The Structure of a Small, Intense Hurricane—Inez 1966

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ABSTRACT

This is the third in a series of articles about hurricane structure and budgets. The two preceding articles, LeSeur and Hawkins (1963), and Hawkins and Rusbos (1966), dealt with a weak and a moderate hurricane (respectively). Hurricane Inez is described here in a very small, intense state and, as such, deserves its own place in the hierarchy of models. It is strongly recommended that the previous articles be kept available for comparison.

On 28 September when the storm was most intense, the inflow layer appeared to extend no higher than the 750 mb level. Budgets constructed for this layer suggested (when taken with other data) a nonlinear relationship between the drag coefficient and the wind speed, moisture convergence in the inflow layer led to postulated rainfall rates ranging from 0.15 in h⁻¹ in the 40 to 50 n mi annulus to 1.9 in h⁻¹ in the 0 to 10 n mi circle. Bowen ratios ranged from 0.11 to 0.16 in the inner 50 n mi of the storm and extensive areas of radar "bright band" characterized the storm beyond the 10 n mi radius.

1. Introduction

The future Hurricane Inez was first revealed (in the Atlantic area) by land and ship reports, and by the ESSA 2 satellite, as a weak tropical depression moving off the west coast of Africa on 18 September 1966 (Sugg, 1967). Allison (1972) has compiled a complete satellite history of Hurricane Inez and has carried the history of the early perturbation back to a mass of clouds over Africa on 15 September. After taking a course to the west-southwest, the disturbance was located at 10°N, 35°W on the morning of the 21st. A reconnaissance flight early on the 24th indicated only slight intensification had occurred during the preceding six days (Fig. 1a). However, by afternoon of the 24th a deepening trend became apparent and the depression became a named tropical storm. At this juncture Tropical Storm (T.S.) Inez slowed its forward progress and took a more westerly course. It was also at about this time that intensification became more rapid in a favored climatological region (Gray, 1968).

On the morning of the 27th, reconnaissance reported that the central pressure had dropped to 961 mb, with maximum winds of 120 mph and hurricane force winds extending out some 50 miles from the center. Passage over Guadalupe (early on the afternoon of the 27th) resulted in increased central pressure (~970 mb) as contact between the circulation and the ocean surface was partially lost. Once clear of the islands, the storm intensified rapidly and became more concentrated while doing so (Kuo, 1959). By late afternoon of the 28th, the lowest observed central pressure (927 mb) was attained. Maximum windspeed of 157 kt (10 s average) was recorded just 6.5 n mi from the center of the eye, and hurricane force winds were confined to an area within 36 n mi of the center. This was an extremely intense, small storm that resembled in many ways a predecessor, Hurricane Flora (1963), in its late season occurrence, its track through the northern Caribbean, and the general structure of its wind field. However, the period of data gathering in Hurricane Flora was relatively brief, the flight path was severely restricted in its horizontal coverage and all of the sampling was done in a relatively shallow mid-tropospheric layer. Another storm of somewhat similar characteristics was Hurricane Daisy, 1958. But again data coverage on 27 August when the storm was most intense was very limited (Colon and Staff, 1961) and, as Hurricane Flora, it did not attain the intensity of Hurricane Inez on 28 September. A compilation of flight data may be found in Shea and Gray (1973).

a. Data

On 26 September, the Research Flight Facility (in support of a scientific team from the National Hurricane Research Laboratory) deployed two DC-6's and a B-57 to San Juan, Puerto Rico. On the 27th, the three planes undertook a research mission into Hurricane Inez. The primary purpose of the mission
(the investigation of hurricane structure) was compromised by the passage of the storm over Guadalupe during the reconnaissance period. This meant that no low-level (1500 ft) flight pattern could be carried out in the core of the storm. The flight patterns actually made good are shown in Fig. 1b.

On 28 September, all three planes returned to Hurricane Inez and executed the flight patterns shown in Fig. 1c. As has already been pointed out (Hawkins and Rubsam, 1967) the storm was a marvelous example of a small, intense hurricane. The low-level penetrations (begun at 1500 ft) encountered moderate to heavy turbulence. Much later, in the evening, a final penetration at 8000 ft (requested by San Juan) measured the 157 kt winds, the strongest encountered by the RFF to that date.

Fig. 1b. Flight tracks (relative to the moving storm center) made good at the indicated pressure levels on 27 September 1966.
Research patterns were flown at five levels: 950 mb (1770 ft pressure altitude), 750 mb (8090 ft PA), 650 mb (11780 ft PA), 500 mb (18280 ft PA) and 180 mb (40870 ft PA).

An intermittent malfunction of the Doppler navigation system aboard one of the DC-6's diminished the value of data gathering efforts on the 28th. Thus, the continuous calculation of winds was prevented. Although the majority of the values appeared reasonable, no great reliance could be placed upon them. Consequently, the wind analysis at 650 mb and (to a lesser extent) that at 500 mb could be used for a crude estimate of wind speed only.

Despite the gaps which marred "complete" data coverage on either day, the total collection represents a unique documentation (the best to date) of a recognized phenomenon—a small, intense Atlantic hurricane.

b. Data compositing

The data were gathered at a rate of one complete meteorological observation per second as the aircraft flew through the moving storm. These observations must be positioned relative to the center of the storm for most analytical purposes. In order to do this, the time-lapse radar film record was used to "fix" the plane relative to the center of the radar eye of the storm as depicted on the film. Between such fixes the plane is positioned by its Doppler navigation system, and the storm is moved along its known track with the relative positions calculated mathematically by computer. Since there are limitations to the accuracy
of such a procedure, there are also limitations imposed on certain derived parameters (i.e., the radial wind) over and above the instrumental reliability of the wind measurements themselves. (A more complete discussion of these considerations is available in Hawkins and Rubsam, 1968.)

2. Hurricane Inez—27 September

As noted earlier, the first penetrations of the research aircraft into Hurricane Inez on 27 September occurred while the storm was passing over Guadaloupe, F. W. I. Adjacent Leeward Islands were contributing interference also, but Basse Terre with its highest peak reaching to almost 5000 ft was a major obstacle, both to the high energy core of the storm and to low-level aircraft navigation. Consequently, the lowest level which received adequate reconnaissance was the 750 mb level.

a. Structure of the wind field

The streamlines (Fig. 2a) show a strong cyclonic circulation with fairly well-marked inflow. As we shall see, on the next day (28 September) the same level marked the top of the inflow layer with little or no inflow actually present at this altitude. Hurricane Hilda, 1964 (Hawkins and Rubsam, 1968), showed inflow up to the 650 mb level at some distance from the center, although the inflow at this level diminished to approximately zero near the storm center. However, Hurricane Inez was (on the 27th) stirring itself on the islands and their peaks. One might expect such mixing to deepen the inflow layer.

The wind speeds relative to the moving storm (Fig. 2b) showed but little weakening from the morning reports of 120 kt. However, in the two sequences where windspeeds of more than 100 kt were recorded, the measurements were made while flying over the major islands of Basse Terre or Grande Terre, and some question of their representativeness could be raised. The central pressure increased about 10 mb as the storm crossed the Lesser Antilles, but began deepening again once clear of the island chain.

The other horizontal analyses presented for this day are the streamlines and isotachs for the 180 mb surface (Fig. 3a and b). These analyses presented a number of complexities, and there is no way of resolving the possibilities (i.e., the upper level state may have been changing and some of the problems may be due to this lack of synopticity, the Doppler navigation unit may have suffered intermittent malfunction, or the analysis may have captured the major features of the upper tropospheric pattern). Certainly, the spiral outflow pattern over the eye (displaced slightly to the east with height), as well as the larger scale trough in which it was embedded, were much as expected. The col to the north-northwest would be anticipated if westerlies dominated the
region to the north of the storm. However, the pattern to the northeast of eye, with wind speeds increasing rapidly in rather strongly divergent flow, is rather disturbing. Nevertheless, we feel that the gross aspects of the overall pattern must be valid and are therefore deserving of display.

The intermediate levels at 650 and 500 mb are not presented because they showed little of interest, other

Fig. 4. Wind speeds relative to the moving storm again show the maximum winds to the rear of the storm.
than the cyclonic vortex itself. At the 650 mb level, the streamlines indicated a very slight outflow in a tight spiral with no conspicuous irregularities or disturbances in the flow field. The outflow was more marked at 500 mb, but again was quite regular with little to distinguish it. The centers of the outflow vortex appeared to be just about vertical over the lower level center, and there was little indication that the inner wind maximum was displaced outward with height. At 500 mb, however a double wind maxima became evident. The outer maximum appears to have prevailed with height as the inner one (located over the lower level maximum) gradually weakened with height. The inner maxima probably disappeared shortly above the 400 mb level.

The latter features may also be seen in the vertical cross section of the relative wind speeds presented in Fig. 4. Here the increasing radius of maximum winds with height is clearly evidenced in the layer from 500 to 180 mb. The most remarkable aspect of the hurricane on this day was the restricted area covered by hurricane force winds. Fig. 4 suggests that such winds were found only within 20 n mi of the center ahead of and behind the storm. Occasionally the smoothing in time and in the vertical introduced seeming inconsistencies with individual constant pressure analysis but these were judged relatively unimportant.

b. Thermal structure

Temperature soundings have been reconstructed using the aircraft data at 750, 650, 500 and 180 mb (Fig. 5). The lower portions of the soundings are dashed since they represent only approximations. It was assumed, as shown by other studies, that the low-level air temperatures changed but little as they spiraled into the eyewall (Hawkins and Rubsam, 1968; Byers, 1944). Also, the lowest cloud base was considered to drop from 1500 ft at 50 n mi radius to 900 ft in the eyewall. With data from the plane at 750 mb one can then roughly estimate the sea-level pressure hydrostatically (using the known attitude of the aircraft), if one assumes in-cloud lapse rates are nearly moist adiabatic and near dry adiabatic below cloud base. The estimate can be refined, should the mean virtual temperature estimate prove too crude. More than one refinement was seldom necessary.

There are several notable features about these soundings: 1) the lapse rate in the lower levels was quite steep (above the mixed sub-cloud layer); 2) the lapse rate was more stable than moist adiabatic from 750 mb to 500 mb with a few exceptions; 3) from 500 to 180 mb a moist adiabatic lapse rate fitted the data quite closely; and 4) the subsidence occurring in the eye resulted in abnormal warmth at the 650 mb level and that suppressed any activity beneath it.

The soundings have, in turn, been used to produce a vertical cross section of temperature anomalies (from the annual mean tropical atmosphere, Jordan, 1958) presented in Fig. 6. The differences among the soundings, and their departures from the normal, are thus brought into focus. These differences are:

1) An isolated center of above normal temperatures in the eye at 650 mb was separated from the main body of warmth around 300 mb. Such a separation was not noted in the Hurricane Hilda or Cleo studies.

2) The low-level anomalies (outside of the eye) are generally near-to-below normal, asymmetric, and give way to consistently warm anomalies around 500 to 200 mb as one approaches the main outflow region.

3) The 180 mb flight was at near normal temperatures, except in the region near the eye. In Hurricane Hilda, the flight at this level was at temperatures about 4.0°C above normal (or warmer). This feature of Hurricane Inez may be attributed to the small size of the vortex, the maintenance of the wall-cloud with height, and perhaps to the fact that the system was quite young and the warmth had not yet been diffused by the outflow then becoming established at higher levels.

4) If the axis of abnormal warmth aloft can be taken as the middle of the effective outflow layer, then this flow must be centered around the 300 to 350 mb layer.

This concludes our description of Hurricane Inez on 27 September 1966 as it was crossing the Lesser Antilles and entering the Caribbean Sea.

3. Hurricane Inez—28 September

When the research planes flew back into Hurricane Inez on the morning of 28 September, they found a classic example of a very small, intense, Atlantic hurricane (Hawkins and Rubsam, 1967). The storm had deepened to 927 mb and was moving slightly north
of west at 14 kt. To illustrate the compact, highly concentrated organization of the storm, Fig. 7 has been included to show a subjectively smoothed “actual wind” speed profile. Peak speeds of 129 kt were observed on the southwest side of the storm and 157 kt on the eastern side. The latter figure was lower than the 173 kt instantaneous or gust speed (reported by Hawkins and Rubsam, 1967) due to post-flight wind speed calibration and the 10 s smoothing used for the current presentation. In all probability, the wind speeds actually exceeded these peaks because they were “Doppler winds” measured under the assumption that the reference plane below, i.e., the ocean, is stationary. It is unlikely that any such condition prevailed, and the mean surface water motion below an observation should be added to the measured velocity. Shea and Gray (1973) have suggested 5 to 10% as the order of the correction. Despite these extreme speeds, hurricane force winds extended only out to 26 n mi on the southwest side and to 33 n mi on the east side. These are remarkable shears for a phenomenon of hurricane scale.

a. Data

To gather data for 28 September, two DC-6 aircraft flew patterns at two levels at or below 500 mb and a B-57 jet aircraft took observations at 180 mb (40 870 PA). The patterns are shown in Fig. 1c.

b. Horizontal analyses

1) Winds

Streamlines for each of the five data levels have been constructed, with the result that the wind fields at 650 mb and 500 mb were judged to be of poor research quality. A malfunction of the Doppler wind system resulted in anomalous wind fields (particularly at 650 mb) which, at best, could be used for a crude estimate of the wind speed only. We will present analyses at two levels: 950 mb and 180 mb.

At 950 mb (Fig. 8a) air motion relative to the moving storm was a strong cyclonic spiral inflow.

Streamlines at 950 mb indicated the strongest winds, in excess of 130 kt (Fig. 8b), were located anomalously in an area to the rear of the moving storm. Except for an open section in the front portion, winds in excess of 120 kt were recorded in all quadrants. Maximum winds were located about 7 n mi from the center. Due to the questionable nature of the flow field at 650 mb, and to a lesser extent at 500 mb, it was impossible to determine the extent of the “neutral layer” or the location of the bottom of the outflow layer.

The streamlines at 180 mb (40 870 ft PA) (Fig. 8c), revealed very little other than gentle cyclonic outdraft reaching from about 10 n mi to 70 n mi from the center. In view of the very compact intense vortex at the surface, the size of the vortex aloft is a little surprising. Even more so is the fact that, within this domain, no major asymmetries appeared, nor was there any strong anticyclonic turning of the outflow evidenced. Wind speed relative to the moving center (Fig. 8d) rose to over 60 kt south of the storm center, and 50 kt winds extended outward to about 20 n mi on all sides of the eye.

An interesting feature of the 180 mb streamlines is the apparent indraft near the center. It has been difficult to determine with any degree of certainty whether this is a product of the data collection instrumentation. Nevertheless, numerical modeling experiments by Rosenthal (1969) have shown inflow in a similar location. This difference in streamlines occurs roughly at the radius where the wall cloud was noted at this level. It may well be that air from the inner edge of the wall cloud and outer edge of the eye are being entrained by the major subsidence in the eye. The simplicity of the field should be viewed with some reservation. The flight tracks reveal considerable areas where data were lacking or widely spaced.

2) Temperature

Analyses of the temperature fields were prepared for all five of the levels flown. No unusual features were brought to light by this procedure. The hurricane was “warm core” at all levels (Haurwitz, 1935).
the 500 mb difference was rather weak. (This does not necessarily imply that the strongest temperature gradients were at the highest levels.) The small 500 mb difference seemed to be attributable to the fact that

temperatures in the area from 50 miles from the eye to the center of the eye ranged as follows at the levels indicated: at 950 mb, 21 to 27°C; at 750 mb, 11 to 18°C; at 630 mb, 5 to 16°C, at 500 mb, -5 to 3°C and, at 180 mb, -55 to 43°C. Thus, the stronger temperature differences were noted at the higher levels, although

Fig. 8a. The streamlines at 950 mb show a strong cyclonic indraft.

Fig. 8c. Most noteworthy is that the high level outdraft (in the field of data coverage) shows no evidence of anti-cyclonic turning.

Fig. 8b. The concentration of high wind speeds and their confinement to a small area near the storm center are most remarkable.

Fig. 8d. Hurricane force wind speeds have been maintained up to the 180 mb level.
the 500 level was in the lower portion of the outflow layer and little contrast with the eye center could be maintained.

The temperatures at 650 mb are presented in Fig. 9. This was one of the stronger temperature fields, but demonstrates the general nature of the thermal fields at all levels. The strongest gradients occurred as the eye was approached and, in fact, generally occurred in the eye wall at all of the levels investigated. Beyond 30 miles from the eye, the gradients were generally weak and the small details in the temperature field appeared to be primarily a function of the presence of cloud and/or rain. The other levels (not shown) were similar to this one.

Another series of temperature soundings was constructed for a NW to SE traverse through the eye of the storm on 28 September (Fig. 10). The major point of interest is to investigate the changes that occurred between 27 and 28 September. Probably the most striking and consistent changes at all radii are the increased stability above 500 mb, and the warmer temperatures at the 180 mb level. Most of the soundings on the 27th were approximately moist adiabatic in this layer. On the 28th, they were definitely more stable.

The lowest data level on the 27th was at 750 mb and any reasonable extrapolation to a realistic sea-level temperature did not allow for a consistent layer
below 750 mb with greater than moist adiabatic lapse rate, particularly on the northwest side of the storm. On the 28th, this lower layer with greater-than-moist adiabatic lapse rate up to 650 mb was apparent at almost all radii, except in the eye. However, in the eye itself, the well-marked pocket of warmth near 650 mb remained as a conspicuous feature, suggesting that any low-level cumulus activity in the eye would have difficulty in penetrating to that level. This was born out by other observations: the decreasing relative humidity in the eye at 650 and 500 mb, and the lack of clouds at these levels noted on the eye passes.

3) Height contours or D-values

The data gathered by airplane present contour fields on a pressure surface using the absolute height (RA) of the plane as measured by the radio altimeter and the pressure altitude as measured by the pressure altimeter.

$$D \text{-value} = RA - PA.$$ 

Standard custom is to mark the pressure altimeter so that it reads off heights (in feet) of the equivalent pressure surface in the NACA Standard Atmosphere. Since the standard atmosphere is not necessarily appropriate to the eastern Caribbean in late September, one can check the effect that these regional differences would have on the D-values. The low-level flight used a reference level of 950 mb or 1770 ft in the standard atmosphere. Jordan's (1958) mean annual tropical sounding suggests the 950 mb level should be found around 1965 ft. Thus, D-values at the 950 mb level will be about 200 ft lower than those calculated in the standard atmosphere. The difference in D-values will increase with height so that at 500 mb the “tropical D-values” are 980 ft lower than the “standard,” etc. Note, however, that none of these considerations change the height gradients on the constant pressure surface.

The contour fields associated with hurricanes are usually not of prime interest. Lowest pressures or heights occur in the eye, and asymmetries in the field are usually rather weak. The most noteworthy items are the gradients, particularly those of the low-level fields and the central pressure or height itself. In warm core systems, the gradients weaken with height until at some (undetermined) altitude the vortex presumably disappears. The contours for the 950 mb surface (Fig. 11) are extraordinary in the strength of the height gradient and the depth of the central D-value (−2200 ft) even after adjustment to mean tropical conditions. Asymmetries were small, for the most part, and seemed as likely to have resulted from slowly changing storm intensity or instrumental vagaries as to meteorologically meaningful differences. The contours at high levels showed the vortex weakening with height, although no D-values were obtained from the jet at 180 mb.

4) Humidity

Aboard both of the DC-6’s, humidity was measured using infrared absorption hygrometers. These data have been converted into mixing ratios and to relative humidities. Despite the subsidence occurring in the eye, the highest mixing ratios were found in the eye, at least up to the 500 mb level. Presumably, there

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**Fig. 10.** The composite soundings indicate that considerable warming took place at the upper levels from the 27th to the 28th. The upper portions of the sounding still shows the “subsidence hump” below 600 mb that was also evident on the 27th.
is enough mixing and turbulent exchange between the eye and the wall-cloud to maintain high moisture levels in the eye and also some evaporation of cloud and/or rain drops. Mixing ratios for the NW–SE traverse at 950 mb (Fig. 12) show that 16–17 g kg⁻¹ were the common values from 50 n mi out from the center until the eye was approached. Through the eyewall, mixing ratios rose to 18 g kg⁻¹ or over, and in the eye they rose further to 20–21 g kg⁻¹. Despite this rise in mixing ratios, the relative humidities (also, Fig. 12) fell slightly from around 100% to the 94–95% level. Most of the lower level of the eye was filled with clouds. On the other traverses at this level the eye could not be discerned in the relative humidity trace. This was also true at the 750 mb level, although it was too dark to gage the amount of cloudiness from the time-lapse film record. Frequent lightning was noted on the after-dark penetrations, and mixing ratios of 16–17 g kg⁻¹ were common in the eye at 750 mb.

At the intermediate levels (650 and 500 mbs), the eye could readily be detected in the traverse records. Relative humidities dropped below 50% near the center of the eye despite the fact that mixing ratios at 650 mb rose from about 7.0 g kg⁻¹ 50 n mi out from the center to over 11 g kg⁻¹ in the eye. At 500 mb, mixing ratios ranged from about 4.5 g kg⁻¹ at 50 n mi to over 7 g kg⁻¹ in the eye. Thus, at all levels from which data were obtained, the highest mixing ratios were found in the eye itself. The temperature increases encountered on entering the eye tended to keep the relative humidity nearly constant at the lower levels and were enough to account for significant decreases in relative humidity of the eye at 650 and 500 mb.

### c. Vertical cross sections

Several vertical cross sections have been constructed, under the assumption that data were synoptic in time and superposed in space. Wherever judged necessary, smoothing of the data was applied to allow for time and space differences.

The cross sections were constructed so as to give the distribution of the quantity under consideration for the front and rear halves of the moving storm. Since Inez was moving in a direction slightly north of west, the SE, N and NW flight legs constituted the “front” region, and the NE, S and SE legs made up the “rear.” The data presented are an average of the appropriate passes, although some cases only the NW to SE passes were analyzed.

#### 1) Relative winds

The cross section of relative wind speeds (relative to moving storm) indicates that the most intense

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**Fig. 12.** As noted in the eye of other hurricanes (Shea, 1972) the measures of absolute humidity show a maximum in the eye. Due to the temperature increase in the eye, the relative humidities decrease. At higher levels, the eye is more readily discernible in the relative humidity traces.
winds were located in the rear portion of the storm (Fig. 13). A narrow band of speeds slightly in excess of 130 kt (mean value) was recorded in this section. As mentioned, winds close to hurricane strength were maintained even at 180 mb; in fact, to the rear of the storm 64 kt winds were exceeded. The radius of maximum winds was also well maintained, with height to around the 500 mb level, remaining close to 7 n mi from the center. However, above 500 mb the radius of maximum winds tilted outward to approximately

FIG. 13. The vertical cross section of wind speeds show the preservation of the wind speeds with height and tilting outward of the ring of maximum winds.
11.5 n mi at 180 mb. The RDR-ID vertical cross section radar appeared to verify a significant angle of eye wall tilt (see later section on radar). The slant of the eye wall does not support the idea that only storms with weaker cumulus convection have a tendency for a slope of the eye wall with height (Shea and Gray, 1973). Instead, the eye wall slope in Inez seems to agree more with Palmén (1956), who believed that as the pressure force decreases rapidly with height, the eye wall boundary became more horizontal. Shea’s rationale appears subject to argument; namely vigorous cumulonimbus activity should transport low-level momentum rapidly aloft which, if the pressure gradient weakens with height, should result in the air being flung outward due to lack of sufficient pressure gradient (force) to maintain the air at the low level maximum wind radius. In the case of Inez, the maximum wind speed (a measure of the pressure gradient) begins to decrease quite rapidly at about the same level (∼500 mb) where the radius of maximum winds begins to tilt outward (Hawkins, 1955). It may be that the warm core structure had weakened the pressure gradient at this point so that the winds were no longer held in balance and began to move radially outward as they rose in the wall cloud. The vertical cross section of absolute angular momentum (shown later) suggests momentum tended to be conserved along such a path.

2) Temperatures

The NW to SE soundings (Fig. 10) were used as the basis for a cross section of temperature anomaly...
(Fig. 14), Jordan's (1958) mean annual tropical sounding serving as the normal. A maximum anomaly of greater than +16°C was located at about the 250 mb level, with separate warm anomaly center at 600 mb. The strongest gradients were generally found in the eye wall region and were surprisingly well maintained with height. Minor anomalies were found mainly below 600 mb outward from 20 n mi where temperatures were normal at the 650, 700 and 950 mb layers. Again, as on the 27th there was a small center of anomalous warmth between the 650 and 500 mb levels. The big changes occurred at the higher levels where, as noted previously in the soundings, warming had been common everywhere above 400 mb—at least to the 180 mb level and slightly above. In the eye, warming of about 7°C occurred at the anomaly center with greater warming aloft, i.e., more than 9°C at 200 mb. There is also evidence that the horizontal axis of anomalous warmth had become better marked and was located at a higher level on 28 September when compared to the 27th.

3) D-VALUES

The extreme intensity of Inez is well portrayed by the vertical cross section of D-values (Fig. 15). Negative values of about −2500 ft were found in the eye at low levels. Gradients were strong, particularly, in the eye wall region at lower levels. Once again, the analysis was terminated at 180 mb due to the unavailability of observations.

4) EQUIVALENT POTENTIAL TEMPERATURES

Equivalent potential temperatures ($\theta_e$) were calculated for the NW-SE pass at approximately 1 n mi intervals for all of the observational levels. This
vided for the construction of a detailed vertical cross section (Fig. 16). Readily apparent are the typically high $\theta_e$ values in the eye at the lower and upper levels. A second major feature is the area of $\theta_e$ minimum (less than 352 K), located also in the eye, near the 500 mb level. As indicated on the temperature anomaly cross section, a “cool” pocket of air was located at 500 mb in the same area, and combined with relative humidities of 50% or slightly less, resulted in the lower $\theta_e$ values.

The eye wall region was essentially characterized by conservation of $\theta_e$ with height, as would be expected with moist adiabatic ascent. Fairly good agreement was found to exist between other areas of constant vertical $\theta_e$ and enhanced cumulus convection found on radar films of the different flights. The areas of minimum $\theta_e$'s (~336 K) were located mainly in the 600 to 700 mb layer, a little lower than in the average atmosphere. This may be due to the abnormal warmth aloft and some mixing of this warmth downward.

Comparisons with the pattern of $\theta_e$ obtained by Kurihara and Tuleya (1974) reveal certain gross features in common and many dissimilarities with the equivalent potential temperatures generated by their computer model. The major difference seems to occur at the ocean surface where the model suggested values near 360 K at all radii, not just in the eye. They assumed an ocean temperature of 302 K, which seems a bit high.

Another difference was the lack of any indication of rainbands in the model results. Despite evidence of banded structure in the vertical velocity field there seems little tendency for areas with a constant (or nearly constant) $\theta_e$ with height, other than in the main wall cloud. Of course, the actual observations do reveal something of a banded structure outside of the eye wall, and the warmer temperatures encountered in the central portions of Hurricane Inez correspond to the lower central pressures than were indicated by the model run. Apparently Kurihara and Tuleya feel that the 20 km resolution on the inner grid is inadequate to simulate the detailed structure near the eye.

Another difference of note lies in the upper level values of $\theta_e$ found over the eye. The maximum indicated in the model run was 370 K with an ocean temperature of 302 K. Both the low-level and high-level eye values of $\theta_e$ appear a bit low although the net difference (10$^o$C) agrees well with the observed. The maximum values of 376 K observed must have come from higher levels near the tropopause. Jordan's (1958) monthly mean temperatures for San Juan, Puerto Rico, suggests that such values of $\theta_e$ may be found just below or at the tropopause. Consequently, we cannot argue with assurance that the tropopause

![Fig. 16. In moist adiabatic ascent, the equivalent potential temperature should remain constant with height. Traces of such a regime were evident in the eye wall and rain bands.](image-url)
has been broken and stratospheric air brought down. Certainly, air from near the tropopause has been entrained in the subsidence in the eye (Shea and Gray, 1973) and the origin of the air may have been above the tropopause in the lower stratosphere.

4. Radar

Efforts to digitize the radar tops (in an RHI presentation) proved unsatisfactory. The presentation on the scope was nonlinear, attenuation of the 3.2 cm radar beam was quite evident, even within 10 to 15 n mi of the plane, and the plot-outs suffered from over printing as the plane yawed in the high winds near the eye. One was forced to adopt the philosophy that what the films actually showed had to be accepted with some reservation and that one could not rely on the absence of echoes as indicative of a lack of meteorological targets, especially where attenuation might be a factor.

Fig. 17 is a view from inside the eye of Hurricane Inez. The walls on either side rose above 30 000 ft (5 n mi) and certainly suggested a fairly strong tilt with height above 15 000 ft probably due to a weakening of the vortex with height. (The plane was at an altitude of about 2000 ft.) An inner rainband that lay about 5 n mi outside of the eye wall is also shown. A curious feature of the band was the fact that it appeared to tilt inward with height (on the right hand side). Presumably, this rising hot tower was deficient in tangential velocity and was being deflected inward by the unbalanced pressure gradient. Just how this circumstance came about is open to conjecture.

The radar PPI view of Hurricane Inez suggested that there were quite a number of rainbands, or fragments of rainbands, present. Fig. 18 shows that APS-20 (10 cm) presentation. The eye wall and the next outer rainband usually appeared to be the best marked, but other bands were present and are at least faintly indicated in the figure.

A feature of some concern these days is the extensive area of hurricanes which shows evidence of the radar bright band (Senn, 1966). The band is presumed due to the greatly enhanced reflectivity acquired by ice crystals as they fall, melt, and acquire a covering of water. Obviously, this can occur only where numerous ice crystals are present and, if such conditions are common in hurricanes, what can be the point of seeding hurricanes with silver iodide (i.e., artificial ice crystal nuclei)? Quite an extensive area of bright band was noted in Hurricane Hilda, 1964 Hawkins and Rubsam (1968). Similar conditions were noted in Hurricane Inez, 1966.

The major part of the area between 50 n mi radius and the first rainband beyond the eye wall (at about 10 n mi radius) was characterized by stratiform layer type clouds with a conspicuous bright band. Fig. 19 depicts such an area and shows the iso-echoed bright band with some limited return above the melting layer.
The bright band cover was interrupted by rainbands. Wherever active turrets were present, the bright band regime was disrupted. Fig. 20 suggests such a situation. Bright band iso-echoes prevailed on the right and above the plane. But a cumulonimbus cell to the left iso-echoed at all levels below the melting
level and suggested echo buildup to higher levels than in the bright band area. Similar cells and regimes characterized most of the rainband crossings. Between the eye wall and the first rainband, no evidence of stratiform regime or bright band was noted. Presumably, this area was dominated by a convective regime, but beyond this radius there apparently existed a plentiful supply of ice crystals. The major point here is that the altitude at which they exist is confined to levels above and around 16,000 ft. This is well above the inflow layer, and the lower levels are probably in the base of the outflow layer. Consequently, it is deemed likely that the bulk of the ice crystals are in a mean radial flow that is directed outward. Such a flow is not likely to seed hot towers lying just outside of the ring of maximum winds.

5. Mass flow

An extremely important quantity in gaging the dynamic characteristics of the storm is the distribution of radial velocity with radial distance and with height. The radial ($V_r$) and tangential ($V_\theta$) velocities were computed from tabulations of the wind speed and direction for every 10 n mi of radial distance and every 30° of azimuth (see Hawkins and Rubsam, 1968). This was done at the two lower levels of reliable data, but radial velocities, $V_r$, were not attempted at the higher levels where data were somewhat questionable.

a. Absolute angular momentum

The tangential velocities were used to construct a vertical cross section of absolute momentum (Fig. 21),

$$M = V_\theta r + \frac{f r^2}{2}.$$

It shows that the air which was moving in at lower levels was losing momentum to ocean due to the drag exerted on the sea surface by the moving air above it. Up to at least 700 mb, the isopleths are nearly vertical, suggesting that through this level stirring was quite effective in the inflow layer. These values were degraded when the air was mixed with outflowing air aloft of lower momentum. Air which penetrated the farthest lost the maximum momentum and rose to the highest elevations before turning outward. Because of the sharply peaked wind speed profile, values of momentum 7-10 n mi out were quite high, while those from 40-50 n mi were quite low compared to those in Hurricane Hilda (Hawkins and Rubsam, 1968).
b. Absolute vorticity

The vertical cross section of absolute vorticity,

$$\zeta_a = -\frac{V_\theta}{r} \frac{\partial V_\theta}{\partial r} + f,$$

also reflects the basic character of the sharply peaked windspeed profile (Fig. 22). Near the eye, vorticities approached $5 \times 10^{-4} \text{ s}^{-1}$, a fairly extreme value for azimuthally meanded winds. Fifty n mi from the eye the value has dropped to less than $2 \times 10^{-4} \text{ s}^{-1}$. The greater part of this decrease occurred between the eye wall and the 10 n mi marker at lower levels. This maximum gradient of vorticity tilted outward with height as did the maximum winds in the eye wall.

c. Radial velocities

The mean radial velocities at the lower levels (950 and 750 mb) disclosed an interesting facet of the storm, namely, that the mean inflow went to zero at the 750 mb level and the inflow layer was, for all practical purposes, confined below this level. Fig. 23 shows the distribution of radial velocities (more accurately, the radial velocity times the radius—a quantity proportional to the mass transport across the radius) with pressure (below 750 mb) and radius. The curves have been drawn assuming that the inflow increased with decreasing height from zero at 750 mb; the changes in mass flow across adjacent radii were gradual; and the mass flow across the circumnavigated area (at its mean radius) was quite accurate. These curves are of the utmost importance in the com-
putations that follow. They indicate much stronger radial velocities than those measured in Hurricane Hilda. It is conceivable that the inflow layer was shallower and the inflow went to zero at even lower levels; however, the likelihood of it going to zero at a significantly lower level was deemed remote.

d. Angular momentum budget and surface stress

The budget of absolute angular momentum for the inflow layer was calculated using the $rV_r$ curves and the mean $V_\theta$ for the appropriate radius and thickness layer (Fig. 25). The horizontal fluxes across various radii were evaluated using the approximation

$$F = 2\pi r MV_r \frac{\Delta P}{g}.$$ 

Vertical velocities were derived for each annulus using the $rV_r$ data for the appropriate pressure interval in order to yield $\omega$ at the 900, 800, and 750 mb levels calculated from the continuity equation,

$$\frac{\partial \omega}{\partial r} + \frac{1}{r} \frac{\partial (rV_r)}{\partial r} = 0.$$ 

These mean (over the annulus) vertical velocities were used to calculate the vertical transport of momentum from the top of the “boxes” after the momentum had been computed using a representative mean $V_\theta$ at the appropriate level. The computations were carried out for 5 n mi annuli from 5 to 50 n mi.

The net difference of momentum transport (or residual), i.e., the import less the export per annulus, must represent momentum lost to the sea through drag at the interface. This amount tends to diminish at smaller radii due mainly to decreasing area. However, this was not uniformly true with these data as shown between 30–40 n mi in Fig. 24. The lower enclosed rectangles show that momentum losses (to the sea) per unit area increased with increasing wind speed and decreasing radius, except in the 30–40 mile interval.

In the study of Hurricane Hilda (Hawkins and Rubsam, 1968) stress was calculated in a number of ways with some variation in results but with the conclusion that the budgets derived from the inflow layer were probably the best documented and most reliable. The surface shearing stress in the $\theta-z$ plane, $\tau_{\theta,0}$, can be written

$$\tau_{\theta,0} = \frac{1}{r^2} \frac{\partial}{\partial r} \int_{P_0}^{P_H} \frac{dP}{g} \frac{\omega_H M_H}{\tau g},$$

where $P_0$ and $P_H$ are the pressures at the surface and the top of the inflow layer, and $\tau_{\theta,0}$ is taken to be negligible. Alternately, it may be evaluated from

$$M_s = 2\pi \int_{r_1}^{r_2} \tau_{\theta,0} \sigma^2 dr,$$

where $M_s$ is the momentum transfer to the ocean in the annulus defined by $r_1$, $r_2$.

In addition, $\tau_{\theta,0}$ has been evaluated using the vorticity

$$\tau_{\theta,0} = \int_{P_0}^{P_H} \frac{dP}{g} \frac{dV_\theta}{dz},$$

which neglects the shear term

$$\int_{P_0}^{P_H} \frac{\partial V_\theta}{\partial z} \frac{dP}{g}.$$
usually estimated to be around 10% of the principal term and verified as such in the Hurricane Hilda study. One advantage of the vorticity approach was that the wind maximum occurred at about midpoint in the 5–10 n mi annulus, thus permitting evaluation at the maximum wind speed.

The drag coefficients were computed using both sets of data and they are tabulated in Table 1. Most of the points merged into the previous data for drag coefficients fairly well. The value of $3.4 \times 10^{-3}$ for the 35–40 mile annulus at 26 m s$^{-1}$ was obviously too high but no way could be found to revise the calculation. Similarly, the value of $5.3 \times 10^{-3}$ at 61 m s$^{-1}$ by the momentum approach was assumed to be on the high side.

Drag coefficients derived using the vorticity approach have been plotted in Fig. 25 along with data from Hurricanies Helene (Miller, 1966) and Hilda (Hawkins and Rubsam, 1968) and other, lower wind speed determinations. The higher hurricane speeds continue to suggest that the relationship is nonlinear. There is little doubt that momentum extraction in the high speed core of the storm must be extreme. Mountainous waves, wind-driven spray, and heavy rain aid in the transfer of momentum. A second degree least squares fit to these data suggests:

$$C_D = 1.28 \times 10^{-3} + 7.36 \times 10^{-6} V + 5.68 \times 10^{-7} V^2.$$ 

According to this expression $C_D$ would vary from $1.4 \times 10^{-3}$ at 10 m s$^{-1}$ to $4.6 \times 10^{-3}$ at 70 m s$^{-1}$, which is a significant range. It is obvious that further evaluations at the higher speeds are needed.

![Fig. 24. Fluxes of absolute angular momentum for Hurricane Inez. The indicated fluxes into the sea are computed by calculating the residuals for each annular ring. The figures in boxes are the momentum losses per unit area in units of $10^8$ g cm$^{-2}$.](image)

<table>
<thead>
<tr>
<th>Table 1. Values of the tangential shearing stress computed by the vorticity and momentum approaches are listed for the indicated wind speeds.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drag Coefficient – Hurricane Inez (1966)</strong></td>
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<tr>
<td>(From the vorticity and momentum expressions.)</td>
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<table>
<thead>
<tr>
<th>VORTICITY</th>
<th>MOMENTUM</th>
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<tbody>
<tr>
<td><strong>Radii</strong></td>
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</tr>
<tr>
<td>(nmi)</td>
<td>Wind Speed</td>
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<td></td>
<td>(m/sec)</td>
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<td></td>
<td>$T_{O,D}$</td>
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<td></td>
<td>(dynes/cm$^2$)</td>
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<td></td>
<td>$C_D$</td>
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<td>($10^{-3}$)</td>
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<tr>
<td><strong>Wind Speed</strong></td>
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<tr>
<td>(m/sec)</td>
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<tr>
<td>($10^{-3}$)</td>
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<tr>
<td>5–10</td>
<td>67</td>
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<tr>
<td>10–15</td>
<td>52</td>
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<td>15–20</td>
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</tr>
<tr>
<td>40–45</td>
<td>25</td>
</tr>
<tr>
<td>45–50</td>
<td>23</td>
</tr>
</tbody>
</table>

| Wind Speed |
| (m/sec) | $T_{O,D}$ |
| (dynes/cm$^2$) | $C_D$ |
| ($10^{-3}$) |
| 61 | 216 | 5.3 |
| 52 | 66 | 2.8 |
| 45 | 39 | 1.9 |
| 36 | 37 | 2.4 |
| 32 | 25 | 2.2 |
| 28 | 14 | 1.8 |
| 26 | 28 | 3.5 |
| 25 | 16 | 2.1 |
| 23 | 12 | 2.0 |
5. Vertical transports of sensible and latent heat were computed from

$$Q_s = C_p \rho (T_0 - T_a) VAQ_e = C_e \rho (q_0 - q_a) VA,$$

where $\sim$ indicates areal averaging, $V$ is the total wind speed and $A$ is area.

Computation results are presented in Table 2. Air-sea temperature differences ranged from 2.6°C at 50 n mi out to 3.4°C 15–25 miles out to 2.4°C in the 5–10 mile annulus. These appear to be more reasonable (Miller, 1962; Riehl and Malkus, 1961) than the approximately 5°C inferred in Hurricane Hilda. The air-sea specific humidity differences were also smaller by around 15%, but wind speeds and the corresponding exchange coefficients were higher. Sensible and latent heat losses per unit area (from the ocean) increased from outer to inner radii. In the inner area, latent heat losses were greater than in Hurricane Hilda. The Bowen ratio

$$r_b = \frac{Q_s}{Q_e} = \frac{c_p (T_0 - T_a)}{L (q_0 - q_a)}$$

averaged somewhat less than the 0.20 commonly referred to in hurricanes, suggesting that latent heat transfer from the ocean surface exceeded the sensible heat transfer even more than usual.

A budget was also computed for the inflow layer of the quantity

$$H = c_p T + L q + q_s.$$  

$H$ is sometimes referred to as the static energy or total effective energy, since the kinetic energy seldom contributed significantly to the above total. The computations were made by estimating a mean temperature (at the 10 mile radial intervals) from the reconstructed “soundings” for three layers: surface to 900 mb, 900 to 800 mb and 800 to 750 mb. For the same intervals, estimates of the absolute humidity were made from the flight data near 750 mb and 950 mb and, in es-

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**Table 2.** For the indicated radial intervals, the following quantities are listed in order: the air-sea temperature difference, the air-sea (saturation at sea temperature) specific humidity difference, mean wind speed, exchange coefficients, sensible heat transfer, latent heat transfer, and the Bowen ratio.

<table>
<thead>
<tr>
<th>HURRICANE INEZ</th>
<th>SEPTEMBER 28, 1966</th>
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</thead>
<tbody>
<tr>
<td>SENSIBLE AND LATENT HEAT EXCHANGE</td>
<td></td>
</tr>
<tr>
<td>RADIAL INTERVAL (N MI)</td>
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</tr>
<tr>
<td>$T_s - T_a$ (°C)</td>
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</tr>
<tr>
<td>$q_s - q_a$ (g/kg)</td>
<td>7.7</td>
</tr>
<tr>
<td>$V$ (kt)</td>
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<tr>
<td>$C_p = \rho (\text{ft})$</td>
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</tr>
<tr>
<td>$Q_s$ (cal/cm² sec)</td>
<td>0.115</td>
</tr>
<tr>
<td>$Q_e$ (cal/cm² sec)</td>
<td>0.115</td>
</tr>
<tr>
<td>$r_b$</td>
<td>13</td>
</tr>
</tbody>
</table>
sence, the integral
\[
- \int_{\text{surf}} 2\pi r V_x (c_p T + L_g + g\gamma) \frac{dp}{g}
\]
was evaluated in segments. Since it was not practicable to construct \( rV_x \) curves for the outflow layer, no computations could be made at the upper levels.

The results in Fig. 26 may be compared to the inflow budget for Hurricane Hilda (Hawkins and Rubsam, 1968). At 50 n mi out, the layer 1001 mb to 900 mb carried 1090 units of energy in toward the storm center, over twice that transported in Hilda. This was due principally to the stronger radial inflow in Inez. The total carried by the inflow layer was 1729 units in Inez and 916 in Hilda (at the 50 n mi radial); at 30 n mi these transports diminish to 1149 and 507 units respectively. These data certainly indicate that the effective energy being drawn into Inez was about twice that drawn into Hurricane Hilda. As in Hilda, the horizontal transports decreased with increasing radius, but unlike Hilda, the vertical transport of energy out of the inflow layer increased significantly at the smaller radii.

Another item of interest is a comparison of the amounts of moisture supplied to the air by the ocean surface in \textit{ situ} with that advected horizontally from the periphery of the storm. Occasionally, this relationship has been the subject of debate and can best be seen by examination of Fig. 27, the moisture divergence in the inflow layer. The figures permit comparisons of the relative magnitudes of the water vapor supplied by the ocean in each 10 n mi annulus to that brought into the same annulus by horizontal advection. The percentages decrease from 13% in the 10-20 n mi annulus to 6% in the 40-50 n mi annulus. At first glance these numbers do not appear to be very large. But, the net effect in moistening the inflow layer cannot be so readily dismissed. For instance, between the 50 n mi radius and the 10 n mi radius,

the ocean supplies an amount of moisture that is greater than half that being advected across the 20 n mi radius and greater than that crossing the 10 n mi radius. If data were available out to 100 n mi, the figures would be even more impressive in the sense that the cumulative addition of moisture at the greater radii would build up moisture totals equal to the total horizontal advection at the inner radii.

If one completely ignores the outflow layer and assumes that the moisture converging in the inflow layer all falls out as rain, then one can estimate the rainfall rates corresponding to these convergences. They are indicated (at the bottom of Fig. 27) for the 10 n mi annuli out to 50 n mi. The estimates seem reasonable enough when expressed in hourly rates, although the numbers are rather large when viewed as daily rates. In more practical terms, if the storm passed directly overhead at 10 kt, the gage should record 8.3 in. rainfall during the passage of the inner 50 n mi of the hurricane. This constitutes an acceptable figure because 10 in. is a commonly quoted figure for the complete passage of a hurricane.

6. Recommendations

This completes the range of hurricane strengths over which it is profitable to perform the computations. Hurricanes of a reasonable range of intensities have been examined with the same instrumentation. What remains to be done?

1. There should be a systematic study of the winds in hurricanes so that the Doppler winds are related to the more accurate winds derived from the inertial navigation system. If systematic differences are discovered, then their implications relative to the three papers in this series should be made clear.

2. If opportunity presents itself, a multi-plane mission should be executed with modern instrumentation (including cloud physics and turbulence gear) and

![Fig. 26. Budget of \( H = c_p T + L_g + g\gamma \), the total effective energy, including the flux of latent and sensible heat from the ocean.](image)

![Fig. 27. Divergence of moisture in the inflow layer of Hurricane Inez. Rainfall rates were calculated assuming all the converging moisture fell out as rain.](image)
modern aircraft with the ability to gather data in the mid-troposphere (around 25 000 ft).

3. In addition to #2 above, there should be a surveillance of a storm, or storms, in which megasondes are used extensively to determine what wind shears exists with height in the various parts of the storm.

Acknowledgments. Without the cooperation of the Research Flight Facility, these flights could never have been made. Their efforts on this occasion went far beyond those expected and routine. Mr. S. Pearce compiled the data with the utmost care; Mssrs. Martin and True drafted and photographed the figures. Mrs. F. Midboe typed the original manuscript, and Ms. P. Olson typed the final version.

REFERENCES


