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SIMULATION OF TROPICAL PRECIPITATION USING THE WEAK TEMPERATURE GRADIENT APPROXIMATION TO THE GODDARD CUMULUS ENSEMBLE MODEL

C. L. Perez,[*] A. H. Sobel,[†] G. Gu, D. Johnson, C.-L. Shie and W.-K. Tao [‡]
Columbia University, New York, NY

1. Introduction

Tropical precipitation due to deep convection is typically forced in limited area models by specifying the large-scale vertical velocity or vertical advection terms. Since the dominant thermodynamic balance in the tropics is between adiabatic cooling and diabatic heating (or vice versa), and the latter is due mostly to precipitating convection, the standard approach determines the model precipitation rate almost independently of model physics. The model thus cannot be used to address the question: what causes deep convection to occur or not occur? We apply an alternate approach, based on the Weak Temperature Gradient (WTG) approximation, to the Goddard Cumulus Ensemble Model (GCEM) (Tao et al., 2002), in order to use the model to address this question. In the WTG approach, the horizontal mean temperature profile is specified, and the large-scale vertical velocity is determined by model physics and the assumption that adiabatic cooling balances diabatic heating (Sobel and Bretherton, 2000). In this approach, the precipitation cannot be determined from the forcings independently of the model physics, and so we can use the model to understand what controls tropical deep convection. This approach has recently been applied to a cloud-resolving model by Raymond and Zeng (2003).

2. Cloud Ensemble Model

The GCEM is a full-physics cloud resolving model, run here in 2D on a domain 512 km in the horizontal, with 1km horizontal resolution and 41 vertical levels (for a full model description see Tao and Simpson (1993); Tao et al. (2002)). The horizontal boundary conditions are periodic, and the lower boundary is an ocean surface with uniform sea surface temperature (SST). Artificial momentum forcing is applied to the horizontal mean tropospheric wind to maintain a chosen vertical profile.

3. Weak Temperature Gradient Approximation

In the Tropical atmosphere, horizontal temperature gradients are weak making the dominant balance in the temperature equation between the vertical advection of potential temperature and the total heating. Thus, we can use the domain-mean total heating Q (produced by the model convection, radiation and cloud-scale advection) and the model static stability profile, $\partial\theta/\partial z$ to calculate the large-scale WTG vertical velocity w_{wtg} [called the diabatic vertical velocity by Mapes and Houze (1995)]:

$$w_{wtg} = \frac{Q}{\partial\theta/\partial z}. \qquad (1)$$

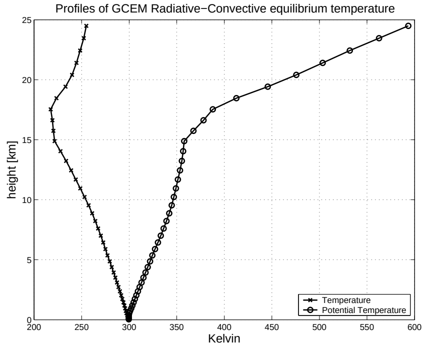

Figure 1: Radiative-Convective equilibrium vertical temperature and potential temperature profiles.

In practice, we don't use the exact WTG vertical velocity, rather we use the Raymond and Zeng (2003) procedure: we add a term which relaxes potential temperature θ towards the radiative-convective equilibrium (RCE) profile, and then the WTG vertical velocity is derived from that term (divided by the static stability). The WTG vertical velocity is then used to do large-scale advection in the moisture equation, assuming zero large-scale horizontal moisture gradient.

The RCE profile (figure 1) was obtained over a 90-day model run with a constant SST=28°C over the bottom boundary and fixed solar insolation of 341 W m^{-2}. The horizontal mean of vertical velocity was maintained at zero in order to allow the surface heating and convective cooling to come into balance. During the RCE run the model produced steady rain.

4. Experiments and Results

Keeping the horizontal mean temperature profile fixed, we varied the SST and examined the resulting statistically steady states simulated by the model, focusing on the total precipitation and rain rate. The domain averaged wind

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[*] Department of Applied Physics and Applied Mathematics and IRI, Columbia University, 61 Route 9W, PO Box 1000, Palisades, NY 10964-8000, *email*:cristina@iri.columbia.edu

[†] Department of Applied Physics and Applied Mathematics, Department of Earth and Environmental Sciences, Columbia University, New York, NY

[‡] NASA Goddard Space Flight Center, Greenbelt, MD

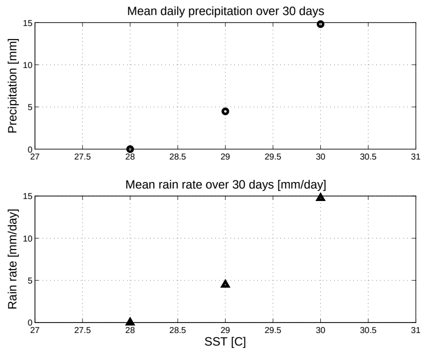

Figure 2: Daily mean total precipitation and rain rates for varying SST over a 30-day period.

was relaxed with a two-hour time scale towards a profile of 5 m s^{-2} easterlies at all levels, so there is essentially no mean vertical shear, in all experiments. Figure 2 shows the daily mean total precipitation and rain rates for three values of SST. As might be expected, the precipitation and rain rate increase strongly and nonlinearly with SST. The precipitation statistics for the wet cases, SST=29°C and SST=30°C, were similar when the model run was continued another month, for a total of 60 days (not shown).

In the experiment with an SST of 28°C, the same value used to obtain the RCE profile, the WTG model does not reproduce the rainfall rate obtained in the RCE simulation; instead, it attained a dry state (figure 2). This result corresponds to one obtained by Raymond and Zeng (2003) in experiments with their cumulus ensemble model when changing the surface wind speed instead of SST.

5. Conclusions

There is a nonlinear relationship between SST and rainfall in our simulations using the WTG approximation. The radiative-convective equilibrium state is not reproduced by the WTG model at the same SST and wind speed for which the RCE profile was obtained. Our next steps in this investigation include studying the effects of varying surface wind speed, vertical shear, and horizontal moisture advection on precipitation.

References

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