Diagnostic Studies of Spiral Rainbands in a Nonlinear Hurricane Model

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(Manuscript received 24 July 1975, in revised form 27 January 1976)

ABSTRACT

Results from diagnostic studies of a nonlinear hurricane model support the conclusion that internal gravity-inertia waves are responsible for hurricane rainbands. The mean relative vorticity differed little between the bands and their environment, a characteristic of gravity waves modified slightly by the earth’s rotation. Small differences in mean radial and tangential velocity components, divergence, and the radial pressure gradient force were noted between the bands and their environment. The upper layers of the bands were responsible for a small increase in the model storm’s kinetic energy due to a net convergence of kinetic energy flux from the environment into the bands. A large net convergence of cyclonic angular momentum flux into the bands occurred in the boundary layer. Conversion of available potential energy to kinetic energy was not significant in the model bands. Finally, latent heating in the bands did not play an important role in the maintenance or propagation of the bands at large radii.

1. Introduction

In view of the current emphasis on hurricane modification, it is important to understand fully the interactions between the rainbands and the larger scale tropical cyclone circulation. The role of rainbands in the kinetic energy, angular momentum, and water vapor budgets of the hurricane is especially important. The difficulty in obtaining simultaneous, high-density data at several levels in the hurricane has hampered previous observational studies of hurricane rainbands. Gentry (1964), in the most complete observational study to date, summarized aircraft traverses of 75 rainbands to estimate the conversion of potential to kinetic energy within inner and outer bands of a “mean” storm. Because of the data collection problems, simultaneous angular momentum and kinetic energy budgets for the bands and the environment have not been computed for a real hurricane.

Nonlinear models of the hurricane provide an excellent tool to study the propagation and maintenance of rainbands, and offer the opportunity to calculate these budgets in sufficient detail to understand better the mesoscale structure of model rainbands and their interaction with the surrounding environment and the entire hurricane.

The application of numerical models for this purpose assumes that natural and model rainbands have a similar physical structure. The convective scale with its large horizontal gradients of temperature, moisture and wind is absent from the model rainbands because latent heating is parameterized in the model. Thus, the mean structure of the model bands is isolated from the more variable convective scale which often masks the small, but possibly significant, mesoscale gradients of atmospheric parameters in natural rainbands.

In a three-layer model of the tropical cyclone (Anthes, 1972), spiral bands of convection were observed to form near the center of the vortex and propagate outward at a speed of 15 m s⁻¹. These bands were about 120 km wide and showed rainfall rates of about 1 inch day⁻¹. The structure of the bands appeared qualitatively similar to their environment.

In a recent paper (Kurihara and Tuleya, 1974), the structure of spiral rainbands which developed in an 11-level model was described in considerable detail. In this model spiral bands of width about 100 km formed near the center and propagated outward at a speed of about 28 m s⁻¹. These bands behaved like internal gravity waves, with a well-defined pattern of low-level convergence and surface pressure tendency. In general, the bands resembled those found by Anthes (1972), although there was considerably more detail in the vertical structure because of the larger number of levels in the model.

In this paper, we investigate in detail the kinetic energy and angular momentum budgets of a model hurricane, with particular emphasis on these budgets of the spiral rainbands. The importance of latent heating on the maintenance and propagation of rainbands is also investigated in an experiment in which the latent heating is artificially eliminated.
2. Nonlinear hurricane model

This section reviews the hurricane model which generated the rainbands for the diagnostic studies. The details on the finite-difference approximations and the parameterization schemes used to approximate cumulus convection and the large-scale release of latent heat are found in Anthes et al. (1971) and Anthes (1972). The basic set of equations is written for the $\psi$-system (Phillips, 1957) in Cartesian coordinates. The horizontal mesh utilizes a grid spacing of 30 km. The grid points are staggered to provide better resolution for the linear pressure gradient terms. Horizontal velocity components are defined at one set of grid points and the other variables are defined at a second set of grid points which are offset by 45° from the momentum points. The horizontal lateral boundary approximates a circle with all boundary points located between radii of 435 and 450 km.

The model atmosphere is devided into an upper (layer 1) and middle layer (layer 2) of equal pressure depth (about 450 mb) and a thinner boundary layer (layer 3) of thickness 100 mb. The temperature and velocity levels are staggered in the vertical from the geopotential and $\psi$ levels.

a. Development of rainbands in the nonlinear model

The model storm develops from an initial circularly symmetric vortex. The symmetry remains until after hurricane strength is achieved. At this time, azimuthal asymmetries become quite noticeable, especially in the outflow layer where horizontal eddies with wave-numbers 1 and 2 become dominant in agreement with real storms (Black and Anthes, 1971). After the outflow layer becomes asymmetric, well-defined spiral bands of upward motion form near the vortex center and propagate cyclonically outward. In the outer region of the storm beyond 200 km, the bands propagate with a radial speed of $\sim 15$ m s$^{-1}$ and with a period of $\sim 3.5$ h.

These wave characteristics agree closely with those obtained in a linear solution by Diercks (1975). The Matsuno time-differencing scheme, with the wavelength of the bands and the time step and grid resolution used in this model, reproduces 75% of the phase velocity of a pure gravity wave. Assuming that this correction applies to the nonlinear model yields an actual radial phase velocity of 20 m s$^{-1}$ for the rainbands. This compares with the radial velocity of 21 m s$^{-1}$ predicted by the linear wave equation (3.39) in Diercks (1975).

The mean upward motion in the bands decreases as the bands propagate away from the vortex center, and rainfall rates average 2-3 cm day$^{-1}$ from the release of latent heat in the bands. There have been relatively few estimates of precipitation rates from observed bands. Syōno et al. (1951) and Staff Members, Tokyo University (1969) estimated the rainfall intensity in rainbands associated with typhoons moving inland over Japan. The greatest peak intensities exceeded 72 cm day$^{-1}$, while the weaker peaks were about 5 cm day$^{-1}$. However, these high rates were appropriate for smaller horizontal scales than those associated with the bands in this model, which are probably artificially wide because of the coarse horizontal resolution. Thus, we conclude that the model rainfall rates are consistent with those of natural rainbands.

b. Initialisation of model for diagnostic studies

Two 6 h forecasts were run for this study during the mature, steady-state stage of the model storm when spiral bands were continuously forming and propagating outward. The first experiment was conducted with all the diabatic processes present in the model (experiment C), while the second experiment suppressed both large-scale and convective latent heating beyond a radius of 144 km from the storm center (experiment D). Forecast data at 84 h from experiment 6, which was previously reported by Anthes (1972), were used to initialize these experiments.

Fig. 1a shows the boundary-layer (level 7/2 in model; Anthes, 1972) vertical motion field ($\omega = dp/dt$) at 86.5 h from experiment C in which spiral bands of upward motion are prominent. Fig. 1b illustrates the propagation of one of these bands by the shading of the upward motion portion of the band at 86 and 90 h.

The $\omega$ field at 86.5 h for the upper level is shown in Fig. 2. The band structure is still evident at this level, although much weaker than in the boundary layer. In order to isolate the properties of the bands,
the hurricane was separated into three distinct regions. These regions are referred to as the bands, environment and inner region and are based on the horizontal structure of the boundary-layer vertical motion field. The inner region has a radius of 144 km and includes the domain around the circulation center where the bands are not clearly defined. This region is depicted within the heavy solid line in Fig. 1. The bands are shaded and include the domain beyond the inner region in which upward motion exists in the boundary layer. The environment includes the area between the bands and beyond the inner region. Although some slight arbitrary smoothing was necessary in making these definitions, the bands are generally regions of ascending motion and the environment a region of descending motion. It was assumed for the budget calculations that the band structure did not have a vertical slope.

3. Mean structure of the bands and their environment

In this section, means for several variables are examined for the three regions defined above to delineate the differences in structure between the bands, environment and inner region. Area means for surface pressure, surface pressure gradient, surface pressure tendency, and surface dissipation of kinetic energy are shown in Fig. 3 for the bands, environment and inner region at 0.5 h intervals between 83.5 and 90.0 h. The curves labeled “total” are means over the entire domain within a 390 km radius from the center of the grid. Both the surface pressure gradient and the surface pressure tendency are slightly less in the bands than in the environment, while the surface pressure fluctuates with a 3 h period. Little difference is noted between the surface dissipation in the bands and environment.

Fig. 4 presents means for selected variables in the inflow layer alone, where the bands are best defined. In the inflow layer, the upward motion in the bands is about 1 cm s⁻¹, compared to a mean downward motion of about 0.5 cm s⁻¹ in the environment. These

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**Fig. 2.** Vertical motion field for level 3/2 (≈225 mb) at 86.5 h. Isopleths are in units of 10⁻³ mb s⁻¹, and shaded regions are less than −0.4 mb s⁻¹.

**Fig. 3.** Area means for surface pressure (a), surface pressure gradient (b), surface pressure tendency (c), and surface dissipation of kinetic energy (d) for the bands (dash-dotted line), environment (dashed line), and inner region (dotted line) at 0.5 h intervals. The curves labeled total are means for the domain within a radius of 390 km from the center of the grid. Units are shown with each graph.
values are an order of magnitude smaller than the mean value of 21 cm s\(^{-1}\) in the inner region. The boundary-layer horizontal velocity fields show a sharp distinction between convergence in the bands and divergence in the environment. The magnitude of the radial pressure gradient force \((\text{as defined by } -P^e(\partial \phi / \partial \theta) - RT(\partial P^e / \partial \theta), \text{ where } P^e \text{ is surface pressure, } \phi \text{ geopotential, } R \text{ the gas constant for dry air, and } T \text{ temperature})\) is consistently lower in the bands. The radial and tangential velocity components are both weaker by about 0.5 m s\(^{-1}\) in the bands compared to the environment. On the other hand, the differences between the bands' and environment's relative humidity, temperature, angular momentum and vorticity are relatively small.

The structures of the bands and their environment for the upper two layers are quite similar in most respects (see Dierckx, 1975). The bands are not as well defined in the upper layer as they are in the boundary and middle tropospheric layers. In the middle layer, as in the boundary layer, the vertical motion reverses sign between the bands and environment. In the outflow layer vertical velocity is upward in both the bands and environment, although ascending motion is slightly stronger in the bands. In the middle and outflow layers, the radial and tangential velocities in the bands are about 0.5 m s\(^{-1}\) lower compared to the environment.

The nearly identical values of relative vorticity in the bands and environment support the conclusion that the model bands are gravity waves, modified slightly by rotation. The relative vorticity of a pure gravity wave is zero.

An important result is the fact that the temperature and moisture structure of the bands does not vary appreciably from that of the environment. The bands are very slightly warmer than the environment in the outflow layer because of the release of latent heat in cumulus convection. The bands are very slightly colder in the inflow layer, probably because of greater adiabatic cooling compared to convective warming in the ascending air. In contrast with the inner region, it is apparent that the release of latent heat and addition of water vapor from cumulus parameterization have only minor effects on the structure of these outer bands. The similarity in structure reflects the short time (\(\sim 1\) h) that air parcels remain in a band. Gentry (1964) also found only minor tem-
perature differences between the bands and environment at radii \( \geq 65 \) km. In these “outer” bands, slight cooling was observed in the lower troposphere below 16,000 ft. In Gentry’s study, the data were insufficient to determine the effect of latent heating on the upper tropospheric temperature structure.

In summary, a comparison of the structures of the bands and their environment shows that the greatest differences exist in the boundary layer, and suggests that internal gravity-inertia waves are responsible for the bands below 450 mb in the model storm. The band structure is only weakly discernible in the outflow layer above 450 mb.

4. Kinetic energy budgets

We next consider two detailed kinetic energy budgets for the model storm. The first budget is relatively simple, but it permits calculation of complete mechanical energy budgets for the bands, environment and inner region. The second budget is more complex than the first and only applies to the entire 390 km radius domain. However, it allows us to look at the kinetic energy budget in a manner that emphasizes the direct or indirect vertical circulation in the bands.

a. First kinetic energy budget

The derivation of Budget 1 is performed in a straightforward manner by forming the dot product of the horizontal velocity \( \mathbf{V} \) with the equation of motion. The resulting equation may be integrated over volume to yield

\[
\int_V \frac{\partial k_e}{\partial t} dV = - \int_V k_e \frac{\partial \mathbf{P} \cdot \mathbf{V}}{\partial t} dV - \int_V \frac{k_e}{\sigma_L} \int_L \mathbf{P} \cdot \mathbf{V} dL d\sigma
\]

(1)

(2)

(3)

(4)

\[
- \int_V (\mathbf{V} \cdot \nabla \mathbf{P} \cdot \mathbf{V}) dV
\]

(5)

In Eq. (4.1), \( k_e \) is the kinetic energy per unit mass, \( \mathbf{V} \) volume, \( \sigma_L \) and \( \sigma_u \) the upper and lower \( \sigma \) surfaces, respectively, in the domain, \( V_u \) the component of velocity normal to the lateral boundary of the domain, \( L \) denotes integration around the perimeter of the domain, \( \sigma \) is \( \partial k_e/\partial t \), and the operator,

\[
\int_V \left( \right) dV
\]

is defined as

\[
\int_V \left( \right) dV = \int_{\sigma_L} \int_{\sigma_u} \int_A (\right) dA d\sigma.
\]

(4.2)

In deriving (4.1), Gauss’ theorem was used to obtain the lateral flux of kinetic energy across the boundary \( L \) by the normal velocity component \( V_u \). The vertical flux of kinetic energy was also rewritten as two terms to be consistent with the finite-difference approximations for the vertical advection of momentum used in computing the \( u \) and \( v \) tendencies in the numerical model. In (4.1), the numbered terms (2)–(5) represent the net flux of kinetic energy across the lateral and vertical boundaries, the production of kinetic energy by cross isobaric flow, and the dissipation of kinetic energy by subgrid-scale eddies. Term (1) is introduced by the transformation to \( \sigma \) coordinates and is generally two or three orders of magnitude smaller than the remaining terms. In later discussions, the budget defined by (4.1) is referred to as Budget 1.

The change of kinetic energy within the entire volume to a radius of 390 km (dashed circle in Fig. 1a) may now be estimated by integrating the right-hand side (rhs) of (4.1) term by term. Term (2) is calculated directly by interpolating \( k_e \) and \( V_u \) to this boundary. The other terms are calculated assuming that each grid point is centered in a small box of area \((\Delta x)^2\), where \( \Delta x \) is the grid interval (30 km).

The left-hand side (lhs) of (4.1) may be evaluated directly from the model to provide an independent check on the budget calculated from the rhs terms. This term may be calculated from

\[
\int_V \frac{\partial k_e}{\partial t} dV = \int_V \left( \frac{\partial \mathbf{P} : \mathbf{V}}{\partial t} + \frac{\partial \mathbf{P} \cdot \mathbf{V}}{\partial t} - 2k_e \frac{\partial \mathbf{P} \cdot \mathbf{V}}{\partial t} dV
\]

(4.3)

where the tendencies are taken directly from the model. As will be shown below, energy budgets calculated with (4.1) over the entire domain are extremely accurate. Differences between the two sides of the equation are three to four orders of magnitude less than individual terms on the rhs, indicating that fictitious net sources or sinks of energy because of truncation errors are extremely small.

The accuracy of Budget 1 is important because Eq. (4.1) may also be adapted for calculating complete, separate kinetic energy budgets for the bands, environment and inner region. The lhs of (4.1) and all the terms on the rhs except the second may be summed separately for mesh boxes which belong to the bands, environment or inner region. For the boxes which comprise the bands, the difference between the lhs and the terms numbered (1), (3), (4)
and (5) on the rhs equals the net lateral flux of kinetic energy $NLF_B$ across the boundaries of the bands. In view of the close check between the two sides of (4.1), this procedure eliminates possible large interpolation errors introduced by directly calculating the lateral flux term across the boundary of the bands. Similar budgets may be calculated for the environment and inner region. Results from applying Budget 1 over the entire domain and the three smaller regions are presented in Section 4c.

b. Second kinetic energy budget

The second kinetic energy budget permits us to estimate the conversion of available potential energy to kinetic energy within the bands, environment and inner region. The correlation of the temperature and vertical motion anomalies within the bands is important in evaluating the bands' importance in the overall energy budget of the storm. Direct circulations, which convert potential to kinetic energy, occur when ascending air within the bands is warm relative to the surrounding environment. Cold ascent within the bands implies an indirect circulation and a consumption of kinetic energy at the expense of the mean kinetic energy of the storm. As seen in Fig. 1, the bands cover a large area of the total domain, and thus they could contribute significantly to the energy budget even though the temperature differences between the bands and environment are less than 0.1°C. Budget 2 also includes processes, such as lateral and vertical fluxes of potential energy by horizontal and vertical eddy motions, which are difficult to compute from observed data.

The derivation of Budget 2 is more complicated than the derivation of Budget 1. We begin with (4.1) by rewriting the vertical flux term, substituting the expression for $\nabla \cdot \mathbf{v} P^* \mathbf{n}$ from the definition of $\omega$ in $\sigma$-coordinates, and expanding the fourth term on the rhs. We obtain

$$\int_V P^* \frac{\partial \mathbf{v}}{\partial t} dV = - \int_V \mathbf{k} \cdot \frac{\partial P^*}{\partial t} dV - \int_V \mathbf{v} \cdot \nabla P^* \mathbf{k} dV \tag{1}$$

$$\int_V \mathbf{v} \cdot \frac{\partial P^*}{\partial t} dV = \int_V \mathbf{v} \cdot \frac{\partial P^*}{\partial t} dV - \int_V \nabla \cdot \mathbf{v} P^* \mathbf{k} dV \tag{2}$$

$$\int_V \left( \frac{\partial P^*}{\partial \sigma} - \frac{\partial \mathbf{v} \cdot \nabla P^*}{\partial \sigma} \right) dV = \int_V \phi \nabla \cdot P^* \mathbf{v} dV \tag{3}$$

$$\int_V \phi \nabla \cdot P^* \mathbf{v} dV = \int_V \frac{RT \omega}{\sigma} dV + \int_V \frac{P^* RT \frac{\partial \mathbf{v}}{\partial t}}{\sigma} dV \tag{4}$$

$$\int_V \frac{RT \frac{\partial \mathbf{v}}{\partial t}}{\sigma} dV + \int_V \frac{\partial P^*}{\partial t} dV + \int_V \left( D_U + D_V \right) dV. \tag{5}$$

Budget calculations based on (4.4) proved unsuitable for this study because terms (4) and (6) generally are opposite in sign and two orders of magnitude larger than the remaining significant terms in (4.4). Numerical roundoff error from these terms produced erratic time continuity and very poor checks between the rhs and lhs of (4.4). For this reason, an equivalent form was derived (Diercks, 1975), which was more suitable for the budget calculation:

$$\int_V P^* \frac{\partial \mathbf{v}}{\partial t} dV = - \int_V \kappa \frac{\partial P^*}{\partial t} dV - \int_V \frac{\partial P^*}{\partial \sigma} \kappa \frac{\partial \mathbf{v}}{\partial \sigma} dV \tag{6}$$

$$\int_V \left( \frac{\partial P^*}{\partial \sigma} \kappa \frac{\partial \mathbf{v}}{\partial \sigma} \right) dV \tag{7}$$

$$\int_V \left( \phi \frac{\partial P^*}{\partial \sigma} \kappa \frac{\partial \mathbf{v}}{\partial \sigma} \right) dV \tag{8}$$

$$\int_V \left( \phi \frac{\partial P^*}{\partial \sigma} \kappa \frac{\partial \mathbf{v}}{\partial \sigma} \right) dV \tag{9}$$

$$\int_V \left( \phi \frac{\partial P^*}{\partial \sigma} \kappa \frac{\partial \mathbf{v}}{\partial \sigma} \right) dV \tag{10}$$

The averaging operators and primes are defined as

$$\langle \langle \cdot \rangle \rangle \equiv \frac{1}{L} \int_L \langle \cdot \rangle dL$$

$$\langle \rangle \equiv \frac{1}{A} A \int_A \langle \cdot \rangle dA$$

Eq. (4.5) is similar to an expression in pressure coordinates given by Palmén (1960). Differences between (4.5) and Palmén's expression are introduced in the transformation from $\rho$-coordinates to the $\sigma$-coordinates used here. The main advantage of (4.5)
compared to (4.4) is its relative insensitivity to truncation errors.

In Budget 2 given by (4.5), the numbered terms (2)–(6) represent the net flux of kinetic and potential energy through the boundaries of the domain, term (7) represents the conversion between available potential energy and kinetic energy within the domain, term (9) represents the production of kinetic energy by subgrid-scale eddies. Terms (1) and (8) are introduced by the transformation to \( \sigma \)-coordinates and are generally two orders of magnitude less than the lhs of Eq. (4.5). Equivalent terms for the terms numbered (1), (2), (3) and (5) in Budget 1 are readily apparent in Budget 2. Term (4) in Budget 1, which represents the production of kinetic energy by cross-isobaric flow, is equivalent to terms (4)–(9) in Budget 2. In Section 4d, the conversion and production terms (7) and (9) in Budget 2 are evaluated separately for the bands, environment and inner region.

c. Results from kinetic energy Budget 1

Time-averaged kinetic energy budgets based on Budget 1 [Eq. (4.1)] are presented in this section for the entire domain and for the bands, environment and inner region. First, budgets are shown for the full depth of the atmosphere; then the budgets are evaluated separately for layer 3 (the inflow layer) and for layers 1 and 2 combined. We find a basic difference between the bands and the environment, with a net positive contribution to the total rate of change of kinetic energy in the bands and a negative contribution in the environment.

Fig. 5 illustrates time-averaged kinetic energy budgets for the entire domain. The averages were computed by calculating all terms in Budget 1 at half-hour intervals from 85.5 to 90.0 h during the life of the model hurricane and averaging the results. The symbol \( P \) represents the production of kinetic energy by cross-isobaric flow; \( D \) represents the dissipation of kinetic energy by lateral and vertical eddy viscosity, including surface drag effects; and \( k_e(\partial P^*/\partial t) \) represents the small contribution from term (1) in (4.1). The horizontal and vertical arrows in Fig. 5 represent net lateral and vertical flux divergence of kinetic energy, and \( \partial K/\partial t \) represents the total volume integral for the rate of change of kinetic energy.

Fig. 5 shows that the main source of kinetic energy production is in the boundary layer where inflow toward lower pressure occurs. In \( \sigma \)-coordinates, the term \( RTV \cdot \nabla P^* \) dominates in the inflow layer, while the positive contribution to kinetic energy production from the term \( P^* \nabla \phi \) reduces the negative contribution from \( RTV \cdot \nabla P^* \) in the outflow layer.

Dissipation of kinetic energy occurs largely in the boundary layer where the surface drag dominates. The difference between production and dissipation of kinetic energy is positive in the boundary layer. This positive contribution balances the upward flux of kinetic energy into the middle and upper layers. This source of kinetic energy in the higher layers is balanced by the significant dissipation and negative production in these layers. The volume integral of kinetic energy change is slightly positive. This increase in kinetic

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**Fig. 5.** Time-averaged kinetic energy budgets for the entire domain within a radius of 390 km for all layers (a), and layer 3 and layers 1 and 2 combined (b). Symbols are given in the text and units are \( 10^4 \text{ W} \).
energy takes place in the outflow layer, where the mean speed for the entire domain increases by 0.9 m s\(^{-1}\) during the period. Much smaller fluctuations occur in the boundary and middle layers. The speed increase in the outflow layer appears to be related to an inertial oscillation which is present in the outflow layer. This oscillation is also apparent in the absolute angular momentum budgets (see Section 5c). Finally, we note in Fig. 5 that the lateral flux of kinetic energy across the 390 km radius is one or two orders of magnitude smaller than the dissipation and production terms.

Time-averaged kinetic energy budgets for the boundary layer and upper two layers of the bands, environment and inner region are presented in Fig. 6. The significant result in Fig. 6 is the positive net contribution from the bands to the total volume integral of \(\partial K/\partial t\). In both the environment and the inner region, the net contributions are slightly negative. From Fig. 6, it is clear that the positive volume integral in the upper layers is responsible for the net increase of kinetic energy within the bands. This is due largely to the net flux of kinetic energy into the bands in the upper layers through the lateral boundaries and across the lower \(\sigma\)-surface. The lateral flux into the upper layers of the bands is larger by a factor of 3 compared to the environment.

The excess of dissipation over the sum of production and lateral inward flux of kinetic energy produces the negative volume integral in the inner region. The negative contribution from the environment is caused by the large net outward flux of kinetic energy, which exceeds the outward flux from the bands by a factor of 2. The production of kinetic energy is larger in the environment, a result of increased radial flow and increased radial pressure gradient in the environment compared to the bands (see Fig. 4). Although the increase in kinetic energy over the domain of the model hurricane occurs within the bands, this fact does not mean that the hurricane's kinetic energy will decrease in the absence of a band structure. Without bands, an increase in kinetic energy could occur within the larger "environmental" domain, or other changes in structure could alter the kinetic energy budget of the inner region.

d. Results from kinetic energy Budget 2

Time series of the total change of kinetic energy and individual components from Budget 2 are discussed in this section. Budgets are presented for the entire atmosphere, and then these are divided into separate budgets for layer 3 and layers 1 and 2 combined. In addition, time series of the components in the kinetic energy budget from the bands, environment and inner region are presented. Finally, a comparison of the rhs of Eqs. (4.1) and (4.3) with independent calculations for the common lhs of these equations shows that both Budgets 1 and 2 are very accurate.

The time series of individual components from Budget 2 for the entire atmosphere are shown in Fig. 7a for the period 85.5 to 90.0 h. The symbols \(D_H\) and \(D_V\) represent dissipation of kinetic energy by horizontal and vertical eddy viscosity; \(D\) is the sum of \(D_H\) and \(D_V\); \(G\) is the sum of the production of kinetic energy by cross-isobaric mean flow (\(\bar{P}\)) and the conversion of available potential energy to kinetic energy (\(C\)); RHS is the sum of all terms on the rhs of (4.5); and \(M\) represents term (4) of (4.5). The terms not shown from Budget 2 are negligible in magnitude compared to the terms plotted. The magnitudes of all terms at 87.0 h are shown for comparison in Table 1.

The uncertainty in the kinetic energy Budget 2,
defined as the difference between the lhs and rhs of (4.5), is small compared to the important individual components. The solid curve in Fig. 7b illustrates the time series of the lhs of (4.5) as calculated from (4.3). The summation of all terms on the rhs is indicated by the short dashed line. The magnitude of the difference between the two curves is approximately $3 \times 10^{10}$ W. In comparison, the magnitudes of the net lateral fluxes across the boundaries of the bands, environment and inner region, which were estimated as residuals, were on the order of $10^{12}$ W, and hence may be considered reliable.

The volume integral of $\partial K/\partial t$ is mainly a balance between the conversion and production of kinetic energy, the lateral flux of potential energy by the mean flow represented by $M$ in Fig. 7a, and the dissipation of kinetic energy by friction. The summation of all terms in Budget 2 oscillates very close to zero during the experiment and is between one and two orders of magnitude smaller than the dissipation, conversion and production terms. The lateral flux of kinetic energy and the lateral flux of eddy potential energy by eddy motions are also small compared to the conversion, production and dissipation terms (see Table 1).

In Fig. 7b, the contributions to $\partial K/\partial t$ by the bands, environment and inner region are shown separately. The contribution from the bands is positive and is approximately the same magnitude as the total volume integral during the experiment. This follows the results already displayed in Figs. 5 and 6 where the time-averaged mean for the bands slightly exceeds the mean for the total volume. The contributions from the inner region and the environment fluctuate around zero, contributing slightly negative values in the time-averaged budgets.

Separate budgets similar to that shown in Fig. 7 were also calculated for the boundary layer and layers 1 and 2 combined. The details of these budgets are included by Diercks (1975) and are only summarized here. The production of kinetic energy by mean cross-isobaric flow and frictional dissipation dominate in the boundary layer. The vertical flux of kinetic energy from the boundary layer to the upper layers is significant ($16 \times 10^{12}$ W). The bands and the environment yield minor contributions to the con-

**Table 1.** Magnitude of terms in kinetic energy Budget 2 at 87.5\'. Numbers in parentheses correspond to terms on the rhs of Eq. (4.5). Units are $10^{12}$ W.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
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<th>Production</th>
<th>Dissipation</th>
<th>Total</th>
<th>Uncertainty</th>
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<td>terms</td>
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<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
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<td>-16.0</td>
<td>-0.053</td>
<td>0.002</td>
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<tr>
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</table>
version and dissipation terms, but together contribute about 25% to the total production of kinetic energy by cross-isobaric flow. Most of the conversion of available potential energy (Curve C in Fig. 7a) occurs in the outflow layer where the release of latent heat in cumulus convection and large-scale processes results in large positive temperature deviations. About 92% of this conversion occurs in the inner region. A direct circulation results because the positive temperature deviations are correlated with ascending air in the inner region. The small positive conversion (about 8% of the total) in the bands and environment indicates a weaker direct circulation.

Although the conversion term is positive in the upper two layers, the production term is negative, as air flows outward toward higher pressure. This negative contribution averages about $-35 \times 10^9$ W compared to the positive production of about $46.7 \times 10^9$ W in the boundary layer (see Table 1).

Term (4) in Eq. (4.5), designated by $M$ in Fig. 7a, represents the rate of work at the lateral boundary, and becomes significant in the outflow layer. In $\sigma$-coordinates, the heights of $\sigma$-surfaces in the high troposphere increase toward the hurricane center, with the result that $(\phi - \hat{\phi})$ is negative. Because $V_n$ is positive in the outflow layer, the contribution from term (4) is positive.

The contributions in the bands, environment and inner region by several important components of Budget 2 are illustrated in Fig. 8. The curves labeled "total" represent the combined contributions in all three regions within the 390 km outer radius. The bands apparently do not have a significant role in converting available potential energy to kinetic energy within the model storm. The nearly equal contributions in the bands and environment are less than 10% of the total conversion, which occurs mainly in the inner region. The slight positive contribution in the bands and environment results from the positive correlation of $\omega''$ and $T''$ in the outflow layer of both regions. The bands, however, in this analysis are only defined beyond a radius of 144 km. The coarse resolution of the model storm prohibits an analysis of inner bands that surround the eye-wall cloud in real hurricanes. These inner bands may convert significant amounts of available potential energy to kinetic energy.

The bands and environment account for approximately 33% of the production of kinetic energy by the mean flow, as shown in Fig. 8. A larger contribution from the bands is explained by the reduced upper level radial outflow in the band circulation. Dissipation by subgrid-scale eddies is about equal in the bands and environment, while the inner region accounts for approximately 90% of the total dissipation. Horizontal eddy diffusion is negligible beyond 144 km; it becomes significant in the inner region where the horizontal wind shear is large.

**e. Summary of kinetic energy budgets**

Two forms of the kinetic energy equation were used in this section to study the energetics of the hurricane, including the contributions by the bands, environment and the inner region. In Budget 1, the production of kinetic energy by cross-isobaric flow was emphasized. In Budget 2, the conversion of available potential energy to kinetic energy through correlations between the temperature and vertical motion fields was con-

![Fig. 8. Time series of the conversion (a), dissipation (b) and production (c) terms from kinetic energy Budget 2 for all layers. Contributions from the entire domain (solid line labeled total), bands (dash-dotted line), environment (dashed line), and inner region (dotted line) are shown in each figure. Triangles represent the environment in (a) and (b).](image-url)
sidered. Both budgets were very accurate as evidenced by the small difference between independent estimates of the budgets. The kinetic energy budget for the entire domain represented a small positive difference between large production and dissipation terms. In the inner region, dissipation exceeded production, but significant amounts of kinetic energy were imported from the bands and environment.

The energy budget showed that kinetic energy in the upper layers of the bands increased during the 6 h time period. This increase was a result of a differential flux divergence of kinetic energy between the environment and the bands. The lateral flux of kinetic energy was into both the environment and the bands at high levels, but the flux into the bands was about 3 times larger than into the environment. Except for the differences in the terms representing the horizontal flux of kinetic energy, the energetics of the bands and their environment were very similar, suggesting that the outer bands play a small role in the overall energy budget of the model storm.

5. Absolute angular momentum budgets

The relationship of the rainbands and their environment to the hurricane circulation may be further studied by considering the balance of angular momentum around the cyclone axis. In the inflow layer, absolute angular momentum decreases inward toward the circulation center because of dissipation by tangential surface stresses. Therefore, angular momentum must be imported across the outer radii in order to maintain the tangential momentum within the hurricane. This influx of angular momentum increases outward to the limits of the circulation, where the inward transport consists largely of the earth’s angular momentum. Above the inflow layer, the dissipation of angular momentum by horizontal and vertical eddy viscosity is relatively small compared to the dissipation by tangential surface stresses. Therefore, air flowing outward in the upper troposphere tends to conserve angular momentum, and thus increases its anticyclonic velocity. Absolute angular momentum budgets are presented in this section for the entire domain and separately for the bands, environment and inner region.

a. Angular momentum equations

As in the case of the mechanical energy equation (4.1), we may calculate complete angular momentum budgets for the bands, environment and inner region. The equation for the volume time rate of change of absolute angular momentum $m_a$, defined by

$$m_a = r v_\lambda + \frac{r^2 v}{2}$$

is (Diercks, 1975)

$$\int_v F^* \frac{\partial m_a}{\partial t} dV = - \int_v m_a \frac{\partial P^*}{\partial t} dV$$

(1)

$$\frac{1}{g} \int_{\sigma_h}^{\sigma_L} \int_0^{2\pi} (m_a v_r P^*)_R d\lambda d\sigma$$

(2)

$$\frac{1}{g} \int_{\sigma_h}^{\sigma_L} \int_0^{2\pi} \left[(m_2 v_\lambda P^*)_L - (m_2 v_\lambda P^*)_H\right] d\lambda d\sigma$$

(3)

$$\frac{1}{g} \int_A \left[(\partial P^* m_a)_L - (\partial P^* m_a)_H\right]_dA - \int_v \frac{\partial P^* \phi}{\partial \lambda} dV$$

(4)

$$\frac{1}{g} \int_A \frac{\partial P^*}{\partial \lambda} \left[(\sigma \phi)_L - (\sigma \phi)_H\right] dA + \int_v r F^*_\lambda dV$$

(5)

where $r$ is radius, $\lambda$ is azimuth, $v_r$ and $v_\lambda$ indicate the radial and tangential velocities, respectively, $F_\lambda$ is the tangential component of the frictional force, and $R$ the radius of the domain boundary as measured from the circulation center. The numbered terms (2) and (3) combine to give the lateral flux of angular momentum across the outer boundary; term (4) is the vertical flux of angular momentum across the lower ($\sigma_L$) and upper ($\sigma_H$) sigma surfaces; terms (5) and (6) are pressure torque terms; and term (7) is the loss of angular momentum by tangential frictional forces. Term (1) is introduced by the transformation to $\sigma$-coordinates and is small compared to the other terms. The lateral flux terms (2) and (3) were integrated in this form, as opposed to using Gauss’ theorem, to better preserve similarity with the finite-difference approximations used to integrate the $P^* u$ and $P^* v$ tendency equations. Terms (3) and (5) are necessary because the circulation center rotates anticyclonically about the grid center. Thus, the circulation center and the grid center do not coincide as shown in Fig. 9. Circles with large radii constructed around the circulation center (dashed circle in Fig. 9) intersect the 390 km radius circle of the domain (solid line) at points $(R, \lambda_1)$ and $(R, \lambda_2)$. Contributions to terms (3) and (5) are derived only from those radii which intersect the boundary of the domain. If the centers of the storm and the domain coincide, then terms (3) and (5) would integrate to zero.

The pressure torque term (5) is retained to yield complete angular momentum budgets for the bands and environment. Torques arising from asymmetrical
pressure distributions between the bands and environment are significant in the angular momentum budgets shown in Section 5b. Term (5) integrates to zero within the circular domain of the inner region.

The change of angular momentum within a radius of 390 km from the grid center may now be estimated by integrating the rhs of (5.2) term by term. Cylindrical velocity components are derived from the Cartesian velocity components forecast by the model. Terms (2) and (3) are calculated by further interpolating $m_z$, $v_z$ and $v_r$ to the outer boundary; the remaining terms are integrated on the Cartesian grid.

The lhs of (5.2) provides a check for the angular momentum budget calculated from the rhs terms. The volume integral for the time rate of change of angular momentum may be rewritten as

$$
\int V \frac{\partial P^*}{\partial t} dV = \int V \frac{\partial P^*}{\partial t} dV
$$

$$
= \int V \left( \frac{\partial P^*}{\partial t} \right)_{v_z} dV. \tag{5.3}
$$

The pressure-weighted tangential velocity tendency is calculated from the Cartesian velocity component tendencies in the model according to

$$
\frac{\partial P^*}{\partial t} = \frac{\partial P^*}{\partial t} \sin \lambda + \frac{\partial P^*}{\partial t} \cos \lambda. \tag{5.4}
$$

Eq. (5.2) may also be adapted for calculating complete angular momentum budgets for the bands, environment and inner region. The lateral boundaries between the bands, environment and inner region are defined for numerical integration in the same way as they were in the kinetic energy budgets. The net lateral flux $NLF_B$ across the boundaries of the bands is estimated as a residual between the lhs and terms (1), (4), (5), (6) and (7) of (5.2).

b. Time-averaged angular momentum budgets

Time-averaged momentum budgets based on (5.2) and (5.3) are presented in this section for the entire domain and for the bands, environment and inner region. Budgets are presented over all layers, and then separate budgets are presented for layer 3 and layers 1 and 2 combined.

Fig. 10 illustrates time-averaged angular momentum budgets, averaged over the period from 85.5 to 90.0 h, for the entire domain. The symbol $D$ represents the loss of angular momentum by tangential frictional forces; $m_z(\partial P^*/\partial t)$ represents the small contribution from term (1) in Eq. (5.2); $T$ represents the combined contribution from the pressure torque terms (5) and (6) in (5.2); the horizontal and vertical arrows represent net lateral and vertical flux divergence of angular momentum; and $\partial M_{z}/\partial t$ represents the total volume integral for the rate of change of angular momentum.

Fig. 10a shows that the hurricane during this period is a sink for angular momentum because dissipation exceeds net inflow at the lateral boundary. In layer 3, net inflow across the lateral boundary is closely balanced by dissipation and vertical flux to the upper layers. The negative volume integral in layers 1 and 2 is due to lateral outflow in the high troposphere. Reflecting this negative volume integral, the mean tangential components of layer 1 steadily decrease during the period. The simultaneous increase of speed implies a gain of anticyclonic momentum in the outflow layer. The contribution from the pressure torque terms in the inflow layer is relatively small compared to the contribution from these terms in the upper layer. This difference in magnitude is a result of the more asymmetric nature of the outflow layer.

Time-averaged angular momentum budgets for the bands, environment and inner region are presented in Fig. 11. The volume integrals reflect a larger loss of cyclonic momentum in the environment compared to the bands. This difference, which is approximately a factor of 3, is a result of the bands importing angular momentum from the environment and the asymmetric distribution of $P^*\phi$ acting through the pressure torque term (5) in (5.2). The distribution of the change of angular momentum due to the pressure torque reflects low values of $P^*\phi$ at the leading edge of the bands and high values of $P^*\phi$ at the trailing edge. The net import of cyclonic momentum slightly exceeds the dissipation of angular momentum in the inner region. Finally, the dissipation rates in the bands and environment are approximately equal.

Time-averaged angular momentum budgets for the boundary layer and upper layers are shown in Fig. 12. The bands in the boundary layer increase their cyclonic...
momentum through a large import of angular momentum across their lateral boundaries. The environment has a small gain of angular momentum across the lateral boundaries, while the inner region is a large importer of angular momentum. In the upper layers, the gain of anticyclonic momentum in the environment exceeds the gain in the bands by a factor of 2.3. The transport of angular momentum from the bands to the environment at this level reflects the mean outward component of air across the bands' lateral boundaries. Again, the contrast between the pressure torque terms acting on the environment and bands is consistent with the $P^\phi$ pattern associated with the traveling gravity-inertia waves.

**c. Summary of angular momentum budgets**

The role of rainbands in the hurricane’s angular momentum budget is summarized in Fig. 13. In the boundary layer, the large net inward transport of angular momentum across the bands’ lateral boundaries and the cyclonic contribution from the pressure torque terms are closely balanced by dissipation and vertical transport of angular momentum to higher
levels. The result of these four processes is a net gain of cyclonic momentum in the boundary layer of the rainbands. A net loss of cyclonic momentum occurs in the outflow layer because of the dominance of the lateral flux of momentum out of the bands.

The rate of change of angular momentum in the entire domain over the period of time between 84 and 90 h [not presented here; see Diercks (1975)] indicated that an inertial oscillation was superimposed on the high tropospheric circulation. This long-period oscillation did not influence the boundary layer where a much shorter 3 h oscillation was found. This short period was probably related to the period of the bands. Evidence for the gravity-inertia wave mechanism was especially pronounced in the contributions from the pressure torque terms and in the net fluxes of angular momentum across the lateral boundaries of the bands and environment in the boundary layer. The distinctions between the bands and environment in the high troposphere were not as strong, possibly due to the absence of a parameterization scheme for the vertical transport of low-level cyclonic momentum by cumulus convection.

6. Importance of latent heat release in bands

An advantage of numerical models is the possibility of isolating certain effects through controlled experimentation. In this section, the role of latent heating in the maintenance and propagation of model rainbands is studied by artificially suppressing the release of latent heat outside the inner region. If latent heating is important in the maintenance of the bands, the suppression of the heating should drastically modify, or even eliminate, the model bands. On the other hand, if latent heating is only of secondary importance to band maintenance, its elimination should produce little effect. Thus, this experiment may provide some insight into whether an important cooperation exists between the cumulus convection and the rainband circulation during the mature stage of the bands.

Mathur (1975) reported on the results of a nonlinear experiment in which nonconvective heating was removed as a source of energy for a developing hurricane. Bands of upward motion, which included stationary and propagating bands, radiated outward from the storm center. In contrast to the bands
studied in this paper, Marthur's bands were best defined in the middle and upper troposphere and rotated clockwise. When latent heat from nonconvective processes was removed from the model, Mathur found that the moving bands failed to develop. Furthermore, the modified storm intensified at a considerably slower rate than in the control experiment. The experiment reported in this section has two important differences from Mathur's experiment:

1) Latent heating from both convective and nonconvective processes is suppressed, but only in the outer region of the storm, in an effort to isolate the effects of heating on the bands alone. Thus the inner region, where most of the latent heat is released, is not affected.

2) Latent heating is suppressed after the storm reaches the steady-state stage and bands are already propagating outward from the storm center.

The approximate characteristic wave equation for the linear model [Eq. (3.39) of Diercks (1975)] suggests that suppressing latent heat in the outer region of the model hurricane should increase the propagation rate of the bands because the atmosphere is more stable without heating from cumulus convection.

Kurihara's (1976) recent results indicated that latent heating played a relatively minor role in the generation of bands in the inner region of the storm. In the outer region, his bands were nearly neutral waves regardless of whether or not latent heat was included. These results suggest that the neglect of heating in the outer region of our model will not alter the basic band structure.

a. Elimination of latent heat release

The 6 h experiment used in the energy and angular momentum budgets serves as the control (experiment C). The modified experiment (D) is identical to the control experiment except that latent heating is not permitted in the bands and environment. Latent energy is conserved in the modified experiment because water vapor assumes a passive role beyond a radius of 144 km. In these regions, water vapor is redistributed only by horizontal and vertical advection and by horizontal diffusion. Supersaturation occurs during the 6 h experiment because water vapor is not condensed in cumulus convection or large-scale lifting processes.

b. Results

The removal of latent heating in the outer region had little effect on the overall storm dynamics. Maximum velocities in the lower and upper layers and minimum surface pressure are listed in Table 2 for the last 3 h of experiments C and D. The differences in Table 2 between the two experiments are insignificant. The total latent heating in the storm of experiment D at 90.0 h decreased by 16% from experiment C, reflecting the loss of latent heat in the outer region. It is interesting to note that the loss of this energy from the hurricane circulation failed to weaken the intensity of the storm. The intensity of experiment D at 90.0 h, as measured by the mean wind speed for the entire storm, slightly exceeds that of the control experiment. This is explained by an intensification of the direct circulation in the upper layers resulting from a larger temperature anomaly between the outer and inner regions.

Boundary-layer band structures at 90.0 h from experiments C and D are compared in Fig. 14. The inner region and lateral boundary of the model are outlined by heavy solid lines. Vertical velocities are analyzed in the bands at intervals of 1X10^-2 mb s^-1. Differences in the two patterns are very minor. The bands in experiment D have moved somewhat faster and are slightly weaker than the control bands. These differences amount to an increase in speed of less than 1 m s^-1 and a decrease in mean intensity of ascending motion of less than 1% from the control experiment.

The main effect of latent heating is found in the upper layer. With latent heat, the bands are higher and ascending motion extends to the outflow layer. Without heating, the band structure is absent in the upper troposphere, and weak subsidence exists above the lower and middle layer band structure. Relative to the environment the bands are again cooler in the boundary layer and warmer in the outflow layer. Adiabatic cooling determines the band temperature in the boundary layer of both experiments. Warming from latent heat release exceeds adiabatic cooling in the upper band structure of experiment C. In experiment D, warming above the bands is caused by weak adiabatic descent as opposed to weak adiabatic ascent in the environment. The structure of the bands in experiment D is similar to Kurihara's (1976) G3 mode.

Thus latent heat must be regarded as an effect rather than a cause of the rainbands, which appear to be manifestations of the convergence of low-level air associated with the structure of the gravity-inertia
waves. The latent heating is too weak and the phase velocity of the bands too high to produce significant warming of the air in the bands. Hence, the gravity-inertia wave is not affected to any great extent by condensation heating.

It is also notable that the neglect of latent heating beyond the 144 km radius did not reduce the intensity of the hurricane as measured by maximum wind speed or minimum central pressure. This result is consistent with the energetics of the hurricane. Available potential energy, which is the potential energy that may be converted to kinetic energy, is generated only when heat is released at relatively high pressure on isentropic surfaces (Johnson, 1970; Anthes, 1974). In the hurricane, the region where latent heating produces a positive generation of available potential energy is the warm region, where the isentropes dip toward higher pressure. In fact, heating in the cool outer region of the storm system may actually reduce the overall baroclinicity and destroy available potential energy.

7. Summary and conclusions

Data from a nonlinear hurricane model were used in diagnostic studies of the energy and angular momentum budgets of model rainbands. In the nonlinear model, spiral bands of upward motion formed continuously and propagated outward from the center of the simulated hurricane. That these bands were traveling gravity-inertia waves was supported by the small differences in mean radial and tangential velocity components, temperature and humidity between the bands and environment. The upper layers of the bands were responsible for a slight overall increase in the storm's kinetic energy during the experiment. This was a direct result of net convergence of kinetic energy flux from the environment into the bands. A strong net convergence of cyclonic angular momentum flux from the environment into the bands was observed in the boundary layer.

The mean temperature of the bands was considerably cooler than the temperature of the inner region of the storm and only very slightly warmer than the immediate environment. Therefore, conversion of available potential energy to kinetic energy was not significant in the bands of this study. Because of the coarse grid resolution, it was not possible to define the bands within 144 km of the storm center where significant conversion may take place in the inner bands of natural storms.

Latent heating from convective and nonconvective processes was suppressed in the bands in a second nonlinear experiment. The bands of upward motion continued to form and propagate out of the model domain in the modified experiment. Without latent heating, the bands propagated somewhat faster and did not rise as high into the troposphere. The overall storm intensity was virtually unaffected by the neglect of latent heating in the outer bands.

The nonlinear experiments support the conclusion that gravity-inertia waves are responsible for hurricane rainbands. Because of the small horizontal scale, the effect of the earth's rotation is relatively minor, and the traveling waves are nearly pure gravity waves. The mean relative vorticity differed little between the bands and their environment, a characteristic of gravity waves modified only slightly by the earth's rotation. There was some speculation originally that the maintenance of the bands might be significantly enhanced by a cooperation of the latent heat release associated with cumulus convection and the mesoscale convergence associated with the band. However, latent heating in the bands appeared to be a result of the
convergence pattern associated with the traveling wave and did not play an important role in the maintenance or propagation of the bands at large radii. In general, these conclusions support the findings of Kurihara and Tuleya (1974) and Kurihara (1976).

Observational studies in the vicinity of hurricane rainbands would provide data to determine the extent that these conclusions apply to natural rainbands. These observational studies should be designed to measure the following characteristics of the band-environment structure:

1) Phase speed and wavelength of the bands.
2) Mean temperature and moisture in the bands and environment.
3) Low-level vorticity and divergence patterns.

In these studies, equal emphasis should be placed on longitudinal and perpendicular traverses of the rainbands. The longitudinal traverses are required for the precise determination of the mean properties within the bands.

Future numerical studies should concentrate on experiments with higher horizontal and vertical grid resolution to better determine the effects of grid resolution on the wavelength and phase velocity of model rainbands. Higher grid resolution would also allow the inner bands to be differentiated from the mean hurricane motion.

Acknowledgments. This research was supported by the National Science Foundation under Grant GA-36324.

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