VALIDATING MODELED KWAJEX CONVECTIVE SYSTEMS

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Abstract. *Experimental data are used to verify simulations from the Goddard Cumulus Ensemble (GCE) Model of tropical convective systems observed during KWAJEX to determine whether model simulations driven by observations (i.e. 'continuously forced convection') can realistically represent observed precipitation fields while maintaining accurate boundary layer characteristics. Focus is placed on a convective event that occurred between August 7 and 12, 1999, and on the lower 1000 meters of the atmosphere, where tethered balloon data capture important convective boundary layer characteristics. Comparisons are made between fourteen tethered balloon profiles and instantaneous model values, which are averaged over the domain and sampled from the nearest hour. The lowest six vertical model grid points are used. Results agree with previous findings that the GCE model, like other cloud resolving models, tends to have a cold, dry bias, despite being continuously forced by observations. The model immediately develops a temperature bias at a mean rate of approximately -0.5^{o}C day^{-1} resulting in a final bias of about -4^{o}C, with the higher levels of the model performing slightly better. The model resolves humidity slightly better at the lower levels, and in the initial stages of the simulation, but eventually degrades to a specific humidity bias of approximately -4g kg^{-1}. Model calculated fluxes agree well with measured eddy covariance fluxes. Qualitatively, simulated precipitation matches features observed with radar, which shows the relatively short-lived and unorganized nature of the convective systems observed during KWAJEX. The crucial model calculation, precipitation amount, also matches observations well.*

INTRODUCTION

Cloud resolving models are an important tool and have been used to study many processes in atmospheric science, including trace gas transport (Scala et al., 1990; Pickering et al., 1992; Thompson et al., 1997), cloud-ocean surface interactions (Tao et al., 1991; Wang et al., 1996, 2001), and radiative transfer processes (Tao et al., 1991, 1993, 1996; Sui et al., 1998). The Tropical Rainfall Measuring Mission relies on cloud resolving models (i.e. the Goddard Cumulus Ensemble Model) to validate remotely sensed estimates of precipitation and diabatic heating, and also provide a continuous description of the fields retrieved from space (e.g. Tao et al., 1990, 1993). This helps in achieving TRMM project goals (Simpson et al., 1998), and achieving important science objectives, such as understanding the variability of tropical rainfall and diabatic heating, over a range of spatial and temporal scales.

Successful numerical cloud modeling relies on having quality initial and boundary conditions, as well as verification and evaluation with reliable observations. This study presents a verification of the GCE model using a high quality tethered balloon data set acquired during KWAJEX. Measured eddy covariance fluxes and precipitation are also used to verify the model. Issues related to assimilating the spatial and temporal resolution are discussed.

METHODS

Site characteristics

As part of the ground validation of the Tropical Rainfall Measuring Mission (TRMM), the Kwajalein Experiment

(KWAJEX) took place during July to September, 1999 at the Kwajalein Atoll, Republic of the Marshall Islands, in the tropical Pacific. To validate remotely sensed estimates of rainfall from the TRMM satellite, a precipitation radar and network of rain gauges were established on the Kwajalein Atoll. For further validation, boundary layer dynamics were investigated through the use of aircraft, radiosondes, a tethersonde, and a micrometeorological tower. Data sets from a combination of these platforms have been used to analyze and model three separate convective events during KWAJEX.

Measurement system

This paper focuses on the lower 1000 meters of the tropical marine boundary layer. To examine the dynamics of this layer, and also validate the GCE model output, we use data collected by a tethered balloon system. The tethered balloon was operated coincident with the micrometeorological tower, located at Meck Island, Kwajalein Atoll, (Latitude N 8° 43', Longitude E 167° 44'). A 10-meter tower located 3 meters from the high tide line on the windward side of the island served as a platform to measure surface meteorology, including temperature at five heights, relative humidity at two heights, wind speed and direction, dewpoint temperature, water vapor concentrations at 4 heights, incoming solar and ultra-violet radiation, and atmospheric pressure. An eddy covariance system was deployed on the tower at 9.5 meters above the surface. The system consisted of a 3-D sonic anemometer (Gill K12) and closed path infrared gas analyzer (LiCor LI-6262) operating at 10 Hz, and provided half-hourly fluxes of sensible heat, water vapor, and momentum. The tethered balloon lifted an instrumented sonde, which ascended and descended at a fixed rate of 1 m/s through the use of a hydraulic winch. The tethersonde measured wind speed and direction, temperature, relative humidity, and atmospheric pressure at 2-meter vertical resolution. Conditions permitting, boundary layer profiles were made with the tethersonde system every six hours: 05:00, 11:00, 17:00, and 23:00 Local Time (Local Time = UTC+12 hours).

Model characteristics

The GCE model is described in detail in Tao et al. (1993), Tao and Simpson (1993), Simpson and Tao (1993), with recent improvements included in Tao et al (2002). This study includes results from the two-dimension version of the GCE model. The model flow is anelastic, i.e. sound waves are filtered out by omitting the local time change in air density in the mass equation. Cyclical lateral boundary conditions are used in this case, and a stretched vertical coordinate (height increments from 103 to 1120 m) is used to maximize resolution closer to the surface, with a total of 37 vertical grid points, and horizontal domain size of 512x512 km. Cloud microphysics includes a two-category water scheme (cloud water and rain) and three-category ice scheme (cloud ice, snow, and hail/graupel). Shortwave and longwave radiative processes as well as a subgrid-scale (1.5 order) turbulence scheme are also included in the model. The scalar variables, potential temperature, water vapor, turbulence coefficient, and all five hydrometeor classes, use the Multi-dimensional Positive Definite Advection Transport Algorithm (MPDATA, Smolarkiewicz and Grabowski, 1990) for advection. The dynamic variables (horizontal and vertical winds) use a second-order accurate advection scheme and a leapfrog time integration (kinetic energy semi-conserving method). The large-scale forcing (time series of Q1 and Q2) derived from an observational network of rawinsondes by M. Zhang is applied to the model to generate ‘continuously forced convection’.

Comparison logistics

For boundary layer data, comparison periods are limited by the frequency of tethered balloon flights. The nature of the tethered balloon allows for flights to only occur during relatively quiescent conditions. Therefore, deviations from the nominal 6-hour schedule occurred, and data were never recorded *during* active convective disturbances. Model data were outputted every hour, so comparisons were made between available tethered balloon data and the closest corresponding hour of model data. In the vertical, overlap occurs between the tethered balloon and the lowest 6 model points corresponding to: 40, 145, 280, 440, 630, and 850 meters. Raw tethered balloon data are recorded at 2-meter resolution. For comparison purposes, the tethered balloon data are despiked and linearly interpolated to 10-meter resolution, and data from the 6 corresponding heights are extracted.

Measured eddy covariance fluxes are available every 30-minutes. The model uses the TOGA-COARE flux algorithm (Fairall et al., 1996) for computing fluxes every three minutes. Model fluxes are computed using the model temperature, humidity, and wind speed at the lowest model grid point (40 meters) and are recorded once an hour. To achieve some coherency with the tethered balloon data, both measured and modeled fluxes are averaged over 6 hours.

A series of precipitation observations were compiled and subjected to variational analysis by M. Zhang (ftp://atmgcm.msrc.sunysb.edu/pub/trmm/kwjx/readme). Radar measurements come from the radar operated by the University of Washington on Kwajalein Island. Three-hourly radar data at 2x2 km resolution were averaged over the domain to produce 6 hour averages. Rain gauge data come from sites on Carlos, Gagan, Kwajalein, and Roi islands. The final operational product is a 6-hour average rain rate from a combination of the radar and network of four raingauges.

RESULTS

Comparisons of flux data shows that the model successfully resolves the marine fluxes using the TOGA-COARE algorithm. Figure 1 shows the time series of modeled and measured sensible and latent heat fluxes. The modeled sensible heat flux captures many of the features and temporal variation of the eddy covariance flux. However, the measured flux is consistently slightly higher than the model. The model fluxes are computed using the TOGA-COARE algorithm for open ocean. Fluxes were actually measured at the edge of Meck Island, so there is potentially some land effect augmenting the heat flux. Modeled latent heat flux is very similar in magnitude to the measured flux. The model matches some of the observed features, but the variations are subtle, and the measured latent heat flux is slightly noisy, so that the actual correlation is relatively low.

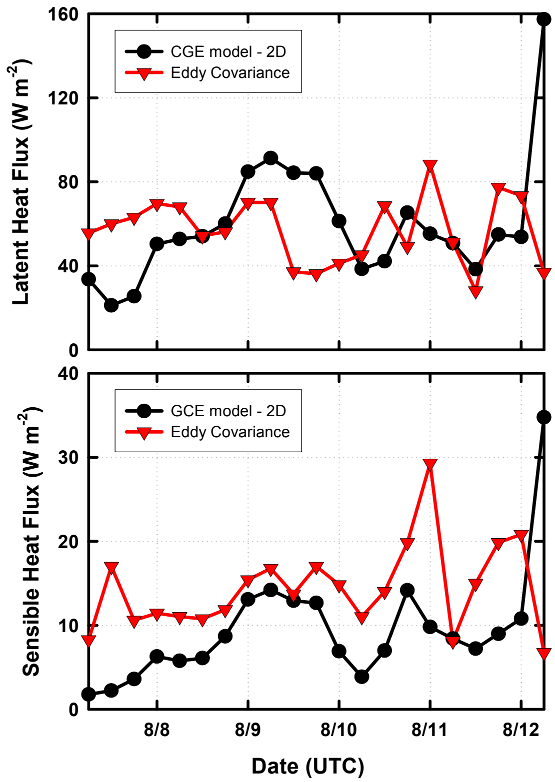

Figure 1. Time series of latent and sensible heat fluxes from both the GCE model and eddy covariance measurements during August 7-12, 1999.

Results from the tethered balloon comparison reveal some inconsistencies between measurements and model. Figure 2 shows the comparison of model air temperature versus tethered balloon temperature. Although the correlation of the two quantities is high (R^2=0.85), the model exhibits an average bias of approximately -3.0 degrees from measurements. To illustrate more clearly how this model bias evolves in time and space, Figure 3 shows the time series of model air temperature bias ($Tair_{model} - Tair_{tethered\ balloon}$). The bias is plotted for each model height that was available for comparison. The first comparison occurs at approximately 10:00 UTC on August 7, four hours after model initialization. By this time, the model generates air temperatures roughly 1.5 degrees lower than measurements. As the simulation progresses, the model temperature continues to diverge from measurements at a rate of approximately -0.5 ^{o}C day^{-1}. At the end of the simulation the model is roughly 4 degrees too cool, with the deepest model layer in the comparison (850m) performing slightly better.

Figure 4 shows the relationship of model relative humidity versus measured tethered balloon relative humidity. In this case, the correlation is quite low (R^2 = 0.027), as the model humidity is restricted to a smaller range than the measured humidity, which ranges from 70-100%. This inconsistency is largely related to the common complication of verifying model data with measurements of different temporal and spatial resolution. In this case, the measurements represent a point, a single vertical profile of the atmosphere at a discrete time. Although the model data also represent a discrete moment in time, we have used a domain average for comparison purposes. In the case of relative humidity, this means that a domain average represents a combination of both saturated and unsaturated cells, such that the average can never be saturated. This is illustrated in Figure 4, where on the plot the model data are constrained to a relatively narrow band, while the tethered balloon measured parcels of air ranging from relatively dry for the tropical atmosphere, to saturated. Thus, in this manner, a comparison of relative humidity will always be flawed.

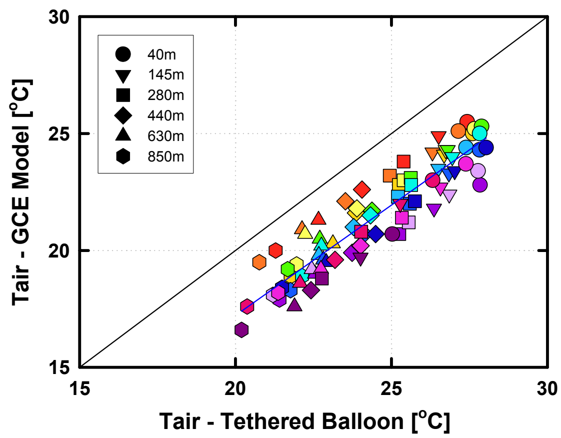

Figure 2. Model air temperature versus tethered balloon temperature for August 7-12, 1999. The legend indicates the comparison heights in meters. The linear regression and 1:1 lines are shown for reference.

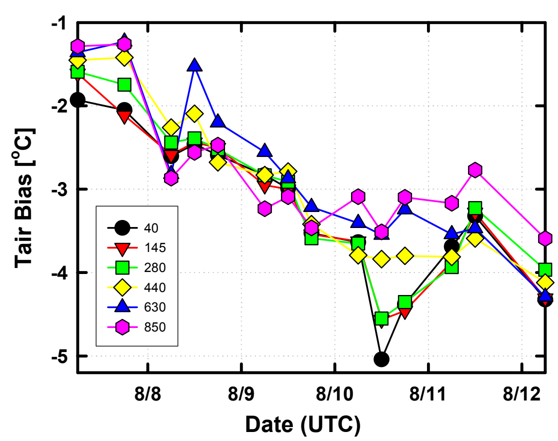

Figure 3. Time series of model bias in air temperature, defined as $T_{model} - T_{tethered\ balloon}$. Heights are indicated in the legend in meters.

The time series of the bias in relative humidity (Figure 5) more clearly illustrates how the model evolves in time. Initially, the three levels closest to the surface are too moist by about 5%, while the deeper three layers are too dry, also by about 5%. As time progress, the lower levels do well, staying close to the zero bias line. Eventually, the simulation ends with only the points at 280 and 850 meters resulting too dry. Averaged over the whole simulation, the lower two model levels were too moist by 2.5%, the 280m level had zero bias, and the deepest 3 layers were too moist by 3.2%.

Figure 6 shows the relationship between modeled and measured specific humidity. The least squares regression line has R^2 = 0.44, indicating that the model captures a significant amount of the variation in measured specific humidity. But the position of the regression line illustrates that on average the model is drier than measurements. Figure 7 illustrates how this dry bias evolves with time. At the first comparison point, after four hours of simulation, the lowest three model points are biased by -0.8 g kg^{-1}, and the highest three points are biased by -2.1 g kg^{-1}. This stratification remains mostly in tact until precipitation begins to fall around 00:00 UTC on August 9. After this point, the bias at all heights becomes similar, and begins to settle to a final average bias of approximately -4 g kg^{-1}.

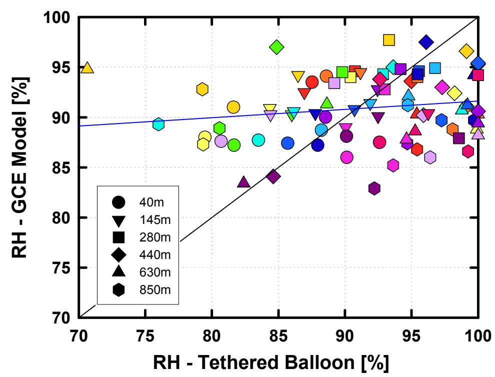

Figure 4. Model relative humidity versus measured tethered balloon relative humidity (%).

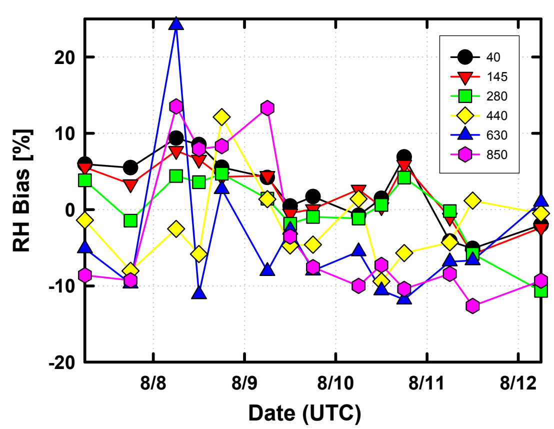

Figure 5. Time series of the model bias in relative humidity (%).

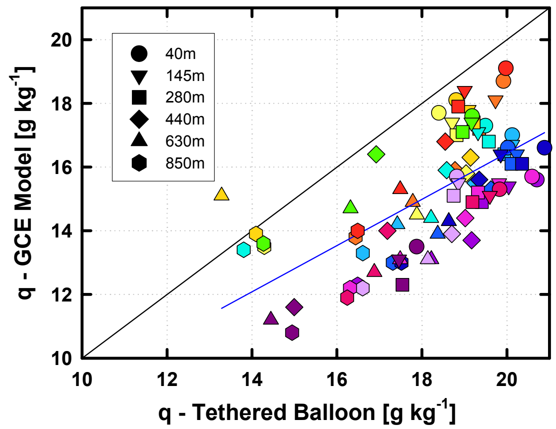

Figure 6. Model specific humidity versus measured tethered balloon specific humidity.

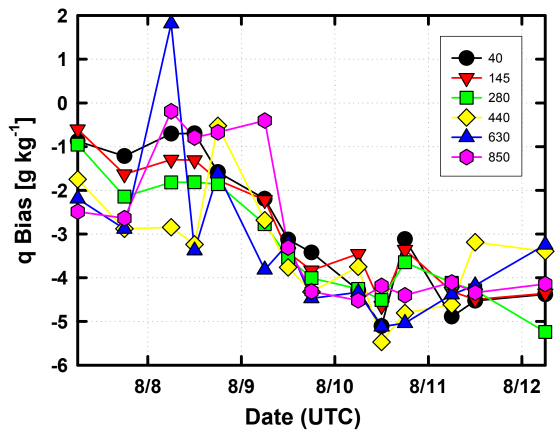

Figure 7. Time series of model bias in specific humidity (g kg^{-1}).

In the context of TRMM and this study, the ultimate success of the model depends on its ability to resolve the major precipitation features of convective systems observed during KWAJEX. Figures 8 and 9 illustrate the model's ability to successfully resolve the qualitative features of convection observed by radar. Radar observations (e.g. Figure 8) recorded the relatively short-lived and unorganized nature of convection at Kwajalein. The model simulated surface rain rate shown in Figure 9 illustrates how the model captures these same features observed with radar.

Quantitatively, Figure 10 shows that the model reproduces the amount of precipitation falling in the domain very well. Both the moderate and deep convective events of 8/10 and 8/12, respectively, are resolved well by the model. The timing and amount of modeled rainfall agree closely with observations.

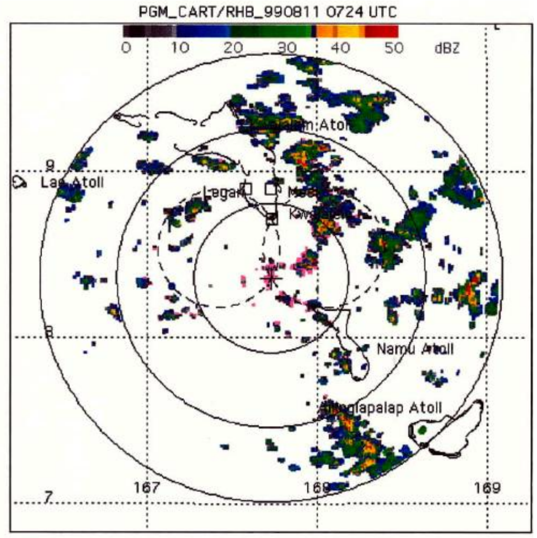

Figure 8. Base reflectivity for 07:24 UTC during the moderate convective disturbance on August 11. The domain shown is 400x400 km (courtesy Shie et al., 2003).

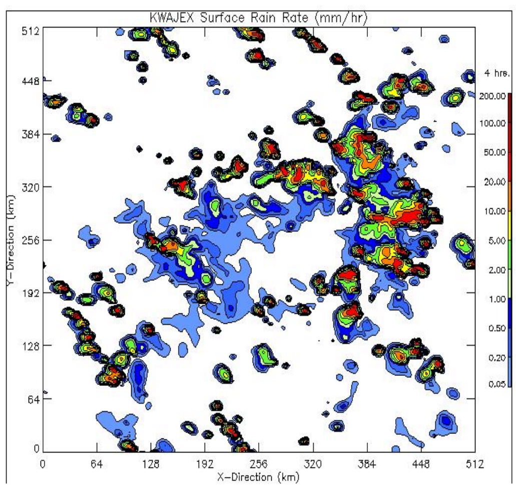

Figure 9. Surface rain rate simulated by the model for the same period shown in Figure 8. The model domain is 512x512 km (courtesy Shie et al., 2003).

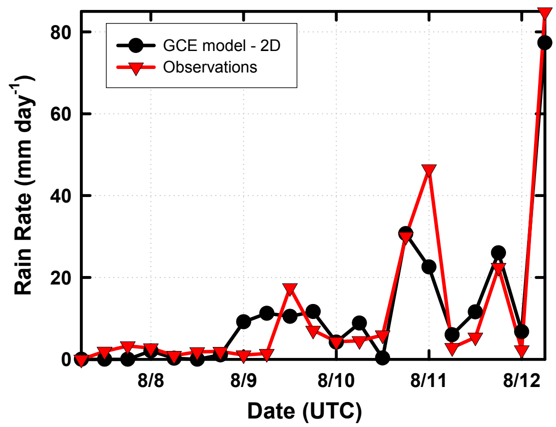

Figure 10.

DISCUSSION AND CONCLUSIONS

Results from this study show that although the model has accurate input of energy from the surface (i.e. heat fluxes), the mean model boundary layer characteristics diverge with time from observations similar to those used to force the model. However, despite the lowest 1 kilometer of the model being too cool and dry, the model nevertheless realistically resolves both the quantity and temporal variability of precipitation observed during KWAJEX. The reason for this is unknown, and is a currently being investigated. A likely mechanism is the model radiation calculations. Because the model becomes too dry and too cool, there could be a water vapor-temperature feedback in which the model is cooling due to the lack of warming from water vapor absorption. Decreasing simulated temperatures in the model would lower the calculation of the saturation vapor pressure, artificially increasing RH. However, the actual vapor pressure is decreasing as well, as illustrated by the drying seen in specific humidity.

Issues related to comparing the model domain versus the point measurement also affect the results of the comparison, and reflect on the fidelity of the model output. Rather than using a domain average, data could be sampled from the undisturbed areas of the model. Using the model point corresponding to the geographical location of the measurements is not possible because of the cyclic boundary conditions used in the model. However, using better sampling techniques may not effect or improve the results presented in this study very drastically. For example, this study found that the model simulated conditions that were too dry, even when a domain average was used, which included saturated or disturbed model cells. Excluding these cells would seemingly only produce drier model results. Effort should therefore be placed on determining the dynamics of the model that are producing the inconsistencies, rather than on improving the sampling techniques for verification.

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