External Influences on Hurricane Intensity. Part I: Outflow Layer Eddy Angular Momentum Fluxes

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ABSTRACT

Outflow layer winds were objectively analyzed every 12 h for 6 days during the life cycle of Hurricane Elena (1985). A high correlation was found between angular momentum fluxes by azimuthal eddies at large radii and central pressure changes in the storm 27–33 h later. Momentum flux by eddies exceeded that by the azimuthal mean outside the 800 km radius, while vortex spinup by the eddies reached instantaneous magnitudes as large as 25 m s^{-1}/day. Outflow maxima and minima repeatedly appeared more than 1000 km from the hurricane center and tracked inward with time. The results provide evidence of significant environmental control on the behavior of the storm.

After reaching hurricane strength, Elena experienced a major secondary intensification associated with a large inward cyclonic eddy momentum flux produced by the passage of a middle latitude trough north of the hurricane. An outflow maximum appeared radially inside of the eddy momentum source, consistent with balanced vortex theory, and tracked inward with the eddy momentum source during the following 24 h. When the outflow maximum reached the storm core, an extended period of rapid pressure falls followed. It is speculated that these pressure falls represented a response to midlevel spinup forced by the outflow layer momentum sources.

Although environmental forcing dominated the later stages of Elena, the rapid initial intensification of the storm as it moved from land to water appeared to be a precursor to subsequent environmental interactions. The enhanced anticyclonic outflow from this initial deepening reduced the outflow-layer inertial stability, allowing a more radially extended region for external forcing. The secondary intensification of Elena is thus viewed as a cooperative interaction between mesoscale events at the hurricane core and synoptic-scale features in the upper tropospheric environment.

1. Introduction

A dichotomy has existed in the literature for many years with regard to proposed mechanisms of tropical cyclone intensity change. Observational studies usually assign a major role to forcing by the tropical cyclone environment. The majority of theoretical and numerical modeling papers, on the other hand, treat both the incipient and mature storm as existing in a passive, symmetric environment. These latter studies leave little doubt that tropical cyclones can intensify in isolation, but it remains unclear how often they do so in nature.

Tropical cyclone intensification is a mesoscale instability driven by local energy sources in the form of oceanic heat and moisture fluxes and latent heat of condensation. In this sense, internal processes dominate, and it is unlikely that the energy for intensification could come directly from environmental interactions. Rather, the key questions are the extent to which environmental forcing can accelerate or even trigger hurricane intensity change, and the processes by which this could occur.

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The greatest potential for interactions between a tropical cyclone and its environment exists in the outflow layer, where inertial stability is generally lowest. The current work will review observational and modeling studies of the influence of the outflow layer on hurricane behavior, and will describe the evolution of the outflow layer wind field in Hurricane Elena (1985) over a 6–day period as it evolved from a tropical depression to a mature hurricane. The sequence of events between outflow, eddy angular momentum fluxes, and inner core intensification will be described. A mechanism will be proposed by which the hurricane outflow layer environment can influence intensity change.

2. Review of outflow layer influences

a. Definitions

For the purpose of discussion, the atmosphere and upper ocean will be taken together as making up the hurricane, so that sea surface temperature effects and surface interactions will be considered internal to the hurricane system. The term "environmental forcing" will refer to the exchange of energy and angular momentum between the storm and azimuthally asym-

metric features in its environment, features whose origins are usually independent of the existence of the tropical cyclone. Because storm and environment cannot be uniquely separated, this definition by necessity contains some ambiguity.

The term "momentum" will refer to scalar relative angular momentum around a vertical axis at the center of the moving storm, expressed as rv_L, where v_L is the storm-relative tangential wind and r the radius.

b. Phenomenological outflow-layer studies

Riehl (1950) was an early proponent of the importance of upper tropospheric environmental processes in hurricane development, noting that some forcing was needed to insure that upper-level outflow did not sink in the immediate storm environment and ultimately destroy the radial temperature gradient required to intensify the storm. He argued that outflow layer inertial instability (Sawyer 1947) rarely occurred in incipient hurricanes and could not be responsible for extended outflow channels. Instead, he proposed that the strength and orientation of outflow channels depended upon the presence of, and interactions with, preexisting upper anticyclones or extratropical waves. Frank (1963) and Alaka and Rubsam (1965) showed that intensification could occur without preexisting upper anticyclones; instead, anticyclones often formed in place, presumably due to latent heating in the incipient storm.

Upper tropospheric influences on hurricane development were also emphasized by Miller (1958), Colón and Nightingale (1963), Fett (1966), Erickson (1967), Yanai (1968), Ramage (1974), Sadler (1976, 1978), Gray (1979), Chen and Gray (1984), and Merrill (1988a). All but one of these authors gave examples of intensifying tropical cyclones having an extratropical or subtropical trough in the upper troposphere several hundred kilometers westward and poleward of the surface center. Miller (1958) composited 200 mb geopotential heights from five mature hurricanes which reached their hypothetical maximum achievable intensity, as determined by a simple parcel model based on the mean sea surface temperature within 450 km of the center. The use of compositing allowed Miller to construct a time sequence of events from 2 days prior to 1 day after minimum central pressure. Despite the smoothing inherent in the process, Miller found large-amplitude outflow layer asymmetries, the most striking of which was an extratropical trough which shifted inward toward the storm center and intensified during the 24 h prior to minimum central pressure. The hurricanes deepened until the trough began to move northeastward away from the circulation.

Without exception, the tropical cyclone studies listed above show large-amplitude outflow layer asymmetries, and thus the potential for the storm environment to influence subsequent behavior. In particular, the presence of a trough to the northwest allows well-defined anticyclonic outflow channels to be maintained (Miller 1958), presumably providing an upper-level mass sink and momentum source for the storm. Nevertheless, such troughs are present in some nonintensifying cases as well (Colón and Nightingale 1963; Merrill 1988b). In the above studies a clear mechanism for coupling synoptic-scale forcing to the mesoscale instability represented by hurricane intensification has not been described.

c. Quantitative and modeling studies

With few exceptions (Ooyama 1987; Pfeffer and Challa 1981; and Tuleya and Kurihara 1981), numerical model simulations have not included asymmetric forcing from the storm environment. Ooyama (1987) simulated the hurricane outflow layer using a divergent barotropic model forced by fixed mass and momentum sources at the storm core. In the absence of environmental forcing, outflow was symmetric and largely confined to within the 400 km radius. Ooyama's addition of a simple asymmetry in the form of a meridionally sheared zonal wind induced a strongly asymmetric structure, with outflow channels extending beyond the 800 km radius. The results suggest that previous numerical studies with no environmental forcing, while contributing significantly to the understanding of internal dynamics, could not address the possible influence of the outflow layer on hurricane behavior.

Pfeffer (1958) proposed that the calculation of lateral transport of angular momentum by azimuthal eddies provided a quantitative basis for evaluating the role of environmental asymmetries in hurricanes. Anthes (1970) showed that eddies must supply cyclonic angular momentum in a steady state storm at outer radii. Black and Anthes (1971), Frank (1977), and Holland (1983) showed that such fluxes are observed in the outflow layer of tropical cyclones in nature. In a study of composited tropical cyclones, McBride and Zehr (1981) found that developing storms contained large inward eddy fluxes of cyclonic angular momentum at outer radii, which were confined almost entirely to the outflow layer of the composite storm. [See Pfeffer and Challa (1981) for a graphical display of McBride and Zehr's results.] McBride and Zehr found that nondeveloping tropical disturbances contained much weaker and more diffuse (though still inward) cyclonic eddy momentum fluxes. Because the presence of anticyclonic outflow jets almost insures inward cyclonic eddy momentum fluxes, these composite-based calculations are consistent with the individual observations presented earlier.

Pfeffer and Challa (1981) conducted a series of experiments in which McBride and Zehr's (1981) observed eddy momentum fluxes were inserted into a balanced axisymmetric numerical model. They found that the composite developing storm forced by its as-

sociated eddy momentum fluxes rapidly intensified to hurricane strength. The composite nondeveloping storm with its weaker eddy fluxes did not intensify. Most significantly, the developing storm with its eddy forcing removed also did not intensify, suggesting that the eddies were not a by-product of development but rather a contributing cause. Pfeffer and Challa (1981) proposed, using solutions of the Eliassen (1951) balanced vortex equation, that the radial–vertical circulation was enhanced by the observed eddy momentum source distribution, thus providing a potential mechanism for intensification. Uncertainties exist in these results with regard to the fixed eddy source in the model, which is unlikely over several days in nature, and with regard to the use of a balanced model, in which the adjustment to the eddy forcing is instantaneous. Nevertheless, the results of Pfeffer and Challa (1981) provide evidence that upper-tropospheric asymmetries, by importing angular momentum into the storm volume, may play a major role in the development process.

Holland and Merrill (1984) computed similar balanced vortex responses to idealized momentum source distributions. They proposed a model of development in which tropical cyclones intensified beyond minimal hurricane strength by a cooperative interaction with their outflow layer environment. In their conceptual model, an approaching trough poleward and westward of the storm produces enhanced anticyclonic outflow, in part due to the frontogenetical effects of confluence between the trough circulation and outflow from the tropical cyclone. The associated cyclonic momentum source and subsequent evolution of vertical shear produces a stronger warm core. Stronger outflow also lowers inertial stability, which may enhance coupling of outer regions with the storm core. Holland and Merrill thus provided physical hypotheses consistent with Pfeffer and Challa's (1981) modeling results and with various earlier observational studies.

Several questions still remain, primarily because such an evolution has never been quantitatively shown to occur in nature in a single tropical cyclone. Such questions include: (i) Can a cause-effect relationship between environmental forcing and subsequent tropical cyclone intensity change, such as that proposed by Holland and Merrill (1984), be shown to occur in a given storm; (ii) What is the sequence of events; for instance, enhanced eddy fluxes may precede deepening, or may simply reflect that deepening is underway (Ooyama 1982); (iii) By what process(es) does upper-level environmental forcing at large radii produce intensity changes at the storm core; and (iv) To what extent are hurricane intensity changes in nature triggered by environmental forcing, rather than associated solely with mesoscale processes in the storm core. By examining 12 consecutive observation times in Elena, the current study will address the first three questions and speculate on the fourth.

3. Data and analysis

a. Data sources

Wind data came from two sources: the international rawinsonde network, and high-level, satellite-derived cloud motion vectors generated operationally by the National Hurricane Center. Rawinsonde data was taken only from the 200 mb level. The high-level cloud motion vectors were assumed valid at 200 mb, following Black and Anthes (1971). For both sources, data were accepted only at or within 1 h of each analysis time. Analyses were done every 12 h from 0000 UTC 28 August to 1200 UTC 2 September 1985, when Elena was about to make landfall.

Figure 1 shows the region used for objective analysis and two datasets representing the lowest and highest mean data density of the 12 analyses within 2000 km of the center. A few subjectively generated bogus data were added for cosmetic reasons, but these had almost no influence on the results, as will be shown in section 3c. It is apparent from the data that inner core processes cannot be examined. Rather, the emphasis will be placed on the evolution of synoptic-scale features in the hurricane environment.

Differences in objective analyses often relate predominantly to quality control procedures on the original data (Carr 1987). In the current study, obvious errors, such as 300 m s^{-1} wind speed, were removed, and the remaining vectors plotted. Each vector was subjectively compared to its neighbors and to vectors at similar locations at previous and subsequent times, and, if necessary, to vectors at adjacent levels in the vertical. Vectors were removed which could not be fit into a subjectively reasonable pattern. Because small eddies and sharp shear lines are common in tropical cyclone outflow layers, this process was done conservatively, with fewer than 1% of observations removed.

b. Analysis method

The analysis scheme used a successive–correction approach with anisotropic weighting functions, following Benjamin and Seaman (1985). Their method essentially creates a coordinate system aligned with the local streamline curvature, and rotates the along- and cross-stream components of the correction vector appropriately to simulate along-flow correlations of the wind. The influence region was curved ("banana-shaped") only when the wind speed exceeded 15 m s^{-1} and the radius of curvature was less than three times the specified influence radius. The influence region was elliptic for high wind speeds and small curvature, and circular for wind speeds less than the 15 m s^{-1} critical value. In order to obtain an initial guess field for the evaluation of streamline curvature, a purely circular weighting function was used with a zero first guess field for six iterations. This curvature field was used to determine the shape of the weighting function for each
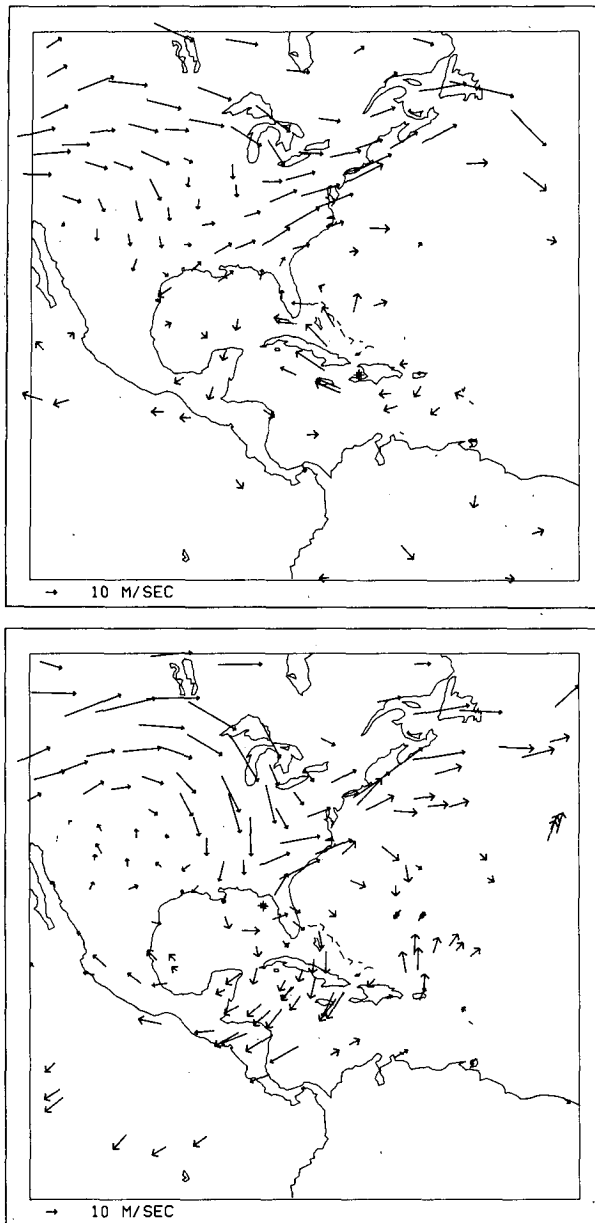
FIG. 1. Outflow layer (200 mb level) winds for (a) 0000 UTC 28 August and (b) 1200 UTC 31 August. These two periods represent, respectively, the lowest and highest mean data density for the 12 analysis times, as determined for a 2000 km radius region around the storm center. Satellite–derived winds are distinguished by long arrowheads, rawinsonde winds by short arrowheads, and "bogus" winds by a circle at the center of the vector. The storm position is indicated by an asterisk. The rectangular map background represents the region used for all objective analyses. The wind vectors are oriented according to the Lambert conformal projection.

data point during six iterations of a second analysis cycle. The initial influence radius was 3.2 times the average station separation, and was reduced by 30% on each of the subsequent five scans (N. Seaman, personal communication 1986).

The analysis was carried out on a Cartesian grid containing equally spaced points 100 km apart over a region 6500 km on a side. For subsequent calculations, storm-relative winds were computed, then bilinearly interpolated to a cylindrical grid with 100 km radial and 15° azimuthal resolution, out to a radius of 2000 km. Effects of the earth's curvature were neglected in the calculations. This produces a maximum error in radial distance of 3.1% at the 2000 km radius.

The analysis method of Benjamin and Seaman provides a fit of the data with no dynamical or statistical constraints. This may be preferable in the outflow layer of a tropical cyclone, because it is difficult to define appropriate dynamical balances or statistical models of wind covariance in a divergent, sometimes inertially unstable flow in a highly convective environment. A similar analysis method was chosen by Bergman and Carlson (1975) for analysis of hurricane data. One disadvantage of this approach is that random errors in the data are transferred without constraint to the analysis, particularly for such sensitive quantities as deviations from the azimuthal average. The interpolation to cylindrical coordinates introduces further error, particularly in inner regions of the storm. In the following section the overall importance of such errors will be evaluated.

c. Analysis sensitivity

Several analysis parameters were varied and the analyses redone to provide a measure of stability and accuracy. In order to provide the most demanding error measure, the eddy momentum flux, which involves products of deviations at each grid point summed for each radius, was computed for each analysis test. A fractional difference in calculated eddy flux between the control analysis and each test was computed by normalizing the actual difference by the time-averaged eddy flux magnitude at each radius, using

$$F(r) = \frac{\frac{1}{N} \sum_t |E_{\text{control}}(r) - E_{\text{test}}(r)|}{\frac{1}{N} \sum_t |E_{\text{control}}(r)|}, \quad (1)$$

where E represents the eddy momentum flux, which is given by Eq. (6).

Table 1 lists the various analysis tests. The first two changed the size and the third changed the shape of the influence radius. Test 4 removed the five-point smoother used after the last scan of the analysis. Test 5 introduced typical rawinsonde speed and direction errors into the original data. Following Golden et al. (1986), the speed error was 3 m s^{-1}, randomly either higher or lower than observed (if a speed became negative, it was instead reduced by 50% from its original value). A speed-dependent direction error, with the

TABLE 1. Analysis sensitivity tests.

Number	Variation from control
1	Increase influence radii by 33%.
2	Decrease influence radii by 33%.
3	Circular influence radii only.
4	Remove smoother after final scan.
5	Impose random errors on raw data.
6	Remove "bogus" winds.

sign of the error again randomly imposed, was determined from the expression (Golden et al. 1986)

$$\cos^{-1}\left\{\frac{s + 6.05}{(s^2 + 12.5s + 53.4)^{1/2}}\right\}, \qquad (2)$$

where s is the wind speed in knots. Equation (2) gives direction errors of 34° as speed approaches zero, and 7° for a speed of 40 knots. These errors are also similar to those of high cloud motion vectors (Black and Anthes 1971). The final analysis test (number 6) removed the bogus winds which had been added to the dataset.

Figure 2 shows fractional errors in eddy momentum flux (Eq. 1) as a function of radius. At all radii, the influence of the bogus data was negligible, as noted earlier. Differences introduced by the removal of the smoother also were unimportant, because even the smallest influence radii were large enough (about two Cartesian grid distances) to limit small-scale noise on the grid.

For the remaining analysis tests, errors in eddy momentum flux estimates were less than 20% (35%) outside $r = 800$ (400) km, then rapidly increased at the innermost radii. This error profile reflects in part the radius-dependent scale of the cylindrical grid; at the 100 km radius, for instance, a cylindrical grid point has only one-quarter the area of the Cartesian grid points used in the analysis.

The analysis sensitivity tests provided an extreme measure by determining differences in a quantity which involves products of perturbations. Figure 2 indicates that the innermost radii eddy flux estimates are questionable, the outer radii values (beyond 800 km) carry a high degree of confidence, and the middle radii values must be interpreted with some caution. Nevertheless, the variation of eddy momentum flux between time periods is generally much larger than the typical error (see Fig. 4a).

Not surprisingly, the actual wind components from which the flux was computed contained much smaller errors. The maximum root-mean-square difference in radial or tangential velocity between the control and the various test analyses was 1.6 m s^{-1} (even for the random error analysis, because random errors from multiple data points tended to cancel). The influence of data and analysis errors was further reduced by examining only azimuthally averaged quantities.

d. Calculation procedures

Skubis and Molinari (1987) found that the differences in Eulerian and Lagrangian (following the storm) momentum budgets can be the same order as the largest term in the Eulerian budget if the storm is rapidly moving or in a nonuniform environment. One or both conditions is met for every observation time in this study, and all calculations were done using Lagrangian budgets and storm-relative winds. The total relative angular momentum over a given pressure depth following a moving cylindrical volume of radius r is

$$M_L = \frac{2\pi}{g}\int_{p_2}^{p_1}\int_0^r (r\bar{v}_L)r\,dr\,dp, \qquad (3)$$

where the bar indicates an azimuthal average. The storm-relative wind vector is given by

$$\mathbf{v}_L = \mathbf{v} - \mathbf{v}_c, \qquad (4)$$

where $\mathbf{v}$ is the total velocity and $\mathbf{v}_c$ the storm velocity. The latter is computed as a 12 h average using interpolated storm positions.

In the current study a complete momentum budget cannot be attempted because only one layer of data is available. Instead, the focus will be on lateral fluxes of relative momentum by the azimuthal mean and eddy circulations. Following Holland (1983) these are written
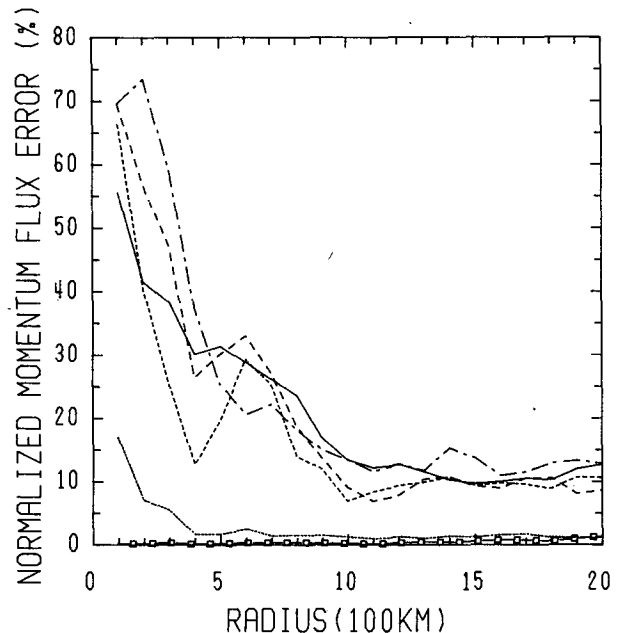

FIG. 2. Differences in calculated eddy momentum flux between the control analysis and the analyses given in Table 1, normalized by the time-averaged eddy momentum flux magnitude at each radius [see Eq. (1) in the text]. Solid line: large influence radius; large dashes: small influence radius; medium dashes: purely circular weighting function; small dashes: smoother removed; dash-dot curve: random errors imposed on data; curve with squares: bogus data removed. See Table 1 and associated text for details.

$$\left.\frac{\partial_L M}{\partial t}\right)_{\text{mean flux}} = -\frac{2\pi r^2}{g}\int_{p_2}^{p_1}\bar{u}_L\bar{v}_L dp \qquad (5)$$

$$\left.\frac{\partial_L M}{\partial t}\right)_{\text{eddy flux}} = -\frac{2\pi r^2}{g}\int_{p_2}^{p_1}\overline{u'_L v'_L}\, dp, \qquad (6)$$

where u_L is the storm-relative radial component, the prime indicates a deviation from the azimuthal mean, and

$$\frac{\partial_L}{\partial t} = \frac{\partial}{\partial t} + \mathbf{v}_c \cdot \nabla. \qquad (7)$$

Because by definition the storm motion vector does not vary in space, Eq. (5) could also be written with $\overline{uv}$ in the integrand (Holland 1983). The vertical integration in (5) and (6) is carried out by assuming that the 200 mb winds represent a layer 200 mb thick.

4. Results

a. Storm history

At 0000 UTC 28 August the tropical depression which was to become Elena contained several weakly organized convective clusters. As the storm moved rapidly (12 m s^{-1}) west–northwestward onto the island of Cuba it became more organized in its convective structure and reached tropical storm strength at 1900 UTC 28 August while still over land. Nevertheless, convection remained east of the center, more characteristic of a wave in the easterlies, and little evidence of a closed circulation was present. At about 0400 UTC 29 August, Elena moved from Cuba over warm Gulf of Mexico water. Satellite loops show discontinuous behavior in convection, which explosively grew over the center of the circulation while the convection to the east rapidly decayed. Elena reached hurricane strength within hours of crossing the Cuban coast. Figure 3 shows the variation of minimum central pressure in Elena starting from 1000 UTC 29 August, when an early reconnaissance flight was made. Rapid deepening associated with the storm reaching water continued for more than 24 h, followed by 10 h of filling, slow deepening, then a second extended deepening period starting about 2200 UTC 31 August. Elena made two major direction changes during its time in the Gulf of Mexico, and finally made landfall just after 1200 UTC 2 September.

The initial intensification and final weakening of Elena appear to be related entirely to the changes in underlying surface, not to synoptic scale forcing. This paper will focus on intensity changes in the storm during the period it remained over water.

b. Momentum flux versus deepening

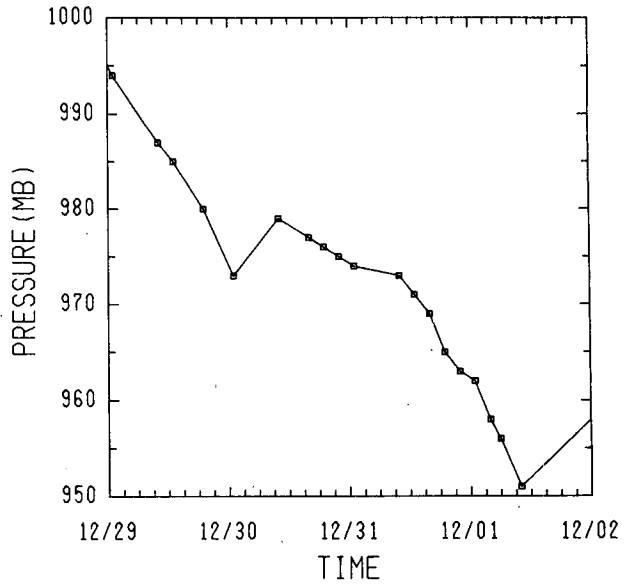The most striking result of the momentum calculations was a high correlation between outer radius eddy

FIG. 3. Time variation of minimum central pressure in Hurricane Elena. The squares represent pressure estimates from aircraft reconnaissance. The trace begins 6 h after Elena traveled from Cuba to the Gulf of Mexico.

fluxes and the deepening rate of the storm 27–33 h later. Figure 4 shows an example of this using the 1500 km radius eddy flux and the central pressure tendency 30 h later. Table 2 gives correlation coefficients at middle and outer radii for various lag times. In both the figure and the table, only those times for which the storm remained over water after the given time lag were included. The high correlation between eddy momentum flux and subsequent deepening holds over several hundred kilometers of radius. The presence of the time lag, which has not previously been described, shows that eddy forcing clearly preceded deepening.

Figure 5 shows a radius-time (hereafter r–t) section of the eddy momentum flux given by Eq. (6). A calculation of the balanced vortex response to this forcing would show whether it would act in such a way to enhance or weaken the radial-vertical circulation of the storm. Unfortunately, such a calculation is impossible in the current study because it requires knowledge of the vertical derivatives of both the mean and eddy velocity fields, neither of which is available from the single level of data. Instead, we note from previous studies (Willoughby 1979; Pfeffer and Challa 1981; Shapiro and Willoughby 1982; Holland and Merrill 1984) that a positive eddy flux will produce inflow somewhere below 200 mb, over a depth which depends on the vertical gradient of eddy flux, and will produce enhanced outflow at 200 mb just inside the eddy flux maximum.

Figure 6 shows an r–t section of azimuthally averaged radial velocity. Two major outflow events oc-
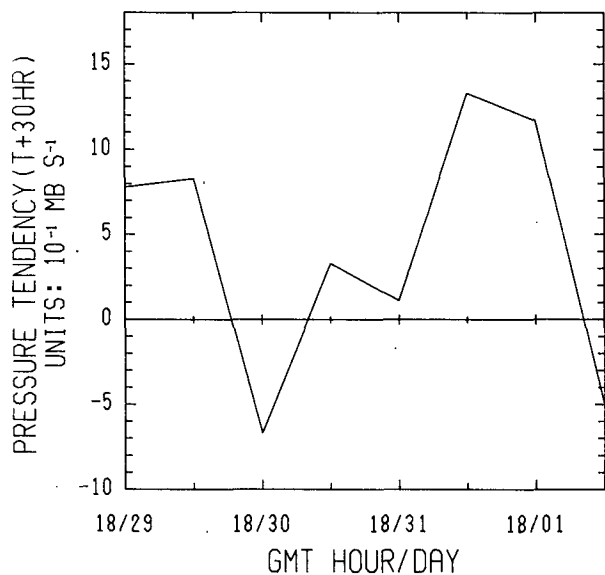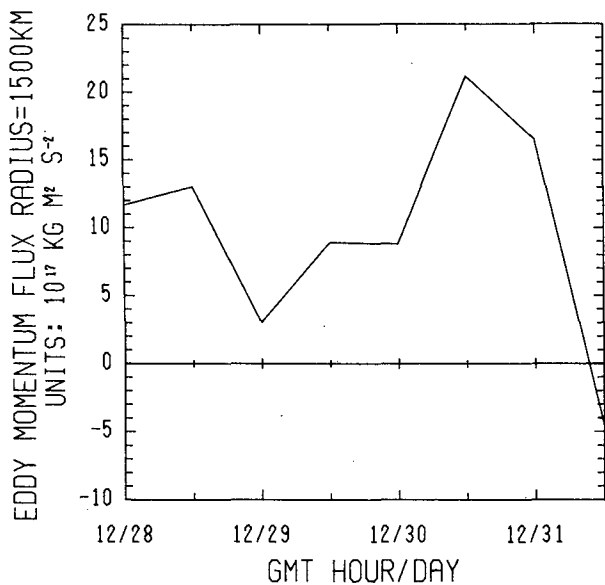
FIG. 4. (a) Eddy momentum flux [Eq. (6)] at the 1500 km radius, plotted only for those times in which the storm remained over water 30 h later. (b) Deepening rate of the storm at times 30 h after those of part (a).

TABLE 2. Linear correlation coefficients at various radii between eddy momentum flux [Eq. (6)] and central pressure tendency in the storm, for various lag times.

Radius (km)	Lag time (hours)					
	21	24	27	30	33	36
1900	.025	.361	.826	.756	.875	.084
1800	.069	.392	.840	.788	.881	-.074
1700	.109	.413	.851	.831	.878	-.276
1600	.118	.427	.855	.888	.859	-.444
1500	.108	.409	.837	.934	.818	-.489
1400	.067	.324	.759	.914	.715	-.416
1300	-.012	.251	.668	.838	.606	-.339
1200	-.092	.188	.622	.789	.549	-.308
1100	-.149	.143	.596	.757	.516	-.306
1000	-.143	.133	.599	.753	.516	-.308
900	-.122	.099	.579	.723	.485	-.343
800	-.105	-.055	.501	.657	.397	-.471

In order to obtain a clearer picture of the relationship between the eddy momentum source and outflow at inner radii, the tangential velocity eddy flux convergence was computed:

$$\left.\frac{\partial \bar{v}}{\partial t}\right)_{eddy \ flux} = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 \overline{u'v'}. \qquad (8)$$

This quantity, which is $1/r$ times the relative angular momentum flux convergence, contains physically interpretable units of m s^{-1}/day. Figure 7 shows that during the major cyclonic eddy flux event, the eddy spinup exceeded 25 m s^{-1}/day at the 650 km radius,
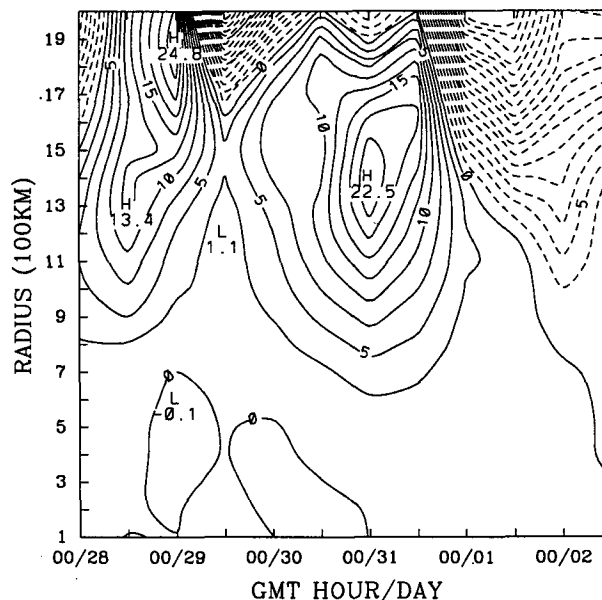
curred in Elena. In the first, outflow increased over the inner 1200 km for 24 h after the storm moved over the Gulf of Mexico from Cuba. In the second, an equally strong mean outflow originated at the 1200 km radius at 0000 UTC 31 August, just inside the large eddy flux maximum shown in Fig. 5, as would be qualitatively predicted by the balanced vortex response. In the following two 12 h periods, this latter outflow maximum shifted inward toward the center. An extended period of deepening was initiated (Fig. 3) after the outflow maximum reached the storm core.

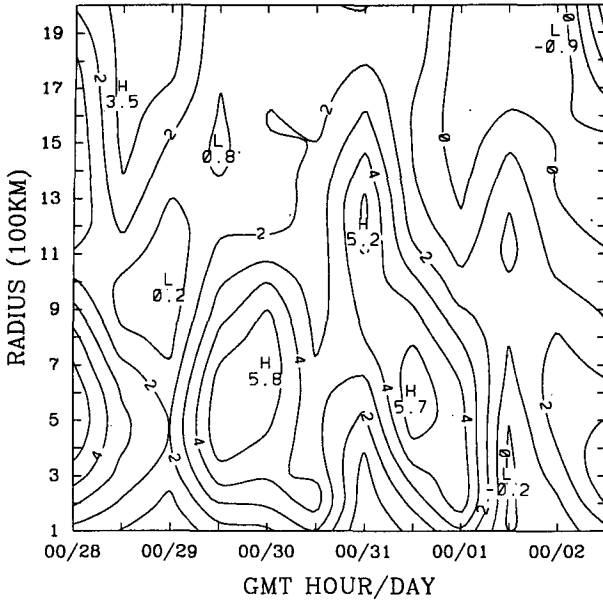FIG. 5. Radius–time section of eddy momentum flux [Eq. (6)]. The plotting increment is 2.5×10^{17} kg m^2 s^{-2}.

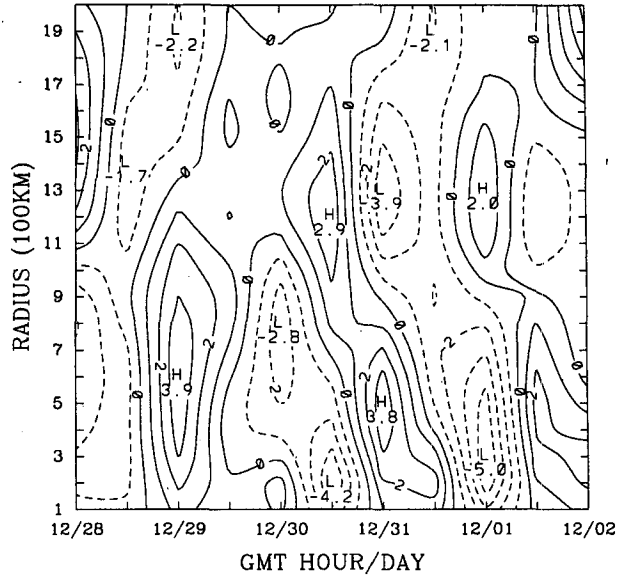FIG. 6. As in Fig. 5, but for azimuthally averaged radial velocity (plotting increment 1 m s^{-1}).

FIG. 8. As in Fig. 5, but for the changes in mean radial velocity (m s^{-1}) for 12 h ending at the time shown. Positive values indicate an increase in outflow or decrease in inflow. The plotting increment is 1 m s^{-1}.

and remained positive subsequently as it shifted inward to the storm core. The inward shift of the outflow maximum on 31 August appears to be associated with a concomitant shift in eddy forcing. In addition, the major storm filling event (1300–2200 UTC 30 August) and deepening event (2200 UTC 31 August–2200 UTC
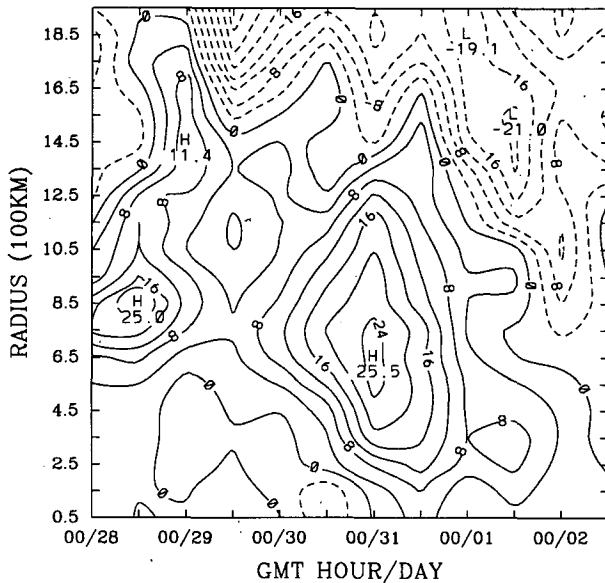

FIG. 7. As in Fig. 5, but for azimuthal eddy flux convergence of tangential velocity from Eq. (8). The zero line is darkened. The plotting increment is 4 m s^{-1}/day.

1 September) were preceded by inner radii eddy flux convergence of the appropriate sign.

The inward shift of an outflow maximum with time has not previously been described. The phenomenon shows most clearly in Fig. 8, which displays 12-h changes in mean radial velocity. The passage of Elena over water and subsequent rapid deepening on 29 August produced an intense transient increase in outflow. After this initial intensification to hurricane strength, however, every subsequent radial velocity change originated at middle or outer radii and shifted inward with time, against the mean outflow. These results provide circumstantial evidence of strong environmental forcing.

During the period of inward propagation of the outflow maximum, Elena was moving toward the United States Gulf coast, and thus toward the rawinsonde network. The analysis could have been influenced by the availability of data at progressively decreasing radii. The relative position of coastal rawinsondes could not have produced spurious propagation, however, because the storm moved less than 100 km (12 h)$^{-1}$ toward the coast during 31 August and 1 September, while the outflow maximum shifted inward at a rate of about 600 km (12 h)$^{-1}$.

Because the balanced vortex response cannot be computed, a question remains as to whether the observed eddy flux magnitudes would be sufficient to produce a radial velocity response of the magnitude shown. The "D3" composite developing storm of McBride and Zehr (1981) produced a maximum eddy

momentum flux, expressed in the form of (6), of 8.8 units (10^{17} kg m^2 s^{-2}) at about the 1600 km radius (see Pfeffer and Challa 1982), with smaller values for the developing composite storms at earlier stages. The largest eddy forcing in the current study reached 22 units at the 1400–1500 km radius, and averaged about 12 units (Fig. 4a). Because the mean radial velocity in Elena is of the same order as that from McBride and Zehr's composite, it is likely that the large observed eddy forcing would be sufficient to produce the 5 m s^{-1} response seen in Fig. 6.

Comparison of Figs. 3, 5, and 6 reveals that radial velocity sometimes did not respond to eddy flux in the manner predicted by the balanced vortex equation, and the central pressure did not always fall in response to an outflow maximum reaching the storm core. Thus, for instance, the high correlation between eddy flux and deepening did not shift from outer to middle and inner radii as lag time decreased. The process described in the preceding paragraphs can account for the rapid deepening late on 31 August, but not for other intensity changes. Nevertheless, the relationship between outer radius momentum flux and subsequent deepening held throughout the period that the storm remained over water.

Results up to now have shown the azimuthally symmetric structure and response of the vortex, but not the spatial variation of the associated eddies. Figure 9 shows the analyzed total wind field on 0000 UTC 31 August, the time of maximum eddy momentum flux.
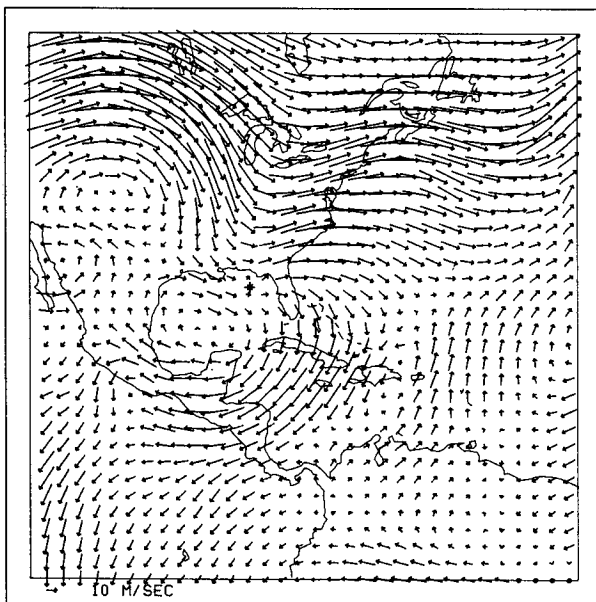

FIG. 9. Analyzed total (as opposed to storm–relative) wind field at 200 mb for 0000 UTC 31 August, the time of maximum inward cyclonic eddy momentum flux at the 1500 km radius. Analyzed winds are shown at half their actual resolution for clarity. The asterisk represents the location of the hurricane center.

Calculations of $u'v'$ (a "local" eddy flux) as a function of azimuth at the 1500 km radius (not shown) indicate that the eddy source arose from three regions: (i) in the northwest flow behind the trough, where cyclonic momentum was being added to the volume; (ii) in the west-southwest flow ahead of the trough, where anticyclonic momentum was being removed; and (iii) south of the storm in the outflow jet, where anticyclonic momentum was being removed. The subsequent inward shift of the momentum source was almost entirely due to the relative motion of the trough, however, while the outflow jet simply propagated out of the volume. The momentum source remained in the same parts of the trough through 1200 UTC 31 August, then became sharply negative (Fig. 5) as the trough axis passed east of the storm. Thus, the trough represented the major momentum forcing prior to the extended period of deepening after 31 August. Merrill (1988a) also noted that a significant eddy momentum source existed in the westerlies north of Atlantic tropical cyclones. The details of the asymmetric and vertical structure of the interaction between the hurricane and the trough will be described in Part II of the paper.

In summary, the observations showed a high correlation between outer radii eddy momentum flux and intensity change of the storm 27–33 h later. After the initial intensification of the storm when it moved from land to water, outflow maxima and minima originated outside of the 1000 km radius and shifted inward with time. In the major such event, the position and movement of the outflow maximum appeared to be forced by eddy momentum fluxes. These fluxes were themselves associated primarily with the passage of a mid-latitude trough from west to east just north of the center. When the outflow maximum reached the storm core, an extended period of deepening followed.

5. Discussion

a. Limits of a single case study

As is true of any other case study, the question arises as to whether the behavior of Hurricane Elena is relevant to a larger group of tropical cyclones. Figure 10 shows the ratio of the time–averaged magnitude of the mean momentum flux [Eq. (5)] to that of the eddy momentum flux. Consistent with Holland (1983) and Merrill (1988a), the mean dominates near the storm core, contributions are equal at the 700–800 km radius, and the eddies dominate at outer radii. As noted earlier, the average magnitude of eddy fluxes is the same order as that of McBride and Zehr's (1981) composite developing storm. Thus, Elena does not appear to represent an extreme example of environmental forcing. The evolution of the upper tropospheric environment of Elena prior to its intensification is consistent with previously proposed qualitative relationships between troughs in the westerlies and intensifying tropical cy-
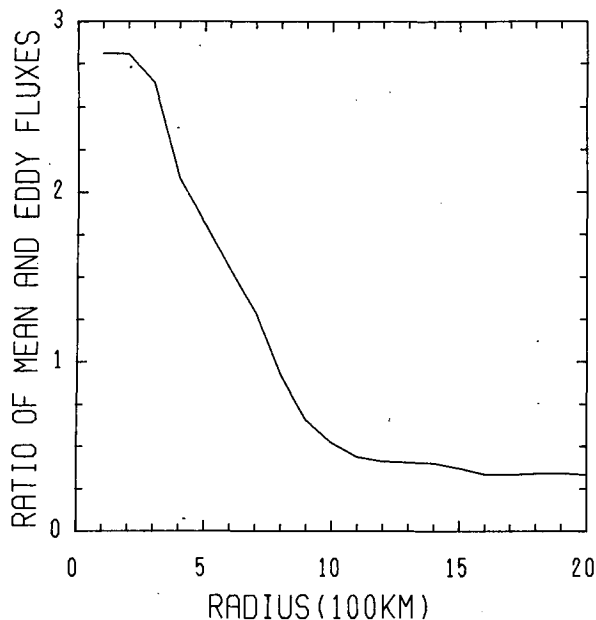
FIG. 10. Ratio of the time-averaged magnitude of momentum flux by the azimuthal mean flow to that by azimuthal eddies.

clones. It is thus conceivable that the process described for Elena represents a common mode of hurricane intensification, particularly for storms poleward of 20° latitude, where interaction with traveling baroclinic waves would be most common.

In principle, eddy momentum flux calculations could benefit operational forecasts of tropical cyclone intensity because they measure the integrated effects of whatever lies in the storm environment, regardless of the complexity of the interactions. In practice, such calculations may be feasible if a storm is near enough to land to allow use of rawinsonde data to describe surrounding circulations, or if a remote sensing method can be developed to supplement cloud motion vectors with clear-air estimates of outflow layer winds (e.g., Velden 1987). It will remain difficult to quantitatively predict the ultimate surface pressure change produced by eddy momentum fluxes until a clear mechanism for their influence is established. Nevertheless, the routine calculation of such fluxes may provide an additional tool for forecasters which goes beyond the use of empirically favorable outflow patterns alone.

b. Relative importance of external forcing of tropical cyclones

Merrill (1988b) has argued for a much simpler framework for external forcing. He views the presence (or absence) of vertical shear over the storm core as a major influence on tropical cyclone intensity. Madala and Piascek (1975) have shown such an influence in numerical experiments. This argument gains some support in Elena. Vertical shear can be measured by

the vector mean storm–relative wind at 200 mb within 300 km of the center. Our analyses show that shear increased substantially at the time of storm filling, 1200 UTC 30 August, as the midlatitude trough appeared to cross the circulation at 200 mb. Over the following 24 h, however, nonzero shear continued and even increased, but the filling turned to a slow deepening. Thus a one-to-one correspondence between vertical shear and intensity change did not exist. During later periods of deepening, the shear diminishes, but that could be caused by deepening rather than vice versa; deepening will enhance outflow, and environmental flow will tend to be deflected around the outflow region rather than blowing through it. The vertical shear argument does not appear to be all-inclusive. Nevertheless, the presence of significant vertical shear is likely to disrupt a tropical cyclone regardless of other forcing. This may be the reason that existence of a trough westward and poleward of the tropical cyclone core is not always favorable for intensification (Merrill 1988b).

In a broader sense, Merrill (1988b) argued that environmental interactions with mature tropical cyclones must, in general, contribute negatively to intensity change, by the following reasoning: 1) maximum tropical cyclone intensity is proportional to sea surface temperature; 2) maximum intensity is rarely reached; thus the environment must be exerting a negative influence. Based on the results of the current study, it is proposed that the environment also frequently acts as a positive influence which produces much more rapid intensification than would occur in isolation. Although such forcing could not drive a tropical cyclone past its maximum achievable intensity, because such a storm could not be supported by ocean surface fluxes, it can accelerate the intensification process. The results of Miller (1958) provide support for this view.

In the current study, intensity fluctuations were investigated in the mature hurricane, when environmental interactions are concentrated in the small inertial stability of the outflow layer. External forcing may also play a role at very early stages of hurricane development, when much lower inertial stability at low- and midtropospheric levels allows environmental influences at those levels to play a greater role (Shapiro 1977; Love 1985; Molinari and Skubis 1985). The major deepening event in Hurricane Elena was forced by interactions with a midlatitude baroclinic wave, a clearly external influence which did not owe its existence to the presence of the hurricane. External forcing can thus be viewed as the dominant influence in the evolution of the hurricane. Review of the history of Elena, however, shows that the reality may be more complex. Figure 11 shows an r–t section of azimuthal mean absolute vorticity, which provides a measure of inertial stability. When the storm tracked from land to water, a surge of outflow associated with enhanced convection at the storm core significantly reduced the outflow-layer in-
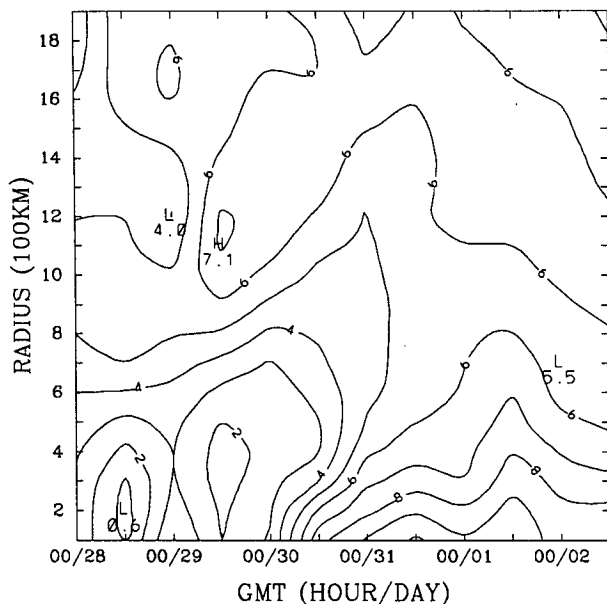
FIG. 11. Radius–time section of azimuthal mean absolute vorticity. The plotting increment is $1 \times 10^{-5} \text{ s}^{-1}$.

ertial stability out to the 1500 km radius over the following 48 h. As noted by Holland and Merrill (1984), lower inertial stability conditions the environment for enhanced interactions. The initial intensification also contributed more directly to environmental interactions, to the extent that outflow jets were enhanced by confluence between the hurricane outflow and the approaching trough and the resulting frontogenetical forcing. By this reasoning, the extended intensification of Elena beginning 31 August was brought about not simply by external forcing, but by a cooperative interaction between previous mesoscale events at the storm core and a favorable synoptic-scale environment. This view differs somewhat from Holland and Merrill (1984) in that purely internal events are seen as initiating the process.

In part II of this work, this "environmental interaction instability" will be pursued by examining the three-dimensional structure of the interactions between the hurricane and the baroclinic wave using available rawinsonde data north of the storm center.

c. Mechanisms for topical cyclone intensity change

The nature of the eddy momentum forcing is such that it does not directly spin up the mean vortex at the outflow level. Instead, the cyclonic eddy spinup is easily balanced by Coriolis torque associated with the enhanced outflow forced by the momentum source. For example, at the latitude of Elena, a 3 m s^{-1} increase in outflow would neutralize the 25 m s^{-1}/day maximum eddy spinup in Fig. 7. Figure 6 shows that outflow

of that magnitude occurred in response to the momentum forcing. As a result, the intensity change associated with the eddy forcing must represent an indirect response.

Ooyama (1982) argued persuasively that inflow above the boundary layer was an essential prerequisite for tropical cyclone intensification. The vortex spinup generated in these layers, relatively unaffected by frictional dissipation, excites in response a removal of mass from the core to restore gradient balance, producing a lower central pressure. By the same reasoning, eddy momentum fluxes may produce deepening by exciting midlevel inflow, either directly or indirectly. Two possible mechanisms are considered:

(i) Upward motion (not shown) occurs at radii inside of the outflow maximum at all times. In this region the column will destabilize and surface pressure may fall in response to the enhanced outflow. Such pressure falls could induce a surface inflow maximum propagating underneath the upper-level outflow maximum. Molinari and Skubis (1985) found such an inflow "surge" in Hurricane Agnes (1972) which propagated inward at 15 m s^{-1} from outer radii, a speed similar to the upper-level feature in this study. It was proposed by Molinari and Skubis (1985) that the enhanced convection accompanying such an inflow surge could provide the necessary middle level inflow via entrainment into buoyant cloud elements. In order to test this hypothesis, surface data for Hurricane Elena were collected and analyzed in a similar manner to those at 200 mb. Although oceanic data density was marginal due to the long-term presence of Elena in the Gulf of Mexico, no evidence of inflow surges coupled with the outflow layer behavior was present. The results do not support the presence of a surface layer response to the eddy momentum fluxes.

(ii) Previous balanced vortex equation solutions indicate that the eddy forcing found in this study would produce enhanced inflow below 200 mb, most likely in the midtroposphere if eddy fluxes in Elena had a vertical structure like that of composite hurricanes (Pfeffer and Challa 1981; Holland and Merrill 1984). As the observed eddy source approached the storm core (Fig. 7), the associated midlevel inflow could produce spinup and subsequent surface pressure falls without the direct contribution of buoyant convective elements. This view is more consistent with the symmetrically neutral structure of tropical cyclones proposed by Emanuel (1986) and Rotunno and Emanuel (1987). In either case, as noted by Ooyama (1982) and Emanuel (1986), maintenance of the more intense state is possible only if sufficient additional energy is added from the ocean surface.

We speculate that the latter process was acting in Elena. The mechanism for intensification becomes simply the enhancement of the radial–vertical circu-

lation in response to eddy momentum forcing, as proposed by Pfeffer and Challa (1981). In the current study, however, a significant time lag occurs between outer radius forcing and inner core response, and the inward shift of the forcing with time appears to play a major role, at least in the case of the extended deepening after 31 August. In addition, this momentum flux reasoning might be incomplete. Frontogenetical forcing in the confluence region between the warm hurricane outflow and the cold trough (Holland and Merrill 1984) may have enhanced the outflow ahead of the trough via thermal wind adjustment. This influence would appear in the balanced vortex equation as an eddy heat flux term, which may or may not act in the same manner as the momentum fluxes. Interpretation is further complicated by changes in the mean field inertial stability during intensification, which produce greater resistance to external forcing (Schubert and Hack 1982). Only a formal numerical solution of the balanced vortex equation with a three-dimensional dataset can address the relative importance of these additional processes.

The reaction of the storm core to the eddy momentum forcing has been neglected in this discussion. Shapiro and Willoughby (1982) and Willoughby et al. (1982, 1984) have shown that intensity fluctuations in mature hurricanes occur via a specific process which is restricted to the high Rossby number tropical cyclone core. In this process, a secondary wind maximum forms, apparently within 150 km of the core, and shifts inward at only 1–3 km h^{-1}. Actual intensification in the pressure field does not occur until the secondary maximum reaches the innermost radii. A complete view of the role of external forcing of tropical cyclones would have to account for the development of such an outer wind maximum. We speculate that this development could be forced by mid-level spinup associated with the outflow layer eddy momentum source. Subsequent to this forcing, internal processes would take over in the storm core. This proposal is consistent with Holland's (1988) suggestion that a critical radius might exist at which environmental forcing resonantly interacted with the inner regions of the storm. The eddy momentum flux would thus be viewed as a trigger or catalyst that releases internal instabilities which themselves are driven by surface fluxes and latent heat release.

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