A Comparison of Deep Cumulus Parameterization Schemes in an Axi-symmetric Tropical Cyclone Model

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1. INTRODUCTION

Since Kuo (1965, 1974) introduced a method for parameterizing deep cumulus convective processes, it (and its relatives) has been used widely in large-scale and mesoscale numerical models. The Kuo method is attractive because it is simple and economical relative to mass-flux type methods and it depicts a physically reasonable link between large-scale moisture convergence and cumulus convection. Tropical cyclone models, to date, also have employed the Kuo (or moisture convergence) scheme popularly.

Someshwar Das *et al.* (1988) tested various Kuo-type parameterizations during the different periods of the Asian summer monsoon using a semiprognostic approach. They concluded that the 1974 Kuo scheme performs well when it is coupled with the moistening parameter calculation method proposed by Anthes (1977). Hobgood and Rayner (1989) studied the sensitivity of model storm evolution to different Kuo-type parameterizations in a three-dimensional tropical cyclone model with four vertical layers. The first objective of this study is an investigation of differences in the Kuo schemes revealed by simulations of an axi-symmetric tropical cyclone model with fine vertical resolution.

In recent years, it has been recognized that in tropical clouds the presence of cloud water has a significant impact on cloud buoyancy (Betts 1982, 1986). In this spirit, Betts (1986) proposed a new convective adjustment scheme that is based upon observations. Baik *et al.* (1990) incorporated the convective parameterization scheme in an axi-symmetric tropical cyclone model and showed that the scheme is capable of simulating the developing, rapidly intensifying and mature stages of a tropical cyclone starting from a weak vortex.

With the axi-symmetric tropical cyclone model employing the moist convective adjustment scheme (Kurihara 1973), Kurihara (1975) found a correlation of 0.75 between the horizontal moisture convergence in low levels and the area-mean precipitation rate, implying a similarity between the moist convective adjustment scheme and any cumulus parameterization scheme that is based upon low-level moisture convergence. The second objective of this study is a comparison of the storm evolution that is simulated with the Betts convective adjustment scheme with that simulated using the Kuo scheme. Tropical cyclone simulations provide a rigorous test of a cumulus parameterization scheme, since the energy to drive them comes almost entirely from latent heat release in deep cumulus clouds. Also, the dynamic and thermodynamic structures of an evolving storm are sensitive to the magnitude and vertical distribution of latent heating.

2. MODEL DESCRIPTION AND CUMULUS PARAMETERIZATIONS

The numerical model includes the conservation equations for momentum, mass, energy, and water vapor and the equation of state. The vertical momentum equation is assumed to be hydrostatic. The system of equations is written with the σ-coordinate in the vertical and axi-symmetric polar coordinates in the horizontal on an f-plane. The model atmosphere is divided into 15 layers of nonuniform thickness and has an equally spaced horizontal resolution of 20 km. The horizontal domain size is 1000 km. This relatively small horizontal domain can be employed by implementing a spectral radiation boundary condition, which uses a different gravity wave speed for each vertical mode. The governing equations are solved numerically using a second-order finite difference method.

The model contains subgrid-scale horizontal and vertical diffusion, air-sea interaction, simple radiation, grid-scale condensation, dry convective adjustment and subgrid-scale moist convective processes with either the Betts scheme or the Kuo scheme.

The initial maximum tangential wind speed is specified as 10 m/sec and the thermodynamic fields for initial conditions are taken from the mean tropical soundings in the western Pacific. Sea surface temperature is set to 28°C and Coriolis parameter is evaluated at 20° N.

The principle behind the Betts convective adjustment scheme is that the local thermodynamic structures are constrained by cumulus convective activity and adjusted towards an observed quasi-equilibrium state. A crucial observational basis for the deep scheme is that, in the presence of penetrative deep convection, a quasi-equilibrium temperature profile below the freezing level closely parallels a moist virtual adiabat. The use of a moist virtual adiabat as opposed to a moist adiabat allows for a parcel buoyancy correction due to cloud water. For the deep scheme, we construct first-guess reference profiles and correct them to satisfy the conservation of moist static energy. The stability weight on the moist adiabat in the lower troposphere is internally computed by assuming that the reference temperature profile below the freezing level exactly follows a moist virtual adiabat. The Betts scheme contains nonprecipitating shallow convection as well as deep convection. However, for the comparison only the deep convection scheme is employed because the Kuo scheme deals with deep convection.

In the Kuo convective parameterization, the moisture that is supplied by large-scale convergence and evaporation from the surface maintains penetrative cumulus convection. The cumulus heating and moistening imparted to the large-scale environment is assumed to be proportional to the temperature and water vapor mixing ratio difference between the environment and cloud. Three moisture convergence schemes are tested in this study – the 1965 Kuo scheme (denoted by K65), the 1974 Kuo scheme (KA1) and the modified Kuo scheme by Anthes (1977) (KA2). The temperature and mixing ratio inside cloud are considered to be the same as those on a moist adiabat passing through the lifting condensation level of an air parcel at the lowest model level. The moistening parameter b in the KA1 and KA2 cases is evaluated using a method proposed by Anthes (1977); that is, $b = [(1-RHe)/(1-RHc)]{*}{*}n$ if $RHc \leq RHe$ and $b = 1$ if $RHc > RHe$, where RHe is the mean environmental relative humidity in the air column, RHc a critical relative humidity and n a positive exponent. For further details of the numerical model and the Betts convective adjustment scheme, the reader is referred to Baik *et al.* (1990).

3. RESULTS AND DISCUSSION

a. Intercomparisons of the Kuo schemes

We first examine the sensitivity of model storm evolution to the moistening parameter b. Figure 1 shows the time evolution of the minimum surface pres-

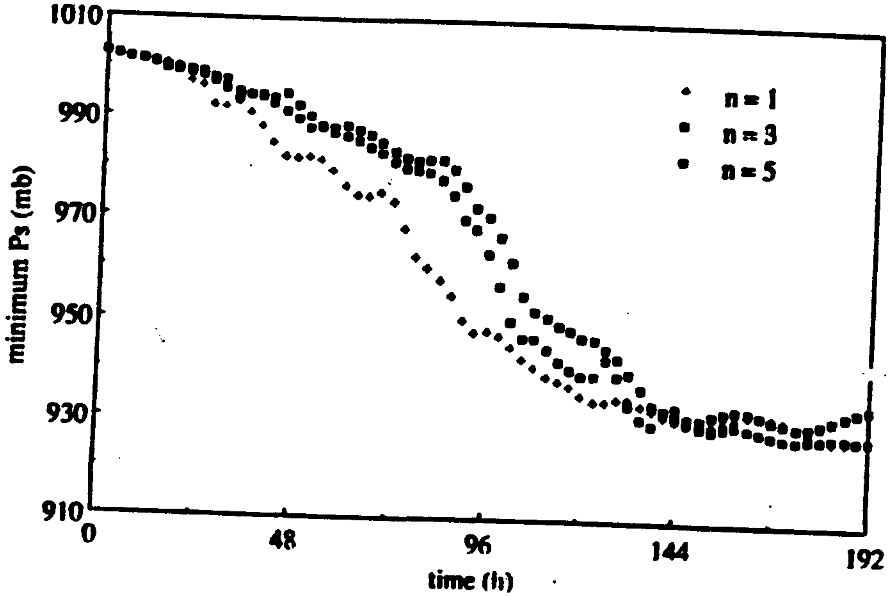

Fig. 1. The time evolution of the minimum surface pressure for the KA1 simulations. The values of n are used with RHc fixed as 0.5.

sure for the KA1 simulations. In these experiments, n is varied ($n = 1, 3, 5$) and *RHc* is fixed as 0.5. For the three cases, the development of a tropical cyclone is well simulated and the model storm attains a quasi-steady state (mature stage) after about 144 h. As n is decreased, the model storm results in earlier development. However, the final intensities are similar. The result that the simulation with decreased n value leads to earlier model storm development appears to contradict previous studies (e.g., Someshwar Das *et al.*, 1988). These studies indicate that, when n is decreased (with *RHc* held fixed), moistening due to cumulus convection becomes high and convective heating is small, implying slower storm development. This discrepancy can be explained by consideration of precipitation rates.

The analyses of the inner 500 km domain-averaged and 96 h time-averaged convective, grid-scale and total precipitation rates for the KAl simulations show that as n is decreased, the total precipitation rate increases and, hence, latent heating becomes large, resulting in earlier storm development, as shown in Fig. 1. The partitioning of the total into the convective and grid-scale precipitations indicates that as n is increased, the convective precipitation increases and the grid-scale precipitation decreases. Diabatic heating from the grid-scale phase change is shown to be larger than that from the subgrid-scale cumulus convection. The fraction of the convective to the total precipitation is 0.22, 0.31 and 0.35 for $n = 1$, 3 and 5, respectively. These analyses imply that, for our tropical cyclone model with the 20 km horizontal resolution, the greater convective moistening for smaller n favors the grid-scale condensation. Accordingly, this moistening leads to earlier storm development, although it slightly reduces the subgrid-scale heating. Nevertheless, this implication should not be generalized to a relatively coarse resolution model, such as a global model, in which subgrid-scale precipitation is large compared with grid-scale precipitation. In that case, a convective system should intensify early as the moistening parameter becomes small, as indicated in previous studies.

Figure 2 shows the time evolution of the minimum surface pressure for the K65, KA1 and KA2 cases. For each case, the model well simulates the developing and mature stages of a tropical cyclone. The storm in the KA2 simulation exhibits slightly earlier development than the storm in the KA1 simulation. But, the intensities at the mature stages do not show a significant difference. The storm evolution fields in the KA1 and KA2 simulations suggest that the two convective parameterizations function similarly.

The storm in the K65 simulation intensifies more rapidly and has a lower central pressure at the mature stage than the comparison simulations. The formulation of the 1965 Kuo scheme gives much more convective moistening than that of the 1974 version. As discussed previously, in our tropical cyclone model the greater convective moistening enhances grid-scale heating, leading to faster storm development. This characteristic is reflected in the time history of the minimum surface pressure in the K65 simulation.

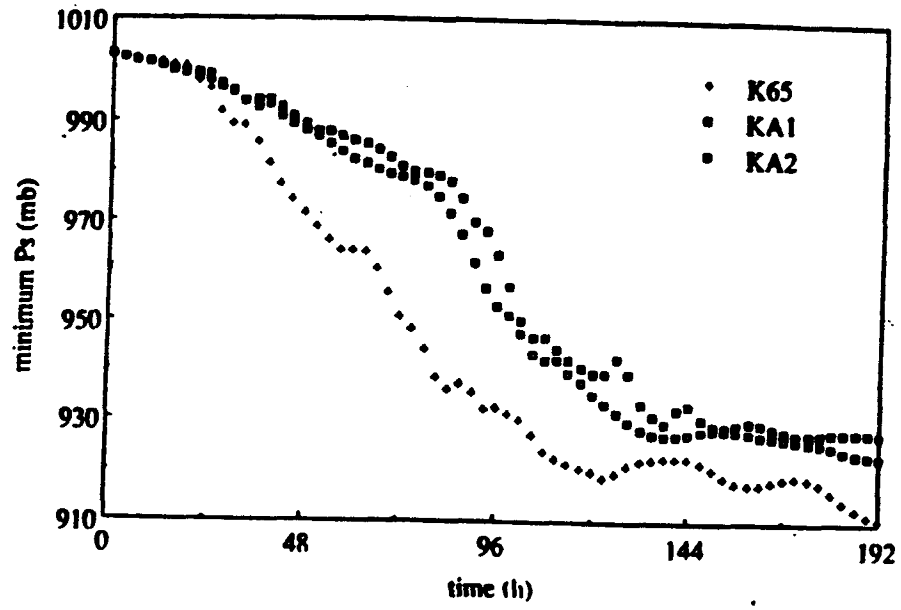

Fig. 2. The time evolution of the minimum surface pressure for the K65, KA1 and KA2 simulations. In the KA1 and KA2 simulations, values of *n* and *RHc* are specified as 3 and 0.5.

b. Comparisons of the Betts scheme with the Kuo scheme

In this subsection, similarities and differences in the model storm evolution fields simulated with the Betts convective adjustment scheme (BETTS) and the Kuo convective parameterization (KA1 with $n = 3$ and $RHc = 0.5$) are discussed.

Figure 3 shows the time evolution of the minimum surface pressure for the BETTS and KA1 experiments. The storm in the BETTS simulation takes longer to develop (with the adjustment time scale of 2 hours), but it has a more intense mature stage than the storm in the KA1 simulation. Also, the storm intensification rate during the rapidly intensifying stage is higher in the BETTS case than in the KA1 case. The minimum surface pressures at the mature stages for the BETTS and KA1 simulations are about 912 and 929 mb, respectively.

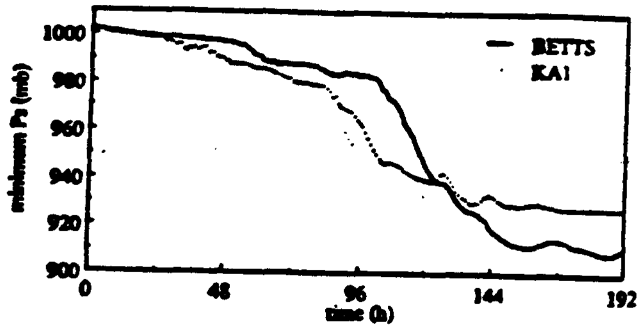

Fig. 3. The time evolution of the minimum surface pressure for the BETTS and KA1 simulations.

An attempt is made to determine whether the model's deep cumulus clouds are present for the initial thermodynamic soundings used at the model lateral boundary. The Kuo scheme allows deep convection, but the Betts scheme does not. The Betts convective adjustment scheme allows model deep cumulus clouds only when the integrated heating rate in the vertical through the deep cloud column is positive. The heating rate is computed using the deep reference profile, which was constructed from observations.

For both simulations, the subgrid-scale latent heating during the developing stage still has a large influence on the final storm intensity, even though it becomes negligible (does not exist in the BETTS case) at the mature stage. Both simulations produce reasonable vertical convective and grid-scale heating profiles. However, the time evolution of the domain-averaged convective precipitation is much smoother in the BETTS simulation than in the KA1 simulation (Fig. 4). An examination of the convective heating fields indicates that, in the KA1 simulation, subgrid-scale cumulus clouds at the outer region continuously appear and disappear. On the other hand, in the BETTS simulation, subgrid-scale deep convection does not take place at the outer region, because even when the calculated cloud height is above level 10, the Betts scheme does not allow deep convection if the vertically integrated convective heating rate is negative. Figure 4 reflects these differences.

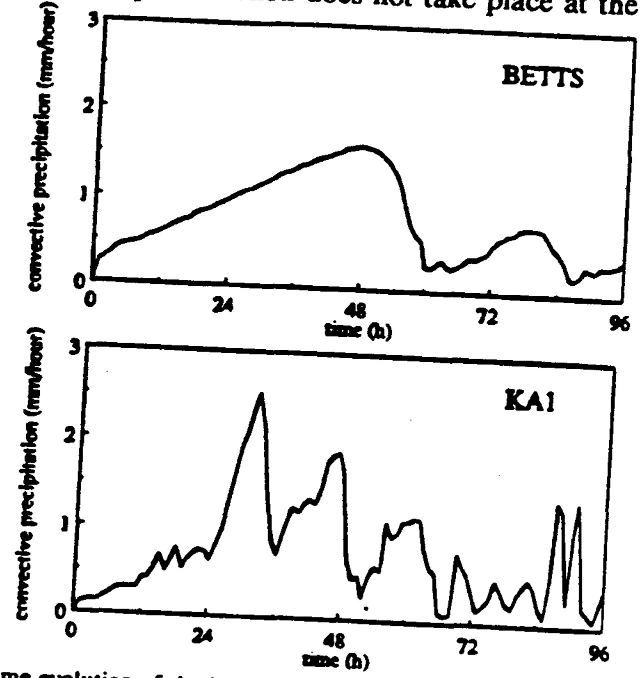

Fig. 4. The time evolution of the inner 500 km domain-averaged convective precipitation rate for the BETTS and KA1 simulations.

To compare the dynamic and thermodynamic structures of the mature tropical cyclones, we analyze the radius-height cross sections of the tangential wind speed (Fig. 5), radial wind speed, vertical p-velocity, temperature deviation from the model lateral boundary and relative humidity at 168 h. Both experiments well simulate the essential features of mature tropical cyclones. A difference between the BETTS and KA1 simulations is that the more intense mature structure is reflected in the BETTS simulation.

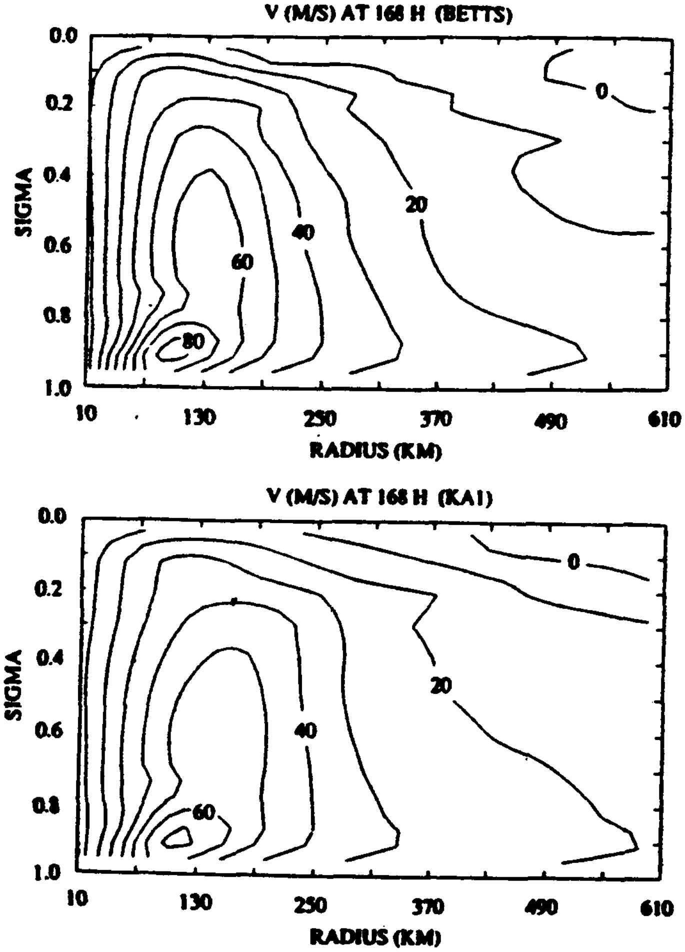

Fig. 5. The radius-height cross section of the tangential wind speed at 168 h for the BETTS and KA1 simulations. The contour interval is 10 m/sec.

Analyses of the surface energy flux show that, for both cases, the magnitude of the latent heat flux is much larger than that of the sensible heat flux during the entire period and the direction of the sensible heat flux is associated with the storm evolution at different locations. Finally, the ratio of the inner 500 km domain-averaged evaporation to the horizontal water vapor transport across the vertical wall at 500 km radius is almost identical (~0.2) for the two model simulations, although the mature storm in the BETTS case is more intense than the storm in the KA1 case.

4. SUMMARY AND CONCLUSION

An axi-symmetric tropical cyclone model has been used to investigate variations of Kuo-type cumulus parameterizations and some similarities and differences between the Betts convective adjustment scheme and the Kuo scheme through numerical simulations. Tests in Kuo-type schemes indicated that, within the framework of present model simulations, the greater convective moistening (for a larger moistening parameter) increases the grid-scale latent heating, even though it slightly reduces the subgrid-scale latent heating. Although some simulated differences between the Betts and Kuo schemes were observed, simulated structures of the tropical cyclones were similar. In this study, we tested cumulus parameterization schemes only in idealized axi-symmetric tropical cyclone model simulations. Research performing three-dimensional numerical forecasting with observed data is needed to compare the Betts and Kuo schemes more rigorously.

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