A Numerical Study of the Role of Eddy Fluxes of Momentum in the Development of Atlantic Hurricanes

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ABSTRACT

The results of numerical integrations of Sundqvist’s (1970) symmetric model for hurricane development modified to include parameterized large-scale eddy fluxes of momentum are presented. The initial wind and moisture distributions, and the prescribed eddy fluxes of momentum, were taken from atmospheric observations of Atlantic developing (prehurricane) and non-developing tropical disturbances as composited by McBride (1981a,b) and McBride and Zehr (1981). For the purposes of the present study, the data for individual stages in the evolution of developing and non-developing disturbances were combined to form a single composite developing hurricane and a single composite non-developing disturbance.

The data reveal the presence of intense, well organized inward eddy fluxes of momentum in developing Atlantic hurricanes and weak, poorly organized fluxes in non-developing disturbances. In the developing disturbances, the eddy fluxes of momentum are organized such that they act as a forcing function for driving the radial circulation, drawing moist air in toward the center of the vortex in the lower troposphere and pumping drier air outward aloft, thereby providing fuel for the explosive growth of the hurricane. In order to test the efficacy of this mechanism, and of Ekman suction and cooperative instability, numerical integrations were performed using the data for the composite developing hurricane, with and without the observed eddy fluxes of momentum, and for the composite non-developing disturbance with the observed eddy fluxes corresponding to this disturbance.

Without eddy flux forcing, the prehurricane developing vortex fails to intensify into a hurricane, even after 20 days of integration. With the observed eddy fluxes of momentum, the same initial vortex intensifies rapidly, reaching hurricane strength within 4 days. Moreover, because of the weak and diffuse pattern of the eddy fluxes of momentum in non-developing tropical disturbances, the initial vortex characterizing these disturbances also fails to develop into a hurricane.

The kinetic energy budgets corresponding to the integrations with the composite developing and non-developing disturbances are presented as a function of time. The calculations reveal that, during the early stages of development of the model hurricane, the conversion (\(E_k\)) from eddy kinetic energy to the kinetic energy of the mean hurricane circulation is larger than the conversion (\(C_k\)) from potential to kinetic energy. The eddy process is, therefore, directly responsible for the early growth of the model hurricane. This is followed by an explosive increase in the rate of conversion from potential to kinetic energy and in the rate of kinetic energy dissipation (\(F\)). During the latter period, \(C_k\) and \(F\) become almost an order of magnitude greater than the peak attained earlier by \(E_k\), and the kinetic energy tendency reaches its peak. Without the eddy momentum flux forcing, no such explosive growth takes place.

The results of these integrations provide evidence that properly organized large-scale eddy fluxes of momentum may be an essential ingredient in the development of Atlantic hurricanes.

1. Introduction

In a recent paper, Challa and Pfeffer (1980) presented evidence to the effect that eddy fluxes of momentum associated with synoptic-scale wave asymmetries may be of fundamental importance to the formation of hurricanes. In that work, Sundqvist’s (1970) symmetric numerical model for hurricane formation was modified to include parameter-

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vergence was prescribed, model hurricane development was suppressed, even when the sea surface temperature was taken to be supercritical such that the purely symmetric model integration produced explosive growth.

In the present paper, we describe the results of numerical experiments similar to the ones in our previous study, but with more realistic distributions of the eddy flux of momentum replacing the somewhat arbitrary distributions prescribed in our earlier study. The eddy flux data and the initial tangential velocity and moisture distributions were taken from the composite data analyses of McBride (1981a,b) and McBride and Zehr (1981). In particular, we used their data relating to Atlantic developing and non-developing tropical disturbances. In order to minimize the cost of computer resources, we decided to test our ideas first with the use of a symmetric model and if successful, later consider integrating a fully three-dimensional model with the eddy fluxes of momentum prescribed only at the initial time.

The details of Sundqvist's (1970) hurricane model and numerical procedures are contained in his original article and a review may be found in our earlier paper (Challa and Pfeffer, 1980). The latter reference presents the model equations with the addition of the parameterized eddy fluxes of momentum. We shall use the notation of that paper in the present discussion.

2. Distribution of eddy flux of momentum in hurricanes

The existence of significant large-scale inward eddy fluxes of momentum in hurricanes was first documented by Pfeffer (1955). The full details of that study were reported by Pfeffer (1958). Similar calculations were also made by Palmén and Riehl (1957). Since that time, eddy fluxes of momentum in hurricanes have been reported by Black and Anthes (1971), Frank (1977) and, most recently, by McBride (1981a,b). In the present study we use McBride's Atlantic tropical data. McBride classified seven categories of Atlantic tropical disturbances. These are the non-developing cloud cluster (N1), the non-developing wave trough cluster (N2), the non-developing depression (N3), the prehurricane cloud cluster (D1), the prehurricane depression (D2), the intensifying cyclone (D3) and the hurricane (D4). For the purpose of the present study, we have further combined McBride's D1, D2 and D3 data into a single composite Atlantic developing hurricane and his N1, N2 and N3 data into a single composite Atlantic non-developing disturbance. Fig. 1 shows characteristic features of each of these disturbances based upon the data at 100 mb intervals from 1000 to 100 mb (which our numerical model requires) and at radii \( r = 0.5, 2, 4, 6, 8, 10, 12 \) and \( 14^\circ \) latitude extracted from McBride's more extensive tabulations. McBride's values of the eddy flux of momentum at \( r = 0.5^\circ \) were not, however, considered accurate enough to use here. In Fig. 1, \( u \) and \( v \) are the tangential (positive counterclockwise) and radial (positive outward) components of the wind velocity and \( q \) is the specific humidity. The overbar represents an azimuthal average and the prime a departure from that average.

While the moisture fields are similar in the developing and non-developing disturbances, the velocity characteristics are quite different. Both the tangential velocity \( (\bar{u}) \) and the inward eddy flux of angular momentum \( (ru^\prime v') \) are more intense and better organized in the developing hurricane than they are in the non-developing disturbance. It should be noted, however, that even in the developing hurricane, the maximum cyclonic wind speed at 900 mb is smaller in magnitude than the value required by most numerical models to form a hurricane by means of Ekman layer inflow and prefrontal instability. It is significant that, in the developing hurricane, the distribution of the eddy flux of momentum is such as to give a substantial vertical derivative of the flux convergence in the upper troposphere. According to the equation governing the symmetrical radial circulation [Eq. (4) in Challa and Pfeffer (1980)], such a configuration represents a forcing function for this circulation which should draw moist air into the center of the disturbance from below and pump drier air out at high elevations, thereby providing fuel for the explosive growth of the hurricane. It is the efficacy of this mechanism that our numerical integrations are designed to test.

3. Grid network, initial conditions and prescribed fluxes

The numerical model contains 10 equally spaced pressure levels in the vertical direction (\( \Delta p = 100 \) mb) in the range 1000 \( \geq p \geq 100 \) mb. The grid interval in the radial direction is \( \Delta r = 25 \) km and the radial extent of the model has been increased to 1500 km, as compared with 600 km in our previous study.

Numerical integrations were performed using the data for both the composite developing and non-developing disturbances. In both, the eddy fluxes of momentum in the region \( 2^\circ \leq r \leq 14^\circ \) latitude were prescribed as shown in Fig. 1. In the region, \( 0 < r < 2^\circ \), the required values of \( u^\prime v' \) were obtained by linear interpolation using the observed values at \( r = 2^\circ \) and setting \( u^\prime v' = 0 \) at \( r = 0 \). The prescribed values were held fixed for the entire length of each integration.\(^4\) In another integration, using the \( \bar{u} \) and

\(^4\) The intensity and radial extent of the inward eddy flux of momentum in the atmosphere are actually observed to increase with each successive stage of development from D1 to D2 to D3 and, to some extent, from N1 to N2 to N3 (see Pfeffer and Challa, 1981). Accordingly, developments in nature might be even more dramatic than those derived in this study.
\( \dot{q} \) data for the composite developing hurricane, the eddy fluxes of momentum were prescribed to be zero everywhere. The purpose of this integration was to test whether the model would be capable of developing a hurricane from a purely symmetric initial vortex of observed strength (without eddy flux forcing), utilizing only the Ekman layer inflow and cooperative instability. In all three integrations, the initial tangential wind and specific humidity distributions in the region \( 0.5^\circ \leq r \leq 14^\circ \) were prescribed as shown in Fig. 1. In the region \( 0 < r < 0.5^\circ \), the specific humidity was taken to be equal to the value at \( r = 0.5^\circ \) and the tangential wind was obtained by linear interpolation using the observed values at \( r = 0.5^\circ \) and setting \( u = 0 \) at \( r = 0 \).

The initial potential temperature distribution was taken to be that of the mean tropical atmosphere (Jordan, 1958), adjusted for thermal wind balance with each initial tangential wind field. The sea surface temperature was held fixed at 300.5 K throughout each integration. This is the critical value required for Sundqvist's symmetric model to form a hurricane.

4. Numerical integrations

The time variations of the maximum tangential wind at 900 mb and the minimum surface pressure in the integrations corresponding to the composite developing hurricane, with and without the prescribed eddy flux of momentum, are shown in Figs. 2a and 2b, respectively. With the observed eddy flux forcing, the vortex associated with developing hurricanes intensifies rapidly, reaching hurricane strength within four days. Without the eddy flux forcing, the same vortex does not develop into a
Fig. 2. (a) Time variations of maximum tangential wind velocity at \( p = 900 \) mb in the numerical integrations corresponding to the composite Atlantic developing hurricane with and without eddy fluxes of momentum. (b) Time variations of minimum surface pressure in the same integrations.

Fig. 3. Time variations of (a) maximum tangential wind velocity at \( p = 900 \) mb and (b) minimum surface pressure in the numerical integration corresponding to the composite Atlantic non-developing disturbance.

Fig. 4. Distributions of (a) tangential wind velocity, (b) radial and vertical velocities and (c) temperature anomalies in the mature stage of the composite Atlantic developing hurricane. Units are \( \text{m s}^{-1} \) for tangential and radial velocities, \( \text{cm s}^{-1} \) for vertical velocity and \( ^\circ \text{C} \) for temperature anomaly.

hurricane even after 16 days of integration. Since the disturbance in the latter case was still intensifying slowly at the end of 16 days, we continued the integration to 20 days, at which time the maximum tangential wind at 900 mb reached 14 \( \text{m s}^{-1} \) and the central surface pressure reached 999.5 mb. At this time there was still no tendency for more rapid growth.

The time variations of the maximum tangential wind at 900 mb and the minimum central surface pressure in the integration corresponding to the composite non-developing disturbance are shown in Figs. 3a and 3b, respectively. In this case the observed eddy flux of momentum, which was present in the integration, is too weak and diffuse (see Fig. 1) to generate a model hurricane.
The results of these integrations suggest that the presence of a sufficiently intense, properly organized, eddy flux convergence of momentum is a necessary ingredient for the development of Atlantic tropical disturbances into hurricanes. The composite vortex observed in developing hurricanes is not capable of intensifying into a hurricane through the sole action of Ekman pumping and cooperative instability; and the eddy fluxes of momentum associated with the composite non-developing disturbance are too weak and diffuse to organize the radial circulation and the consequent influx of moisture in the lower troposphere, which is required to fuel the growth of a hurricane.

In a recent extension of this study, Pfeffer and Challa (1981) have made additional numerical integrations, with and without eddy fluxes of momentum, using the data for D1, D2 and D3 individually. They found that without the eddy flux forcing, the pre-hurricane cloud cluster (D1) and the prehurricane depression (D2) do not develop into hurricanes after 16 days of integration and that the intensifying cyclone (D3) takes approximately 13 days to reach hurricane strength. With the observed eddy flux forcing included in each case, all three initial vortices intensify rapidly into hurricanes, the D3 disturbance requiring less than two days to reach hurricane strength. Moreover, the rates of growth, the final intensities, eye structures and sizes of the model hurricanes are found to be sensitive to the details of the eddy momentum flux distribution. These results lend further support to the hypothesis that eddy fluxes of momentum associated with large-scale asymmetries, and nonlinear interactions between the vortex and its surroundings, might be crucial to the development of hurricanes from tropical cloud clusters, depressions and cyclones. In nature, the results could be even more dramatic than those described here, since the intensity and radial extent of the inward eddy flux of momentum are observed to increase with each stage of development from the cloud cluster through the developing cyclone stage, whereas in all of our numerical integrations, the flux distributions and intensity were held constant with time.

5. Structure and energetics of the mature hurricane

Figs. 4a, 4b and 4c show the tangential velocity, the radial and vertical velocities and the temperature departures, respectively, at the mature stage of development in the integration corresponding to the composite Atlantic developing hurricane with eddy fluxes of momentum present. These distributions are not unlike those for mature hurricanes observed in nature.

Figs. 5a and 5b show the time variations of each of the integrals in the kinetic energy equation [Eq. (7) in Challa and Pfeffer (1980)] over the domain $0 < r < 500$ km in the integrations corresponding to the composite Atlantic developing hurricane, with and without the observed eddy flux forcing, respectively. The most striking difference between the two cases lies in the magnitudes reached by the kinetic energy.

![Composite Atlantic Developing Hurricane](image)

**Fig. 5.** Time variations of kinetic energy tendency and rates of energy conversion in the numerical integration corresponding to the composite Atlantic developing hurricane with and without eddy flux forcing.
tendency \( \partial k/\partial t \), the potential to kinetic energy conversion \( C_a \) and the dissipation \( F \), all of which are much larger in the integration with the eddy fluxes of momentum present. Although the conversion \( E_k \) from eddy kinetic energy to the kinetic energy of the vortex is larger than the conversion \( C_a \) from the potential to kinetic energy only during the early stages of development (during which it gives the hurricane its impetus), its presence dramatically alters the character of the model hurricane development.

The time variations of each of the energy integrals in the integration corresponding to the composite Atlantic non-developing disturbance are shown in Fig. 6. In this case, all of the integrals, including \( E_k \), remain small during the entire length of the integration.

6. Conclusions

The results presented in this paper give evidence of the importance of large-scale eddy fluxes of momentum in model hurricane development. In our previous work (Challa and Pfeffer, 1980) we used somewhat arbitrary distributions of these fluxes in a sensitivity study with various initial conditions. In the present study, we have used observed atmospheric data corresponding to Atlantic tropical disturbances to specify the distribution of the eddy fluxes of momentum and of the initial wind and moisture conditions. Without the observed eddy flux convergence of momentum, the initial vortex associated with the composite Atlantic developing disturbance is not capable of developing into a hurricane through the sole action of Ekman pumping and cooperative instability. With the observed eddy flux distribution, the same initial vortex develops rapidly into a hurricane. Moreover, the initial vortex associated with the composite non-developing disturbance does not develop into a hurricane. This is because the observed eddy fluxes of momentum are too weak and diffuse to organize the radial circulation and the consequent influx of moisture in the lower troposphere, which is required to fuel the growth of the hurricane.

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