# Simulation of Precipitating Shallow Cumuli Using a Vorticity-Based Cloud Resolving Model

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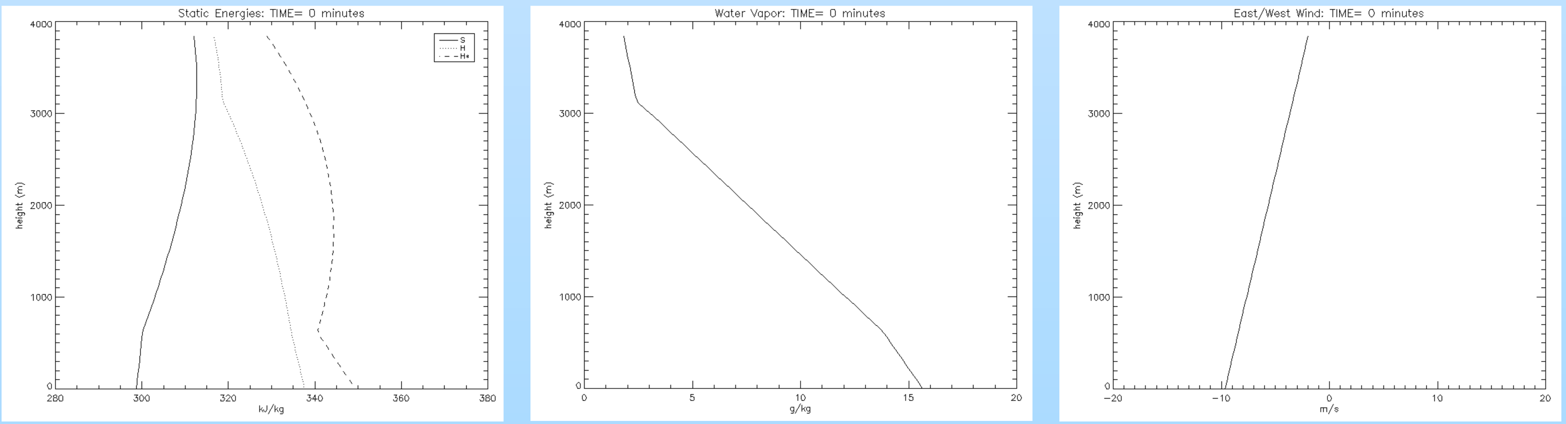
## The Model

Recently, a three-dimensional cloud resolving model was developed by Joon-Hee Jung of Colorado State University and Akio Arakawa of the University of California Los Angeles (Jung and Arakawa, 2005). Instead of using the traditional momentum equations as its dynamical core, the model employs the vector vorticity equation. This approach has several advantages. The elimination of the pressure gradient force term in the prognostic equations allows the motion field to be predicted more directly by buoyancy and avoids the problem of calculating the pressure gradient force around complex terrain. Another advantage of using the vorticity equation prognostically is that analysis of model output using vorticity dynamics is easily facilitated (Jung and Arakawa, 2006).

Experiments designed to validate the model were performed and presented in Jung and Arakawa (2005) and Jung and Arakawa (2006). To further evaluate this model, it is important to perform comparisons of its results with those from similar models using defined test cases. The Global Energy and Water Cycle Experiment (GEWEX) has provided a framework for this purpose with its GEWEX Cloud System Study (GCSS). The goal of GCSS is to improve parameterization of cloud systems for use in climate models. It accomplishes this goal with five working groups designed to facilitate in-depth study of one of the following five types of clouds systems: boundary layer, cirrus, extra-tropical layer, precipitating convective, and polar. Each working group is responsible for providing case study data sets for use in model intercomparisons. For this study, the latest case from the boundary layer working group was used.

## The Test Case

The Rain In Cumulus over the Ocean (RICO) measurement campaign performed in late 2004 and early 2005 resulted in a vast collection of data designed to provide insight into the processes at work inside shallow precipitating cumuli. The GCSS Boundary Layer Working Group developed a test case based on this data. Initial conditions are based on an average of an undisturbed 3 week period during which typical trade wind cumuli were present and a representative amount of precipitation was recorded.

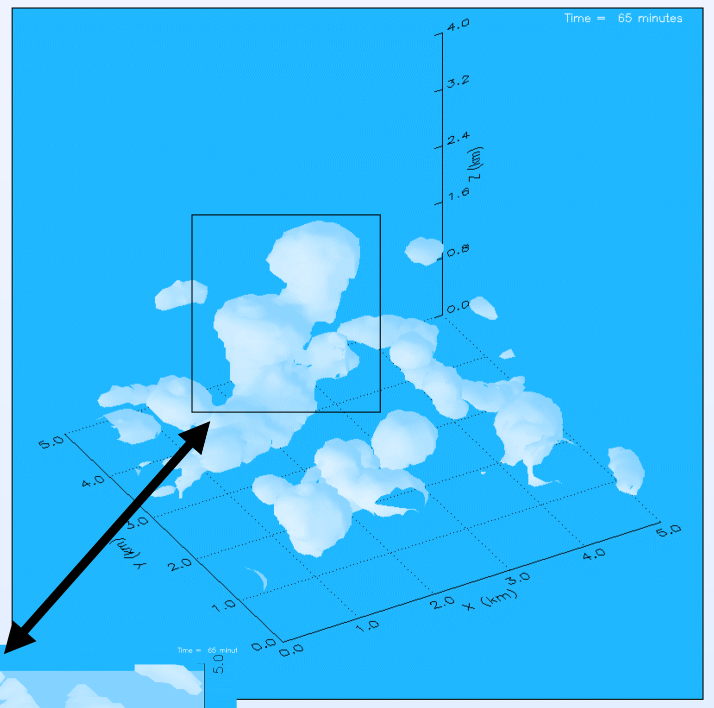



Initial conditions for the RICO case

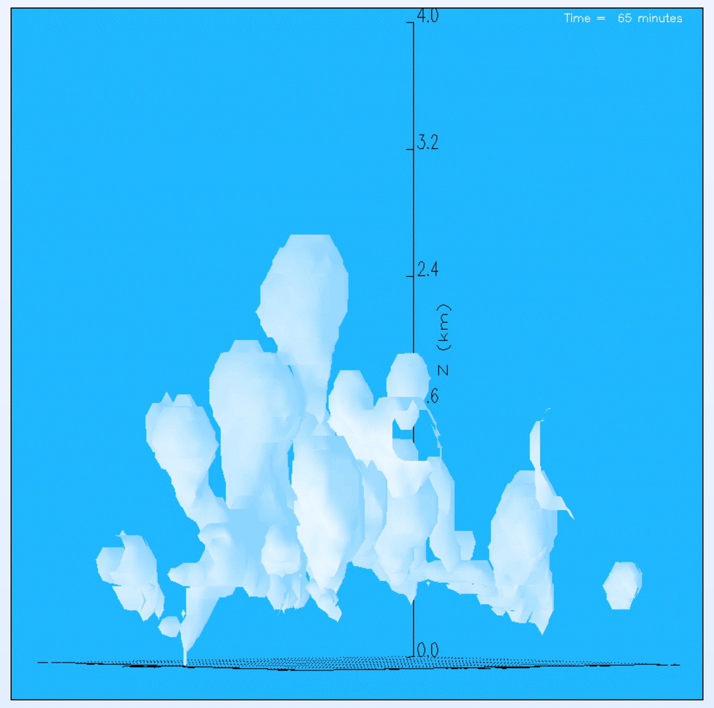
The large scale subsidence rate, temperature and moisture tendencies due to large scale advection, and the net radiative temperature tendency are all prescribed to represent warming and drying due to subsidence in the subtropics as well as other effects of the large scale environment on the model domain. Surface fluxes are parameterized by given bulk formulas. Initially, this test case was run with the first order turbulence parameterization of Shutts and Gray (1994). This introduced unrealistically strong vertical turbulent fluxes, though, so this scheme was replaced with another first order scheme by Hill (1974). To force the model, random perturbations of potential temperature and water vapor of +/- 0.1 K and +/- 2.5 * $10^{-2}$ g/kg are introduced near the surface. For this simulation, $\Delta x = \Delta y = 100$ m and $\Delta Z = 80$ m. With a 1 second timestep, the simulation was run for 12 hours. The model domain was 5 km x 5 km x 4 km.

## Selected Results

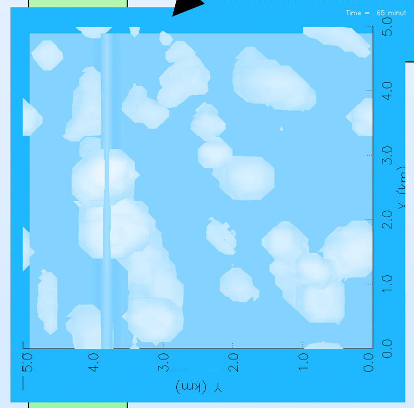
The random fluctuations of potential temperature and water vapor created clouds after about 30 minutes of simulated time. The simulated three dimensional cloud field at 65 minutes is shown below.



View from above

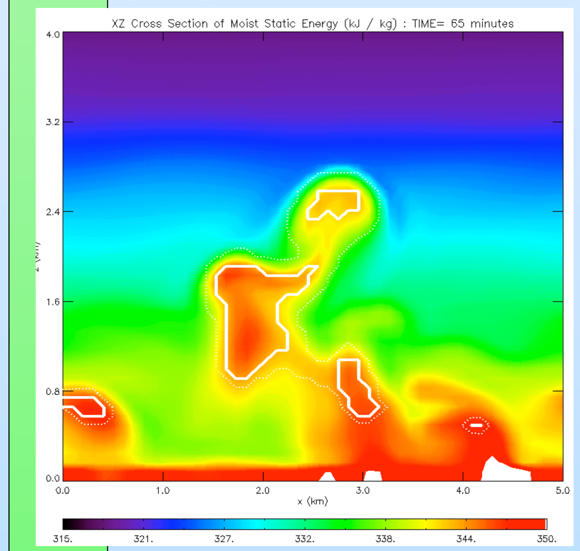


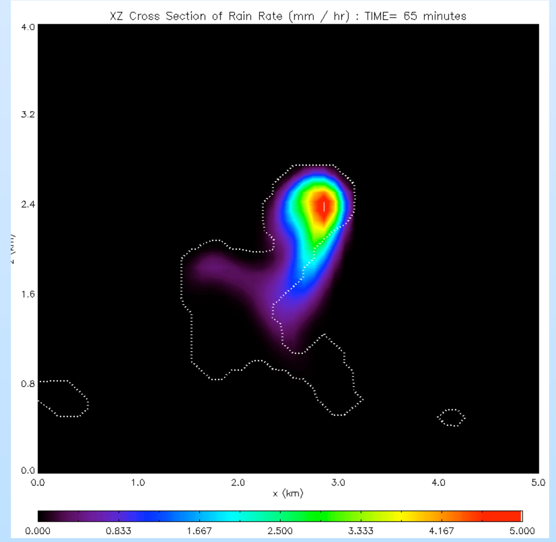
View from ground level

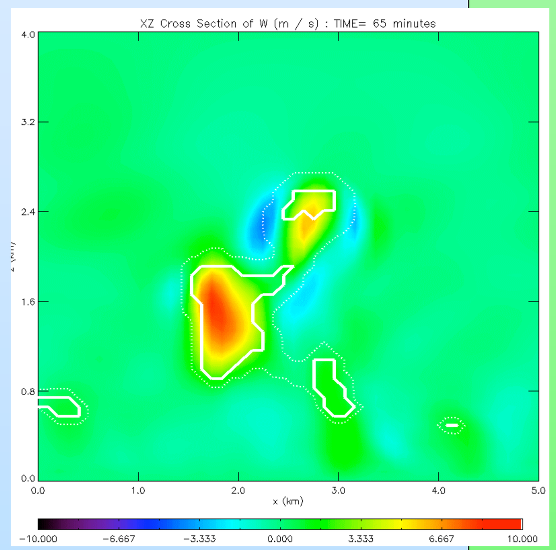


Looking straight down

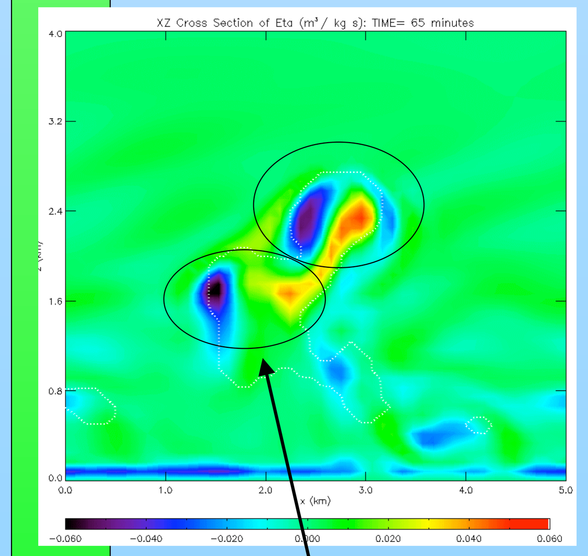
The simulated cloud field looks physical. Based on these figures, it appears as though the model was successfully able to produce shallow cumuli. In order to study a particular cloud in depth, a XZ cross-section cut was made through an active cloud.



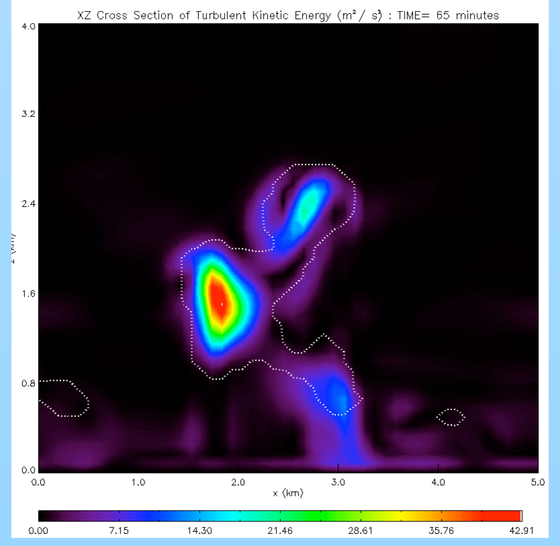




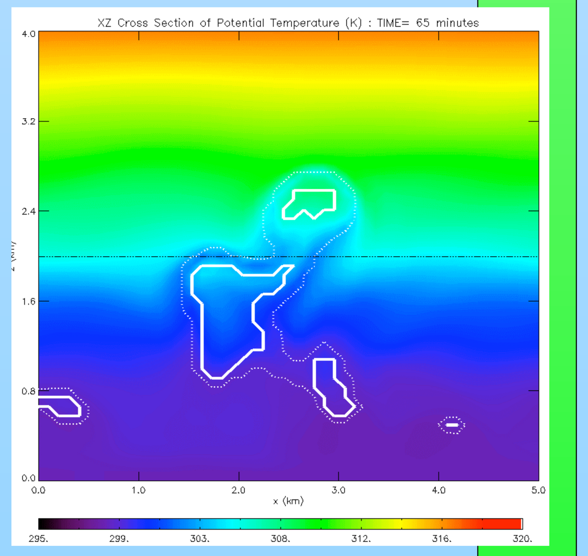
The plot of moist static energy (left) shows high values of moist static energy contained within the edges of the cloud (white dotted lines) with the highest values contained within the buoyant cloud cores (white solid lines). Plots of rain rate (center) and vertical velocity (right) are also shown above. The oldest and highest cloud core has a well-established rain shaft and weakening vertical velocity, indicating that it is in the later stages of cumulus development. The strong cell below and to the left Is just starting to form rain in its updraft. Sinking air on the fringes of the older cell is well-simulated and indicative of cloud and rain droplet evaporation and air rushing down to replace the rising warm air.



The plot of horizontal vorticity($\eta$) shows two distinct vorticity couplets. They develop at the interface between updrafts and downdrafts.

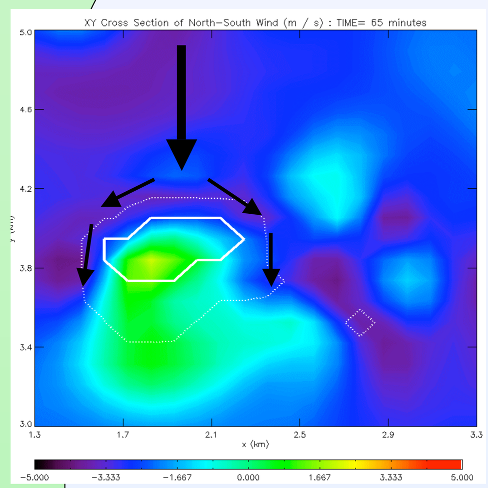


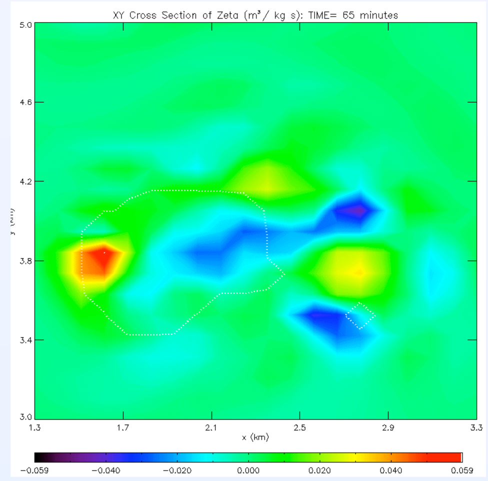
The turbulent nature of clouds is demonstrated by the high turbulence kinetic energy within the cloud edges.



The cloud cores are warm buoyant bubbles. As they rise and encounter the boundary layer top, defined here as the mean height of the maximum potential temperature gradient (dashed black line), they carry the properties of boundary layer air into the free atmosphere and push the boundary layer top upward.

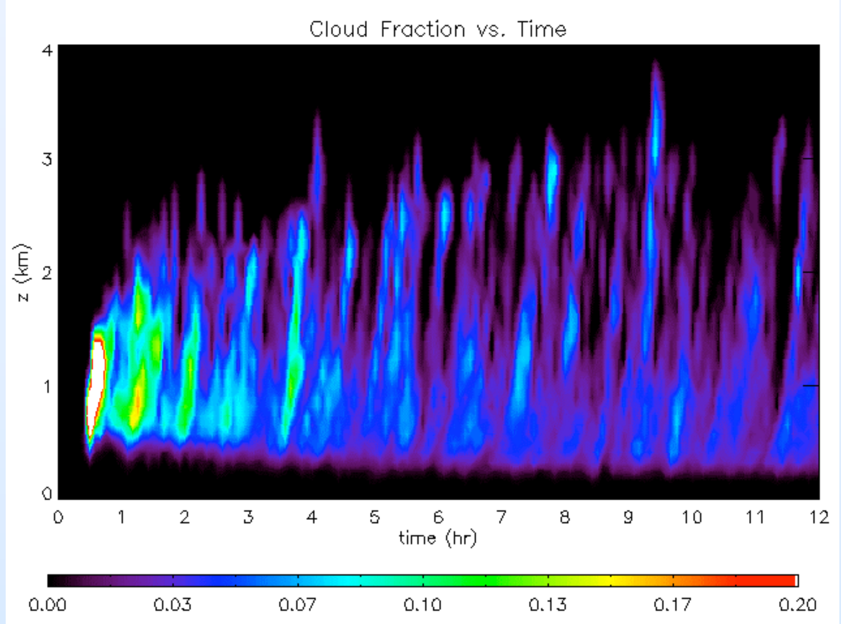
## Results (con't)

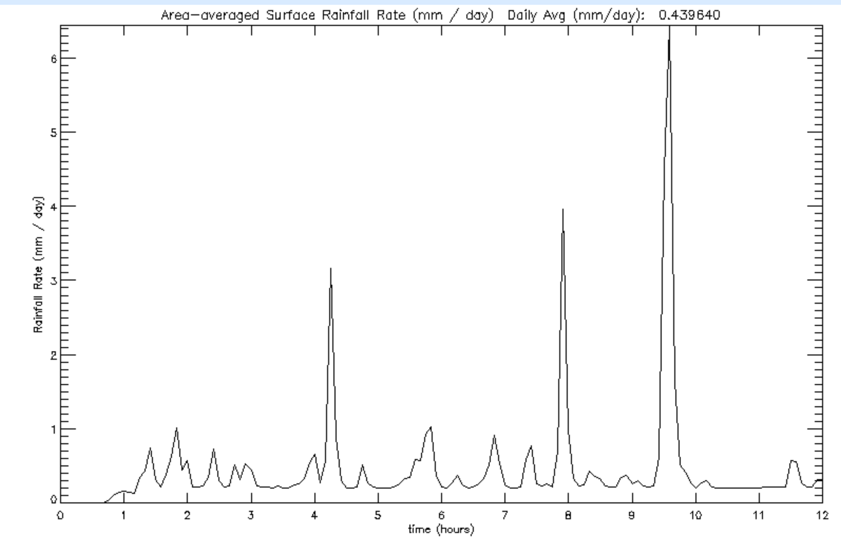


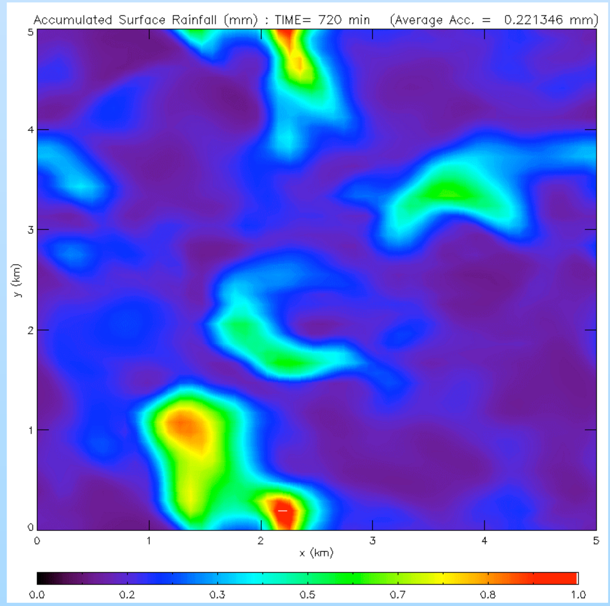


As discussed in Jung and Arakawa (2006), convectively active regions can act as barriers to the flow. Here, the northerly wind encounters an active cumulus and is diverted around the obstacle. The flow creates a vorticity couplet with positive vorticity on the right side of the updraft and negative vorticity on the left, relative to the shear vector.

One of the main questions posed by this case is whether each participating model can reproduce the observed rainfall. During the three week period on which the case was based, the area-averaged rainfall rate was 0.34 mm/day. The area-averaged rainfall rate during this simulation was 0.44 mm/day. While these numbers may be relatively close, upon examination of the rain rate time series (right, bottom), it is evident that the simulated area average may be significantly skewed by a few relatively heavy rain events. These heavy rain events coincide with periods of deeper convection (right, top). One possible explanation for the occurrence of these events is that the simulated boundary layer was allowed to deepen too much. It is possible that the first order turbulence scheme used is to blame, creating stronger than observed turbulent fluxes of moisture, providing an unrealistic amount of moisture available to the deepest penetrating clouds.





The total accumulation of rainfall at the surface is shown on the left. While most areas of the domain received less than 0.2 mm, a few areas positioned under the deepest cumuli received up to 1 mm.

## Future Work

- Continue to compare this model's results with those from other models participating in the GCSS RICO case.
- Develop and implement a 2nd or 3rd order closure turbulence scheme to better represent convective boundary layers.
- Perform sensitivity tests with different microphysics parameterizations.
- Continue to run other GCSS cases from the Boundary Layer Working Group and the Deep Convection Working group.

**References:**

Jung, J.-H., and A. Arakawa, 2005: A three-dimensional cloud model based on the vector vorticity equation. Atmospheric Science Report No. 762, Colorado State University, 56 pp.

Jung, J.-H., and A. Arakawa, 2006: A three-dimensional anelastic model based on the vector vorticity equation. Journal of the Atmospheric Sciences (submitted June 22, 2006), 51 pp.

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