAR model clouds are mainly liquid whereas the GFDL model clouds are mainly ice. With such disagreements, it is not surprising that climate models simulate different cloud feedbacks to climate change. Improving the agreement of these physical quantities with the observations is important to do if the considerable effort being expended on more complex cloud microphysics in climate models (which is driven by the desire to simulate the indirect effect of aerosols on clouds) is to be worthwhile.

It may have been noted that no observations were presented for the ice water path. While no ice water path observations were shown in this figure, ARM has been

developed algorithms that for a majority of clouds can retrieve the ice and liquid water contents and particle sizes from the cloud radar and other data that ARM routinely collects. Multi-year datasets of this type are just now becoming available for the ARM sites and a collaboration has begun with those developing these datasets at Brookhaven and Pacific Northwest Laboratories and the University of Utah.

Tropical Deep Convection

The simulation of tropical convection in climate models is one of the most important problem areas to improve. Tropical convection impacts diverse phenomena such as hurricanes, the Madden Julian Oscillation (MJO), and El Niño. The CAPT project has begun to address this problem by performing weather forecasts for the winter of 1992-93 during which a large field experiment called the Tropical-Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA-COARE, Webster and Lukas 1992) was conducted in the Tropical West Pacific.

Figure 4 shows the time series of daily mean precipitation for the TOGA-COARE location for November 1992 through February 1993 from the observations and the day 3 forecasts of AM2 and two versions of CAM3 that are initialized with ECMWF re-analyses. The observations indicate considerable variability from periods of relatively low precipitation such as occur during November to periods of relatively high precipitation such as occur during December. The December precipitation occurs when the active phase of an MJO, an oscillation with a period between 30 and 50 days, passes through the TOGA-COARE location. The lower left panel shows that the CAM3 fails to simulate this variability with moderate precipitation of ~10 mm day^{-1} present throughout

and thus too much precipitation in November and too little precipitation in December. Another apparent deficiency is that the model has no days with precipitation in excess of 25 mm day^{-1} contrary to the observations which have 3 events in this period. The weak nature of the MJO in the control model is a well-known feature of the NCAR model with the Zhang-McFarlane convection parameterization (Zhang and Mu 2005) – what is new is that CAPT forecasts have shown that the CAM3 fails to simulation MJO precipitation variability even if CAM3 is initialized with the dynamic and thermodynamic structure of an MJO, which is relatively well depicted in the ECMWF analyses. This suggests that the model's representation of moist processes, and parameterized convection, in particular, may be responsible for the poor simulation of the MJO in the NCAR model. Given the poor simulation of precipitation it is not surprising that the circulation anomalies that depict the MJO weaken considerably during the duration of the forecasts. For example, the low-pass filtered 200 hPa velocity potential, a measure of the horizontally divergent flow, shows intraseasonal variability comparable to that in the ECMWF analyses in forecasts for day 3 but much weaker than that in the ECMWF analyses in forecasts for day 6. In contrast to the NCAR model, the GFDL model (upper right panel of Figure 4) appears to simulate the MJO variability somewhat better particularly with respect to the time of events, although it also lacks the strong precipitation events seen in observations. Even though the GFDL simulation of precipitation at the location of the TOGA-COARE experiment is not dramatically better than the NCAR CAM3, the large-scale circulations of the MJO do not fade with time in GFDL model forecasts (at least out to day 6).

An important aspect of the CAPT project is to test the impact of new parameterizations. Guang Zhang (University of California at San Diego) has developed a

new representation of his convection parameterization based in part upon observations of summertime convection at the ARM Oklahoma site (Zhang 2003). In this new representation, convection is restricted to occur only when the large-scale circulation of the model is generating convective instability by cooling the troposphere above the boundary layer. Furthermore, the amount of convective heating is limited to that that balances the destabilization by large-scale processes. With these changes and an additional restriction of convection to times where the boundary layer relative humidity exceeds 80%, a substantially improved simulation of the MJO was demonstrated in the NCAR model (Zhang and Mu 2005). CAPT has formed a collaboration with Guang Zhang to test these changes in our forecast simulations with the NCAR model. Consistent with Zhang's results from climate integrations of the NCAR model, day 3 forecasts with the modified model show considerably improved MJO variability and a greater number of very large precipitation events (lower right panel of Figure 4). Furthermore, the large-scale circulation anomalies of the MJO do not dissipate with time in the forecasts (at least out to day 6) and in fact are stronger than those contained in the ECMWF analyses which are used as initial conditions.

An important result of this work is that it is feasible to learn gain scientifically useful information about the forecast model in the tropics despite the lack of data assimilation for the forecast model. There had been concern that the adjustment problems of the forecast model to the initial conditions provided by the analysis of different model would be so severe that forecast results in the tropics would only provide information about the adjustment. The premise of CAPT is that the adjustment problems are small enough that after a short spin-up period, which is perhaps as short as 12 hours in the

extra-tropics and as long as 2 days in the tropics, the forecasts provide information on the ability of the forecast model, and its parameterizations of moist processes in particular, to simulate the atmosphere. This will be true for as long as the errors simulated by the forecast model remain large compared to the errors induced by the adjustment. Our ability to perform successful forecasts is undoubtedly dependent on the quality of the analyses that we use to initialize the model; our results suggest that the quality of the ECMWF reanalysis in the tropics is high enough to permit meaningful analysis of the forecast results. Furthermore, as the quality of the analyses improves it is possible that the drift of the model in the spin-up period of the forecasts will provide more information about the drift of the forecast model from the observed atmosphere, thus signifying an error of the forecast model, and not the drift of the forecast model from one erroneous depiction to another, signifying nothing.

Subtropical Marine Boundary Layers

The representation of the subtropical marine boundary layer in climate models is very important because the stratocumulus clouds that form over the cold ocean that is to the west of major continents are crucial for reducing the solar radiation entering the ocean and enhancing the latent heat flux exiting the ocean. Without a proper representation of the subtropical marine boundary layer, large positive drifts in ocean surface temperature result when the atmosphere model is coupled to an ocean model. Furthermore, there is evidence from the latest IPCC results (Bony and DuFresne 2005), that the large spread in climate sensitivity of current climate models results substantially from the diversity in model responses of subtropical marine boundary layer clouds to climate change.

Exacerbating the problem is that most models simulate subtropical marine boundary layer clouds poorly.

As part of the interest in marine boundary layer clouds, the National Science Foundation and NOAA have funded a Climate Process Team led by Chris Bretherton of the University of the Washington (Bretherton 2006, http://www.atmos.washington.edu/~breth/CPT-clouds.html). This project has the participation of major climate modeling centers such as NCAR and GFDL and a number of university-based scientists. As part of the project, a liaison scientist placed at each of the modeling centers facilitates contact between university and modeling center scientists. The NCAR liaison scientist, Cecile Hannay, has begun a collaboration with the CAPT project through diagnosis of CAPT integrations in regions of subtropical marine boundary layer clouds. She has performed 5 day forecasts of the NCAR CAM3 initialized with ECMWF reanalyses for June to August 1998 and analyzed the simulation of the marine boundary layer along a line between the Californian coast and the dateline at the Equator (Figure 5). This line passes through the stratocumulus region near 25N, 130W and the Inter-tropical convection zone near 7N, 160W where deep convection occurs. This line has been selected for study as part of the GCSS Pacific Cross-section Intercomparison of climate and weather forecast models (http://www.bom.gov.au/bmrc/wefor/staff/cnj/GCSS_pacific_case_final_files/frame.htm). (GCSS is the GEWEX Cloud Systems Study project (Randall et al. 2003, http://www.gewex.org/gcss.html) and GEWEX is the Global Energy and Water Experiment.) Figure 6 shows the mean CAM3 biases in temperature and water vapor in one and five day forecasts in a vertical cross-section along this line. Within the first day,

the lower troposphere along the whole of the cross-section dries relative to the ECMWF analyses accompanied by a warming in the upper troposphere in the tropical deep-convective zone. By day 5 of the forecasts the upper troposphere warm bias has spread to the sub-tropics with increased warm and dry biases biases between 800 and 900 hPa in the stratocumulus region. These latter biases are indicative of a boundary layer which is too shallow with the consequence that the warmer and drier air that is above the boundary layer sinks to a level of the atmosphere where it should not be. These biases in the stratocumulus region are likely to be caused by the parameterization of boundary layer and shallow convective mixing in the CAM3 and it is hoped that these biases will be alleviated by a new representation that is in advanced stage of testing by Chris Bretherton (Grenier and Bretherton 2001, Bretherton et al. 2004). The correspondence between the errors in day 5 forecasts and the climate errors of the model (shown in the right column of Figure 6) suggests that the errors seen in the forecasts of the model are relevant to climate errors – the premise of the CAPT project.

Future Work

In the last two years, the CAPT project has made considerable progress in broadening its impact by adding the GFDL climate model and examining the simulation of moist processes at sites other than the ARM Oklahoma site. The examination of CAPT forecasts at new locations permits examination of phenomena as diverse as tropical convection, marine stratocumulus, and Arctic clouds.

For future work, CAPT will examine the simulations of tropical convection for two new field experiments of the ARM program. Of particular interest is the Tropical

Warm Pool – International Cloud Experiment (http://science.arm.gov/twpice/) which was conducted at Darwin, Australia in January and February 2006 and had an extensive set of observations including a sounding array network comparable to that in TOGA-COARE. Also of interest is the African Monsoon Multi-disciplinary Analyses experiment (http://www.amma-international.org/) in West Africa in the summer of 2006. It is hoped that observations from cloud and precipitation from radars based in Niamey, Niger will provide an unprecedented view of African monsoon convection. To simulate these periods, access to the operational analyses of the National Center for Experimental Prediction and the Goddard Data Assimilation Office has been secured.

A new area of interest for future CAPT work is greater use of new satellite data, particularly the National Aeronautics and Space Administration (NASA) CLOUDSAT (Stephens et al. 2002, http://cloudsat.atmos.colostate.edu/). The CLOUDSAT was successfully launched in April 2006 and consists of a cloud radar and lidar that provide the first global survey of cloud vertical structure. The CAPT project has received funding from NASA for a post-doctoral student to use CLOUDSAT data to evaluate the clouds simulated in CAPT forecasts.

Another anticipated area of future work includes the evaluation of the next versions of the NCAR and GFDL climate models that are now undergoing intense development. Both climate modeling centers will develop a new model by the end of 2007 and it is hoped that the evaluations of the CAPT project can play an important role in the model development process. In particular, the CAPT project will provide evaluation of the impact on the NCAR model of the new boundary layer and shallow

convection parameterizations by Bretherton and the impact on the GFDL model of the new deep convection parameterization by Leo Donner (Donner et al. 2001).

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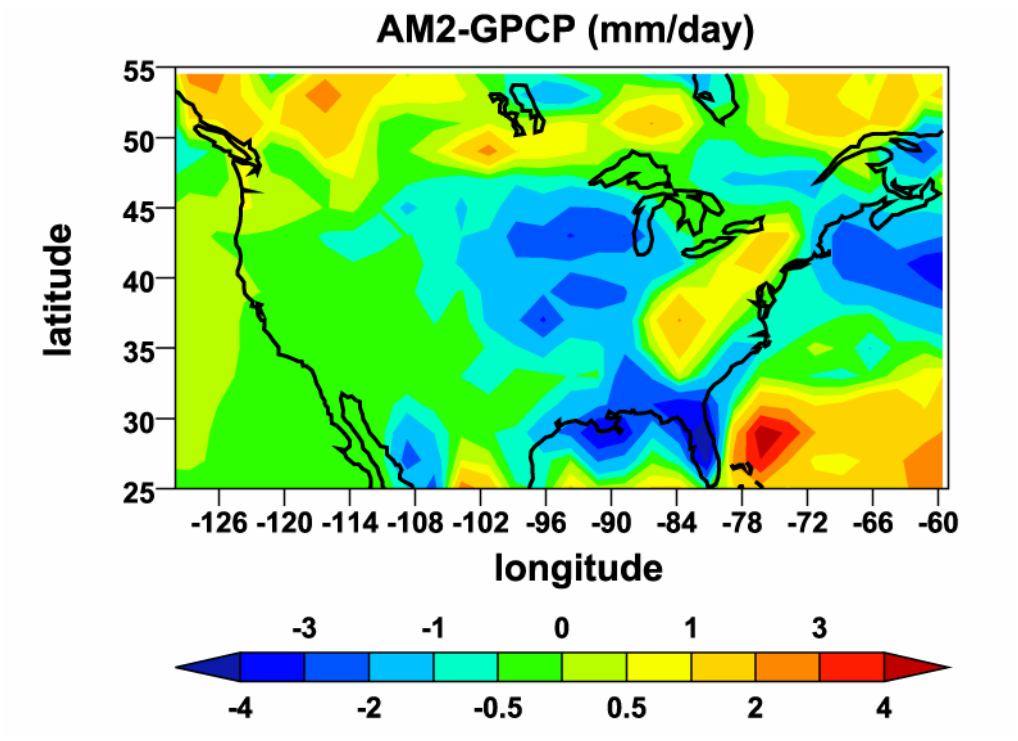
Figure 1. The error in summertime precipitation simulated by the GFDL climate model (model minus observation). The upper panel displays the error in the first day of CAPT weather forecasts for June-July 1997, and the bottom panel displays the June through August error of the model when run in climate mode.

CAPT Forecast Error



Climate Error

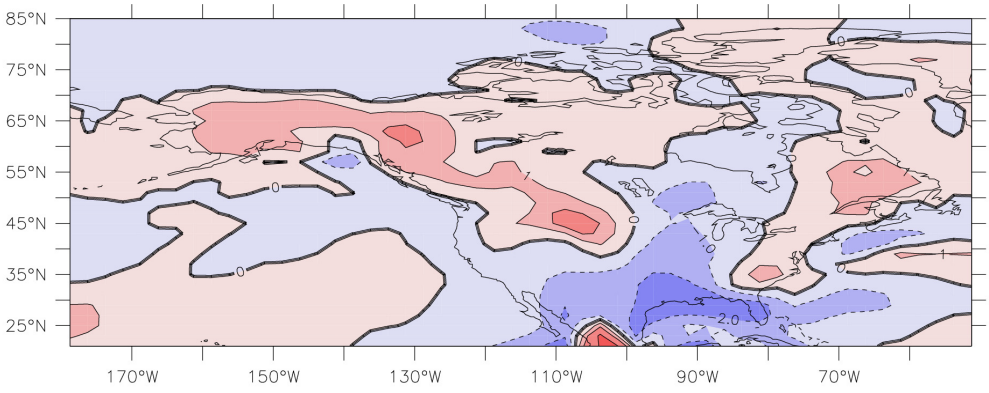


Figure 2. Time-height plots of cloud fraction from ARM observations (ARSCL) and CAPT forecasts of the NCAR (CAM3T85) and GFDL (AM2N90) models for October 2004 at ARM's Barrow, Alaska site. Note that the model data is plotted as a concatenated time series of data from hours 12 to 36 of forecasts that begin every day.

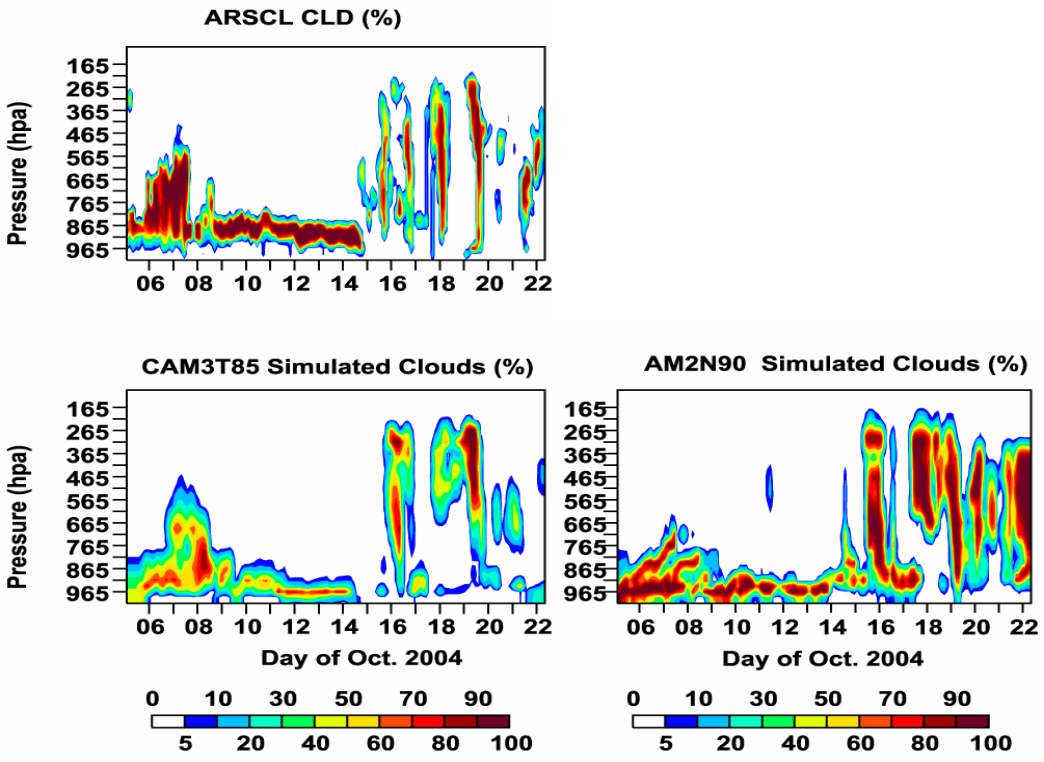


Figure 3. Time series of cloud liquid water path and ice water path for October 2004 at ARM's Barrow, Alaska site. Solid lines indicate the output from CAPT forecasts with the NCAR (red) and GFDL (blue) model as well as that of the ECMWF forecast model (black, ECMWF is the weather prediction model of the European Centre for Medium Range Weather Forecasts). In the top figure, the ARM observations of liquid water path are indicated by the black circles. ARM's observations of ice water path were not available for this comparison. For the CAPT models, data is taken from hours 12 to 36 of forecasts initialized daily.

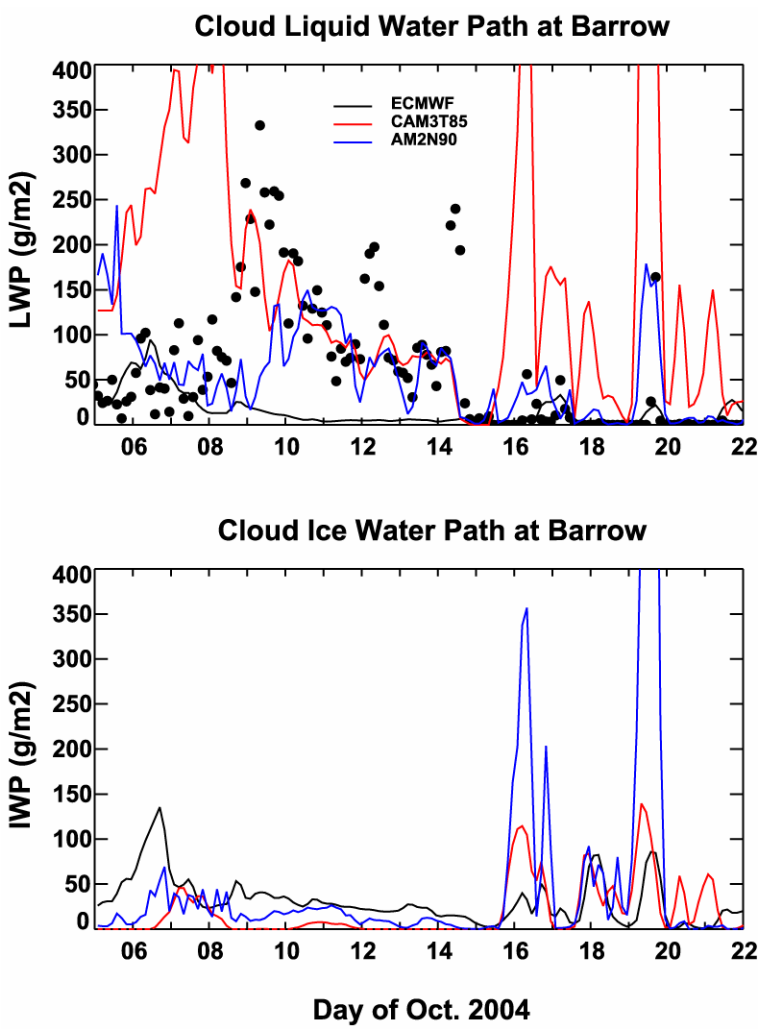


Figure 4. Time series of daily mean precipitation at the location of the TOGA-COARE experiment in the Tropical Western Pacific between November 1992 and March 1993 from the observations and CAPT day 3 forecasts. For the GFDL model, the time series of precipitation from the convection parameterization (Relaxed Arakawa Schubert, Moorthi and Suarez 1992) and large-scale condensation are shown in black and red, respectively. For the NCAR model, the time series of precipitation from the principal convection parameterization (Zhang-McFarlane 1993) is indicated in black whereas the precipitation from the large-scale condensation and the Hack shallow convection parameterizations (Hack 1994) are shown in red and green, respectively.

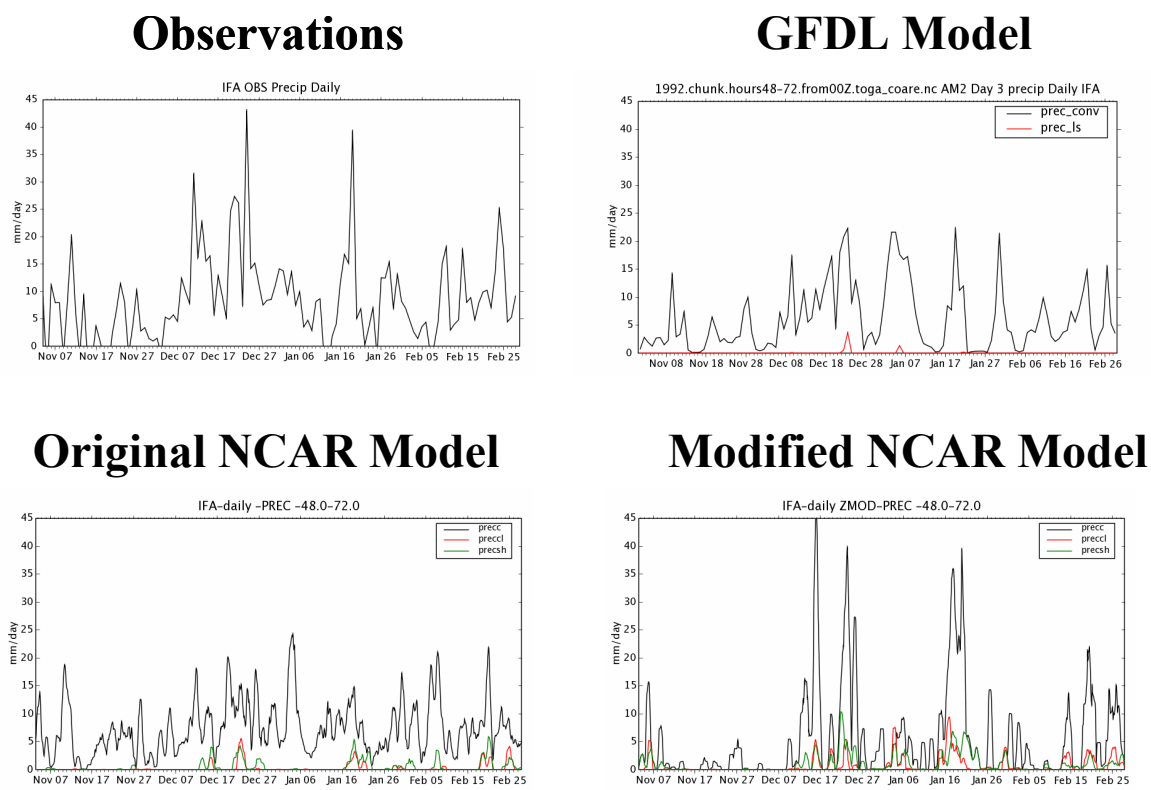


Figure 5. GCSS Pacific Cross-section Intercomparison project analysis line (black line with black circles) overlain on the climatological annual mean amount of clouds at low and higher levels from the satellite observations of the International Satellite Cloud Climatology Project (Rossow and Schiffer 1999).

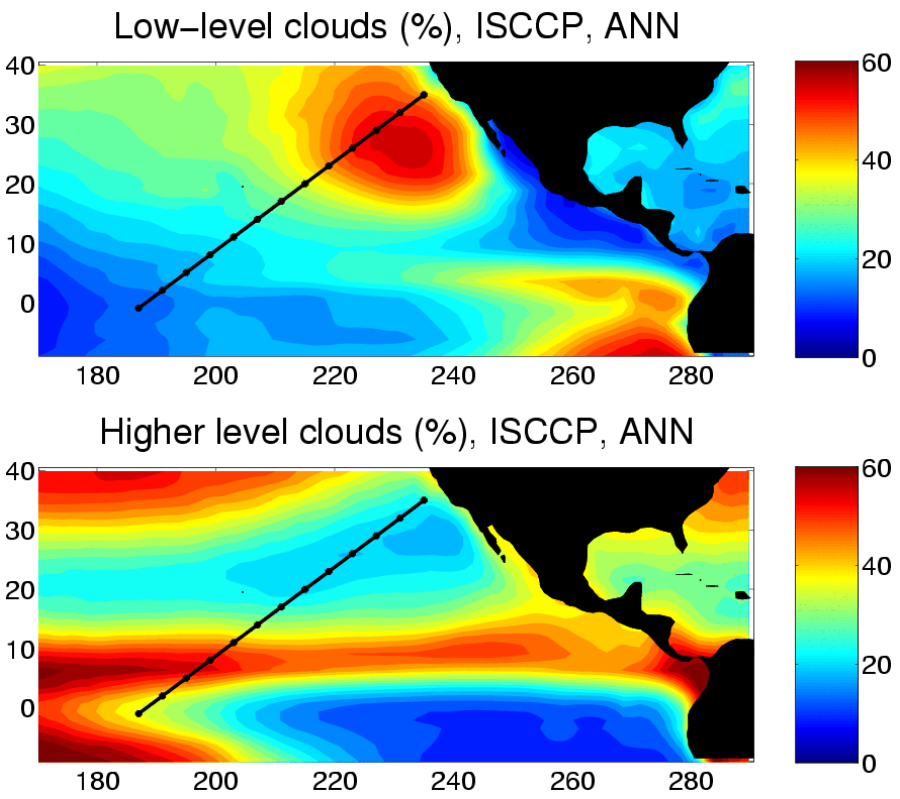
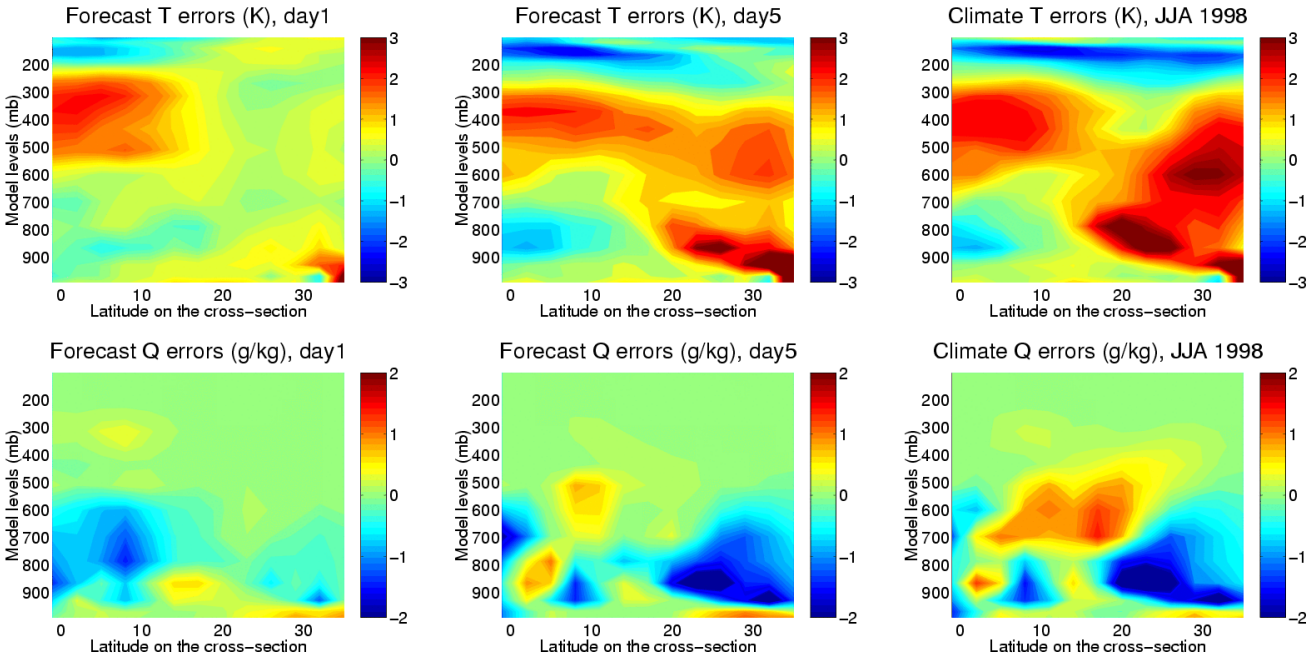



Figure 6. The mean biases relative to ECMWF reanalysis in 1 (left) and 5 day (center) temperature (top) and water vapor (bottom) CAM3 forecasts for June through August 1998 along the GEWEX Cross-Pacific Intercomparison line. Model biases for the same locations and season from a climate integration of CAM3 with observed sea surface temperatures are shown in the right column.