A Test of Convective Parameterizations in a Tropical Cyclone Model

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ABSTRACT

In recent years a number of different methods have been proposed for the inclusion of the effects of cumuli in numerical models of tropical cyclones. In this paper several of the Kuo-type parameterizations have been tested by simulating the development of tropical cyclones from identical sets of initial conditions. The use of the same model and initial conditions made it possible to determine the effects of the various parameterizations. In the simulations without radiative fluxes, significant differences in the rates of intensification were evident in certain cases. In those simulations with radiative fluxes, the various parameterizations also produced different diurnal oscillations of pressure and wind speed.

1. Introduction

The release of latent energy within convective clouds is an important part of the process that intensifies and maintains tropical cyclones. Thus, for a model to be able to accurately simulate the processes within these systems, it is necessary for it to replicate this release of energy. The general nature of the problems that this creates has been reviewed by Frank (1983). Ideally, the effects of convection should be included explicitly within the equations that comprise the numerical model. Indeed, Rosenthal (1978) explicitly modeled convection in an axisymmetric model and Jones (1980, 1986) has done the same with a three-dimensional model. Still, the scales of the individual convective elements require a dense pattern of grid points, especially in areas of active convection. Thus, the explicit representation of convection is computationally quite expensive. In addition, Molinari and Dudek (1986) discuss the development of instabilities which occurred during attempts to simulate the development of a mesoscale convective complex.

In order to avoid the computational expense and the instability problems of explicitly modeled convection, the effects of convection have been parameterized in other models. These parameterizations have generally taken one of two forms. One group of models (e.g., Kurihara and Tuleya 1974) has used a moist convective adjustment to incorporate these effects. In other models (e.g., Anthes 1972; Jones 1977) the Kuo (1965) type of parameterization has been used. Interestingly, Kurihara (1975) found that in the moist convective adjustment scheme there was a relatively high correlation (0.75) between convergence of moisture in the boundary layer and the mean precipitation rate. He concluded that the "behavior" of the moist convective adjustment "may be similar" to other schemes based on convergence of moisture in the boundary layer.

Many variations of these parameterizations have been developed. Anthes (1977b) compared the results derived from a new scheme based on a one-dimensional cloud model (Anthes 1977a) with those from the Kuo-type approach. Later, Molinari (1982) presented vertical profiles calculated from several different parameterizations. Similarly, Kuo and Anthes (1984) tested Kuo-type parameterizations in extratropical convective systems. Finally, Molinari and Dudek (1986) showed that in simulations of the development of a mesoscale convective complex, this type of parameterization outperformed simple explicit representations of convection.

Given the large number of methods that have been developed for including the effects of cumuli in models, it is impossible to test all of them. Thus, this study examines some of the refinements to the original Kuo (1965) parameterization that have been proposed for use in models of tropical cyclones. Testing of these schemes under identical conditions (i.e., the same numerical model, initial and boundary conditions) provides a means of examining the parameterizations' ef-

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fects on the development of the simulated tropical cyclone.

2. Description of the experiments

a. The tropical cyclone model

The model used in these experiments is discussed extensively by Hobgood (1986) and only a brief summary is provided here. The basic equations are derived in the sigma coordinate system developed by Phillips (1957). There are four vertical layers which represent the boundary layer and the lower, middle, and upper tropospheric layers. Along each sigma surface, a horizontal grid with a uniform spacing of 25 km is used. The horizontal velocity components are calculated on a grid which is offset by 45° from the grid used for the thermodynamic variables. The time integration is performed using the method developed by Matsuno (1966) and the time step is 37.5 seconds.

The vertical fluxes of latent energy and sensible heat from the ocean to the atmosphere are determined from the bulk aerodynamic equations using a variable drag coefficient. The sea surface temperature is maintained at a constant value of 302 K in all of the simulations. In one version of the model used for the experiments described in section 3b, fluxes of shortwave and longwave radiation are calculated in the manner described by Hobgood (1986).

b. Anthes (1972) scheme

The version of the model described by Hobgood (1986) contains a cumulus parameterization developed by Anthes (1972). In this scheme the water vapor available for convection is equal to the sum of the horizontal convergence of moisture in the boundary layer and evaporation from the ocean or

$$M_t = -\nabla \cdot p^*\mathbf{V}q_4\delta\sigma_4 + Q_{\text{sea}}, \qquad (1)$$

where M_t is the moisture available for convection, p^* the surface pressure, $\mathbf{V}$ the horizontal velocity, q_4 the specific humidity in the boundary layer, $\delta\sigma_4$ the sigma thickness of the boundary layer and Q_{sea} the evaporation from the ocean. To maintain consistency throughout the experiments (1) is used in all cases, although some schemes (e.g., Anthes 1977b) use the net convergence of moisture in the entire column.

Convection takes place whenever M_t is positive. The latent heating is distributed vertically according to

$$p^* \frac{\partial T}{\partial t_c} = \frac{C_p M_t (T_c - T)}{\sum_{K=1}^{4} [(T_c - T)C_p/L + (q_c - q)]\delta\sigma_K}, \qquad (2)$$

where $\partial T/\partial t_c$ is the latent heating due to convection, C_p the specific at constant pressure, L the latent heat of condensation, T_c the cloud temperature, T the environmental temperature, q_c the specific humidity of the cloud and q the environmental specific humidity. For latent heating to occur in a layer, the difference between the cloud and the environmental temperatures must be at least 0.5°K. The vertical transfer of moisture by convection is specified by

$$p^* \frac{\partial q}{\partial t_c} = (q_c - q)/\sum_{K=1}^{4} [(T_c - T)C_pL + (q_c - q)]\delta\sigma_K. \qquad (3)$$

When the relative humidity is greater than 98 percent, all water vapor is condensed. Furthermore, no more than 20 percent of the latent heating is allowed to take place in the boundary layer. This parameterization forms the basis of the experiments labeled AN72 and AN72R.

c. Kuo (1974) scheme

In the second pair of experiments labeled KUO74 and KUO74R, the Anthes' (1972) cumulus parameterization is replaced with the scheme described by Kuo (1974). The most important change from the previously described method is that the percentages of the moisture available for convection assigned to the enrichment of the moisture content of the column (b) and to the latent heating of the column ($1 - b$) are specified explicitly. In the method used by Anthes (1972) these percentages are determined implicitly by (2) and (3). In the second pair of experiments a constant value of 0.02 is used for b. This is the same value chosen by Kuo for tropical convection (Kuo and Anthes 1984).

The calculations of the vertical distribution of latent heating and moisture transfer are also different in this parameterization. The vertical distribution of latent heating is given by

$$p^* \frac{\partial T}{\partial t_c} = \frac{L(1 - b)M_t(T_c - T)}{C_p \sum_{k=1}^{4} (T_c - T)\delta\sigma_K}, \qquad (4)$$

and the vertical transfer of moisture by convection is specified by

$$p^* \frac{\partial q}{\partial t_c} = \frac{bgM_t(q_c - q)}{\sum_{K=1}^{4} (q_c - q)\delta\sigma_K}. \qquad (5)$$

For the simulations, with this convective parameterization and all succeeding experiments the limit of 20 percent of the latent heating in the boundary is removed and water vapor may be added to the atmosphere until the cloud and environmental specific humidities are the same.

d. Anthes (1977) scheme

While the Kuo (1974) parameterization produces a tropical cyclone when it is included in the model, the use of a constant value for b produces some undesirable side effects. The most important of these is that, even in cases where the upper levels of the atmosphere are quite dry, a certain percentage of the water vapor converging in the boundary layer will condense. Based on work with a one-dimensional cloud model, Anthes (1977a,b) suggests an equation that relates b to the vertical profile of relative humidity (RH). The relationship between these two variables is given by

$$b = \left| \frac{1 - \sum_{K=1}^{4} \mathrm{RH}_K \delta\sigma_K}{1 - \mathrm{RH}_{\mathrm{cr}}} \right|^n \qquad (6)$$

when the average relative humidity of the column exceeds some critical value ($\mathrm{RH}_{\mathrm{cr}}$), or

$$b = 1, \qquad (7)$$

when the average relative humidity of the column is less than the critical value. The constant value for b of 0.02 is replaced with (6) and (7) and Anthes (1977b) suggested values of $n = 1$ and $\mathrm{RH}_c = 0.5$ are used in the third pair of simulations (KU74A77B and KU74A77BR).

Anthes (1977b) also suggests a slightly different means of partitioning the vertical distribution of water vapor by the convection. This new formulation is

$$p^* \frac{\partial q}{\partial t_c} = bgM_t(100\% - \mathrm{RH})q_s(T) / \sum_{K=1}^{4} (100\% - \mathrm{RH}_K) q_s(T)_K \delta\sigma_K. \qquad (8)$$

The advantage of this relationship is that more water vapor is transported vertically to the drier layers of the atmosphere. This expression replaces (5) in the fourth pair of simulations (AN77 and AN77R).

e. Anthes et al. (1982) scheme

In work on modeling the mesoscale environments around severe local storms, Anthes et al. (1982) use a slightly modified version of (8) in which the saturation deficit as defined in terms of relative humidity is removed from the equation. Thus, the vertical transport of moisture by convection is specified by

$$p^* \frac{\partial q}{\partial t_c} = bgM_t q_s(T) / \sum_{K=1}^{4} q_s(T) \delta\sigma_K. \qquad (9)$$

In the final pair of simulation (AN82 and AN82R) (9) replaces (8).

3. Results of the simulations

a. Without radiation

In this section the results from five simulations (AN72, KUO74, KU74A77B, AN77 and AN82), which were performed with a version of the model that did not include the radiative fluxes, are compared. The maximum wind speeds for all five simulations are plotted in Fig. 1. Four of the simulations (AN72, KU74A77B, AN77 and AN82) produced tropical cyclones which attained approximately the same intensity (45–47 m s^{-1}), while the simulation with the Kuo

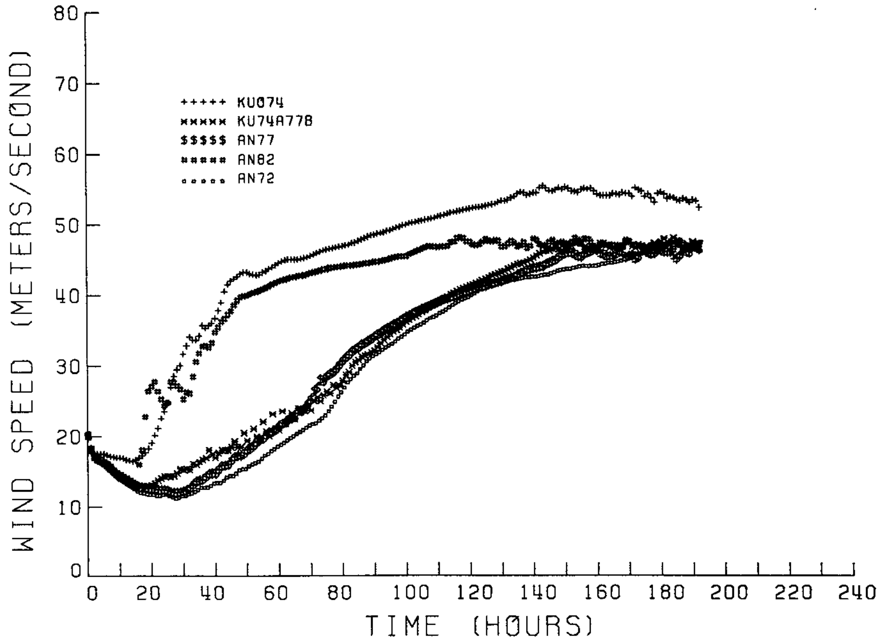

FIG. 1. Maximum wind speeds for the nonradiative simulations.

(1974) parameterization and $b = 0.02$ generated a much more intense system, which possessed maximum wind speed of 55 m s^{-1}. The storms that developed in the KUO74 and AN82 simulations intensified quite rapidly and reached wind speeds of 39 m s^{-1} by the end of the second day (48 hours). In contrast, in the other three simulations (AN72, KU74A77B, AN77) the maximum wind speeds were less than 20 m s^{-1} at the end of the second day.

In order to explain the different rates of intensification it is necessary to examine the release of latent energy in the simulated storms. The primary factor that determines the vertical distribution of the latent heating is quite similar in all of the simulations. As shown in (2) and (4) the difference in temperature between air lifted from the boundary layer and the temperature of a level determines the proportion of the latent heating that is assigned to a layer of the model. Since each simulation begins with the same initial conditions during the period of initial intensification, this difference in temperature is nearly identical in all of the simulations. Therefore, some other factor must be identified as the reason for the different rates of development.

In the case of the rapid intensification of the storm in the KUO74 simulation, the use of a constant value of 0.02 for b produces the observed development. With b as a constant, latent heating occurs whenever there is convergence of moisture in the boundary layer, regardless of the relative humidity in the rest of the atmospheric column. The choice of a small value for b means that only 2 percent of the converging water vapor is used to enrich the moisture content, while 98 percent of this vapor condenses and releases latent energy. For the simulations in which b was a function of the relative humidity, more of the water vapor was initially used to enrich the moisture content of the column and less latent heat was released. Since latent heating is an integral part of the process by which a tropical cyclone intensifies, the greater, early heating in the KUO74 simulation, causes the storm to develop faster.

However, b is a function of the relative humidity in the AN82 parameterization; thus, there must be some other reason for the relatively rapid intensification of the simulated storm. As shown in (3), (5) and (8) the vertically transported moisture is partitioned according to the differences in specific humidities between air that rises from the boundary layer and the air at each level in the model for the other four simulations. In the AN82 scheme, as shown in (9), the saturation specific humidity determines the vertical distribution of water vapor. This will transport the greatest proportion of the water vapor to the warmest (lowest) layers. The result of this process is to enhance the large-scale condensation, which will occur at an earlier stage during the AN82 simulation. Furthermore, any additional release of latent energy in the lower troposphere helps to destabilize the atmosphere and results in faster development of the tropical cyclone.

In the other three simulations (AN72, KU74A77B and AN77) the parameterizations all function in quite similar manners. As seen in (2) and (4) the vertical partitioning of the latent heating is nearly the same in these three schemes. Likewise, as shown in (3), (5) and (8) the enrichment of moisture is partitioned according to the difference between the moisture content of air lifted from the boundary layer and the air already at a given level in the model. In two of the simulations (KU74A77B and AN77) the same method is used to derive b. These factors lead to simulated storms that intensify at approximately the same rate with each of these three parameterizations.

The effects of latent heating on the different rates of intensification can be seen in Fig. 2. During the first day of the simulation the KUO74 parameterization generates much more latent heating than any of the other schemes. Since the release of latent energy plays an integral role in the intensification of tropical cyclones, it seems evident that the greater heating in the early stages of the KUO74 simulation accounts for the more rapid development of that storm. Similarly, the AN82 parameterization generates the second highest rate of heating during the first day of the simulation; thus, the second fastest rate of intensification. The release of less latent energy in the early stages of the other three simulations (AN72, KU74A77B and AN77) is the reason for the much slower intensification of those systems. While the rate of latent heating diminishes from its maximum value on the first day of the simulation, the release of latent energy with the KUO74 parameterization remains consistently greater than in the other four methods. This results in a more intense system throughout the length of the simulation. The rates of latent heating with the other methods tend to converge toward the latter stages of the simulations and this results in storms of similar intensity by the end of eight days. A similar, but not identical, pattern is also evident in the maximum rainfall rates, which are not shown.

b. With radiation

In order to test these parameterizations more completely, a second set of simulations was performed using a version of the model with the explicit radiative fluxes. Since the radiative transfers are strongly influenced by clouds, these simulations provided an opportunity to discover any differences produced by the various parameterizations. These simulations were begun with the same initial and boundary conditions as the nonradiative simulations and were assumed to start at midnight Local Mean Solar Time (LMST). The maximum wind speeds from these simulations are shown in Fig. 3. As was the case with the nonradiative simulations, the simulations with the Kuo (1974) param-

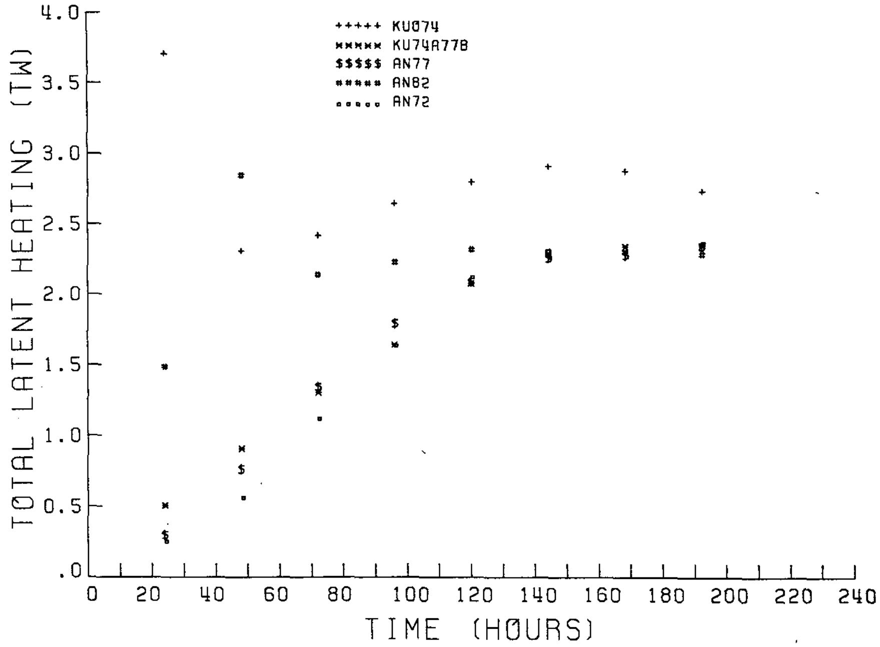

FIG. 2. Latent heating rates for the nonradiative simulations.

eterization (KUO74R) produces the most intense storm. All of the other parameterizations (AN72R, KU74A77BR, AN77R, AN82R) produce storms of similar intensity. Also similar to the nonradiative simulations is the fact that the KUO74R and AN82R storms intensify more rapidly than the others. In all cases the maximum intensities are about 5 m s^{-1} less, when the radiative fluxes are included.

4. Summary and conclusions

The results of simulations that were performed to test variations of the Kuo-type convective parameterizations in a tropical cyclone model have been presented. The Kuo (1974) scheme using $b = 0.02$ (Kuo and Anthes 1984) produced the most rapid intensification and the most intense storms. Of the other pa-

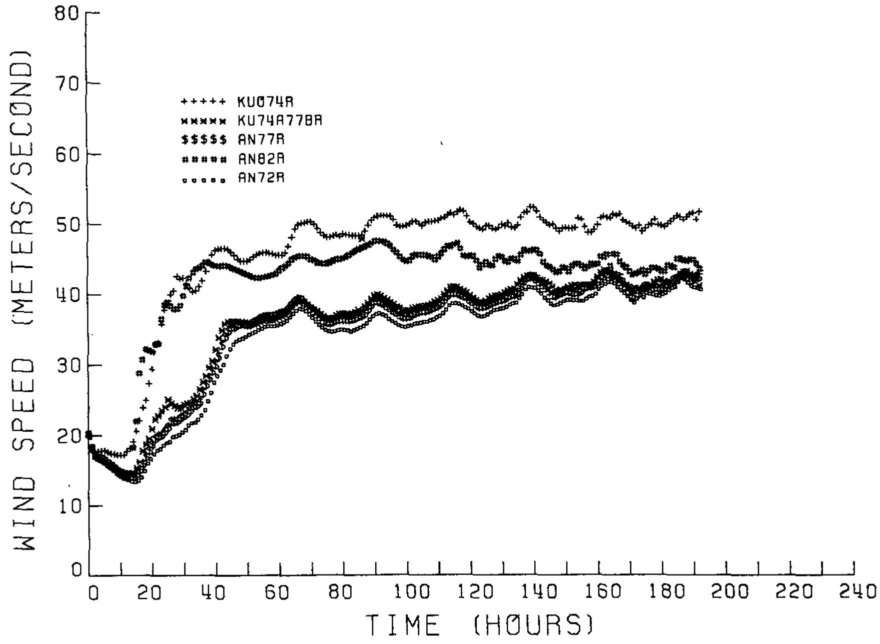

FIG. 3. As in Fig. 1 except for the radiative simulations.

rameterizations, the AN82 variation also produced fairly rapid intensification, but the modeled storm eventually developed similarly to those generated by the other methods in the later stages of the simulations. It seems likely that if a number of simulations were run with the Kuo (1974) scheme, the magnitude of b could be adjusted upwards until it also produced a storm similar to those generated with the other parameterizations. However, this might result in an underestimation of latent heating in the areas of most active convection. The approach of Anthes (1977a) in which b is a function of the relative humidity of the atmospheric column seems to yield better results.

The model seemed fairly insensitive to many of the changes in the vertical partitioning of the distribution of water vapor and latent heating by convection. The addition of explicit radiative fluxes had only a small effect on the intensity of the system and did not alter the relative performances of the parameterizations. In cases where the large-scale variables available at grid points in the model were used to determine the vertical distribution of latent heating and water vapor by convection, the modeled storms were all very similar by the end of the simulations. This would seem to indicate that with the exception of the KUO74 simulation, the cumulative effects on the modeled storms produced by the convective parameterizations tested in this study were quite similar, since all simulations used the same initial and boundary conditions. However, this statement should not be generalized beyond the methods examined in this study. It is quite likely that other initial conditions, boundary conditions or convective parameterizations, especially those not based on a Kuo-type approach, could produce very different results. Further testing of additional methods is required before more generalized statements can be made about the parameterizations tested in this study.

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