9D.1 A RATIONAL APPROACH TO CUMULUS PARAMETERIZATION

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1 INTRODUCTION

Traditionally, cumulus parameterizations in large-scale atmospheric models are simplified treatments based on plausibility arguments and followed by extensive tuning to optimize overall model behavior. The results of this approach are not always satisfactory, and have stimulated the development of so-called superparameterizations, in which a cumulus ensemble model run in each gridbox takes the place of the cumulus parameterization. Though some of the early results of this approach are encouraging, it seems unlikely that computing power will increase sufficiently in the near-term to make this approach generally feasible at spatial resolutions needed to resolve most tropical phenomena.

Assuming that cumulus ensemble models can themselves be verified against observation to sufficient accuracy, an alternative approach is to use such models to improve cumulus parameterizations. However, in order to do so, the cumulus models must be run in a realistic context, so that the full range of behaviors possible in the large-scale model is exercised. Sobel and Bretherton (2000), Derbyshire et al. (2004), and Raymond and Zeng (2000, 2005) have developed such a context, called the weak temperature gradient (WTG) approximation by Sobel and Bretherton. In this context the effects of buoyancy redistribution by gravity waves in the tropics are mimicked by relaxing the average virtual temperature profile of the model to some reference tropical profile. This relaxation may be thought of as being due to the adiabatic cooling from some vertical velocity, called the WTG vertical velocity. Vertical advection and (optionally) lateral entrainment and detrainment from the surroundings follow from this vertical motion, and are used to modify the average humidity field in the model as well. After determining how the cumulus ensemble model responds in this context to known forcing factors for deep convection, such as surface heat fluxes and environmental humidity profiles, the cumulus model is replaced by a cumulus parameterization and adjustments are made to the parameterization to make it mimic the cumulus ensemble model.

In the present paper I use this technique to test a "toy" cumulus parameterization previously used in an equatorial beta plane model to simulate the Madden-Julian oscillation (MJO). In particular, the parameterization is tuned to reproduce the dependence of the cumulus ensemble model's equilibrium mean precipitation rate on surface wind speed over an ocean with fixed sea surface temperature. This dependence has a strong effect on the development of the MJO in the model as well as smaller scale disturbances such as easterly waves, and the tuning of the cumulus parameterization using this technique results in a more vigorous MJO than in previous work with a similar model. The wide variability in predicted MJO behavior across models may be the result of (among other things) variability in this relationship.

2 CUMULUS ENSEMBLE MODEL

Figure 1 shows the results of the cumulus ensemble model in weak temperature gradient mode. The reference profile is one of radiative-convective equilibrium with a mean surface wind of 5 m s^{-1}. Rainfall is zero at low windspeeds, but increases rapidly for winds in excess of 5 m s^{-1}, exceeding the evaporation rate beyond 6 m s^{-1}. Thus, as surface fluxes pump more water into the atmosphere as a result of increased windspeed, more precipitation occurs. The latent heating and net ascent at high winds generates moisture convergence, which boosts the rainfall beyond that associated with surface fluxes alone, whereas moisture divergence at low windspeeds results in a rainfall deficit in comparison with surface

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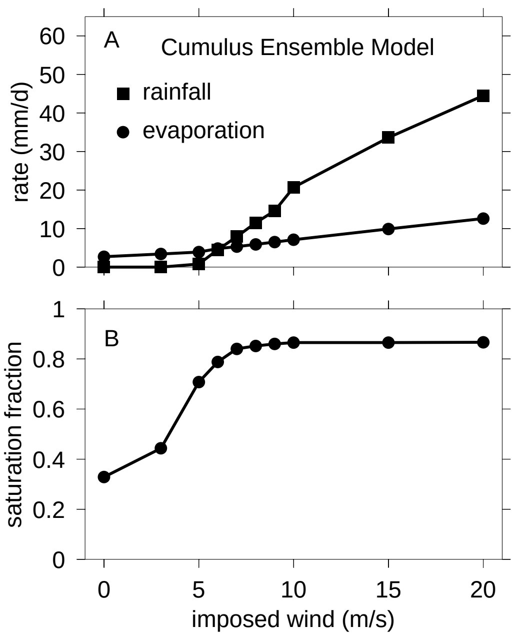

Figure 1: Cumulus ensemble model prediction of the equilibrium dependence on windspeed of (a) rainfall and evaporation rate, and (b) tropospheric saturation fraction.

moisture fluxes.

The saturation fraction of the troposphere, defined as the ratio of precipitable water to saturated precipitable water, asymptotes to about 0.85 for winds in excess of 10 m s^{-1}. The saturation fraction appears to be the primary control on precipitation in the model, with the surface moisture flux acting in a secondary fashion via its effect on the saturation fraction. The results in figure 1 represent the equilibrium state at each wind speed, i. e., after the saturation fraction adjusts to the surface fluxes associated with the imposed wind. The response of the precipitation to saturation fraction becomes very stiff at high windspeeds, which means that the surface fluxes begin to control precipitation more directly in this limit with very little adjustment time.

3 TUNING A PARAMETERIZATION

The results of the cumulus ensemble model, as expressed by figure 1, are used as a target for tuning a toy cumulus parameterization. This parameterization is an updated version of the parameterization used by Raymond (2001) in an idealized model of the MJO.

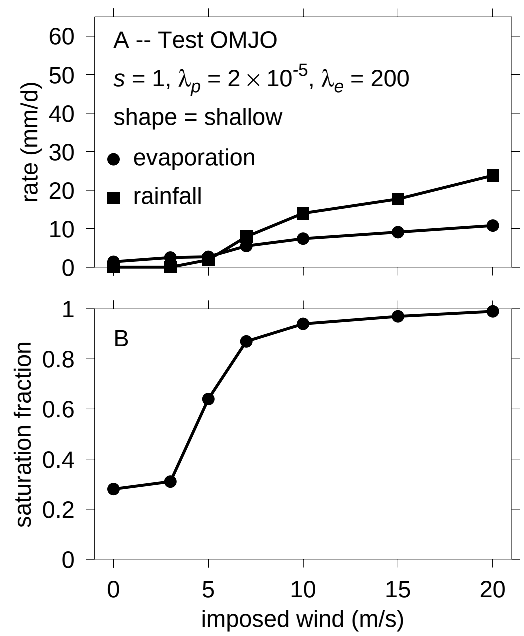

Figure 2: As in figure 1 except parameterization test OMJO.

Figure 2 shows the dependence of rainfall and evaporation rate as well as saturation fraction when the toy cumulus parameterization as used by Raymond (2001) replaces the cumulus ensemble model in the context of the weak temperature gradient approximation. Notice that the precipitation rate is not nearly as sensitive to imposed windspeed as it is in the cumulus ensemble model.

Of the three parameters mentioned in figure 2, the most interesting is the "stiffness" s of the relationship between relative humidity H and precipitation rate P:

$$P \propto H.^s$$

In the example of figure 2, the relationship is not very stiff at all, with $s = 1$. (Details are presented in Raymond, 2006, and are also available on the web at `http://www.physics.nmt.edu/~raymond/papers/mjo3.pdf`.)

Setting $s = 4$, and adjusting other parameters to match, results in a stronger dependence of precipitation rate on imposed windspeed, as figure 3 shows.

Figure 4 shows the RMS variance of the zonal wind as a function of time in a series of simulations with different sets of parameters. We focus here on the simulations S1, S2, S4, and S8. These simulations have values of the stiffness parameter s corresponding to the numbers attached to the simulation names. It is clear from this series of simulations that increasing the stiffness in the rainfall-humidity relationship

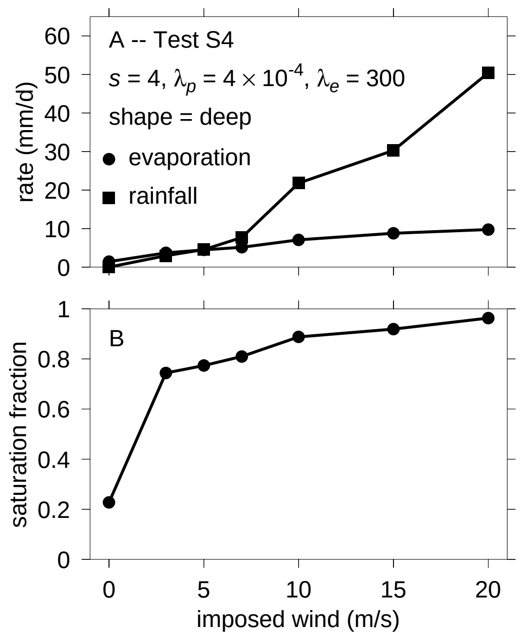

Figure 3: As in figure 2 except test S4.

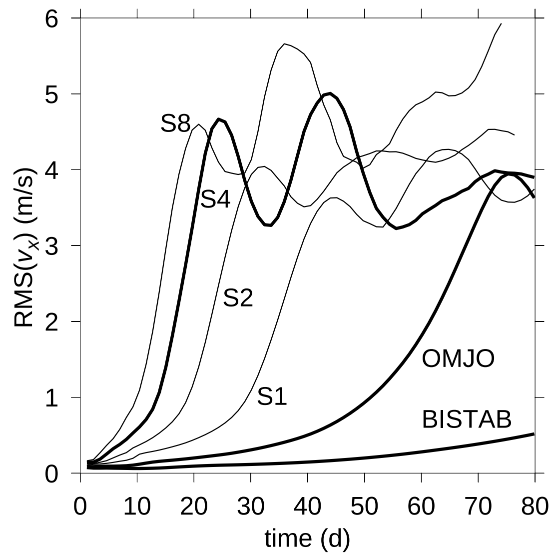

Figure 4: Root-mean-square variance as a function of time of surface zonal wind within 3000 km of the equator for simulations with different values of the stiffness parameter: S1, $s = 1$; S2, $s = 2$; S4, $s = 4$; S8, $s = 8$. The cases OMJO and BISTAB both have $s = 1$, but have other parameters differing from the S1 case.

increases the rapidity with which the simulated MJO grows in amplitude, as represented by the variance in the zonal wind. Other parameters not described here also affect the growth rate, as indicated by the weakly growing cases OMJO and BISTAB. The parameter settings in these cases are not discussed here (see Raymond, 2006 for details), but suffice it to say that the increase of precipitation in response to increased windspeed for these two cases is even weaker than is shown in figure 2. Thus, the slope of the rainfall rate as a function of wind speed is the most important factor in controlling the vigor of the simulated MJO.

4 CONCLUSION

This is just one example of how WTG plus cumulus ensemble models may be used to improve cumulus parameterizations. Systematic application of this technique has the potential to move the subject of cumulus parameterization out of the realm of "black magic".

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