Objective Analysis of Aircraft Data in Tropical Cyclones

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ABSTRACT

A method for objective analysis of aircraft observations in tropical cyclones has been developed. Quasi-horizontal fields of motion, temperatures, mixing ratios, and D-values are analyzed using a modified version of the method of successive corrections. The weighting functions are specified so that the high degree of circular symmetry characteristic of tropical cyclones is incorporated in the analyses. The analyses are performed on a 25 by 25 Cartesian grid of 5 n mi spacing which is centered on the storm. A special feature is the analysis of vertical motions as determined from aircraft flight characteristics. Three Atlantic storms are analyzed in detail: Hurricanes Inez (1966), Debbie (1969), and Ginger (1971). The analyses show the significant larger-scale features and major asymmetries of these storms. Both Inez and Debbie, which were well organized hurricanes, display characteristic vertical motion patterns in which a ring of strong ascent is found immediately surrounding the eye, with marked descent just outside of the annulus of strong ascent. Maximum ascent and descent rates were each indicated to be a few meters per second in these storms. Ginger was a marginal hurricane with poorly organized eye structure and relatively weak and disorganized patterns of vertical motion.

1. Introduction

Computerized objective analyses of meteorological fields are gradually replacing laborious and subjective hand analysis methods. Recently, methods for objective analysis of tropical cyclone data have been developed at the National Hurricane Research Laboratory. A variational optimization analysis technique has been developed by Sheets (1973a, b). The objective analysis scheme presented here is similar to the method of Berghófrssen and Dóös (1955) as modified by Cressman (1959) and Endlich and Mancuso (1968). In this method, a functional relationship is used to assign a relative weight to each observation in the vicinity of an analysis grid point. This weight determines the amount of influence of the observation upon the resulting value at the grid point.

Quantitative measurements of motion, temperature, and moisture in tropical cyclones are almost exclusively obtained by aircraft such as those flown by the Research Flight Facility of the National Oceanic and Atmospheric Administration (NOAA). These aircraft customarily fly a series of straight line passes and circumferential arcs across the high energy portion of the storm. A typical flight path at a single level is shown in Fig. 1. Normally, similar flights are made at four or five elevations in the storm. Several hours may be required to complete the flight path at a particular level. Both meteorological and navigational information at one-second intervals are recorded on magnetic tape aboard the aircraft. These tapes are subsequently processed using routines developed for this purpose (Friedman et al., 1969) and the processed data are placed on user tapes. Both the aircraft coordinates and the horizontal wind components are given with respect to the moving storm center as well as in absolute terms. The nature and reliability of the aircraft data have been frequently discussed in the literature. (See, for example, Gray, 1962, 1965; Hawkins and Rubsam, 1968; Shea and Gray, 1973.)

One of the most difficult variables to measure by direct means is the vertical motion. Carlson and Sheets (1971) have demonstrated that, in the case of individual cumulus clouds, vertical motions can be determined from aircraft flight characteristics that compare favorably with measurements obtained by the stable platform gust probe, at least at wavelengths of vertical motion greater than a few kilometers. This suggests that the vertical velocities determined from aircraft are valid on the scale of large cumulonimbi or clusters of convective clouds in tropical cyclones. Studies by Gray (1965) and Carlson and Sheets (1971) indicate that aircraft-determined vertical motions have realistic profiles along flight tracks in hurricanes.

The objective analysis method described in this paper is well suited to depicting the spatially smoothed and time-averaged large cloud cluster scale vertical motions found in tropical cyclones. The method may be used to analyze any (or all) of six basic fields:
vertical velocity, tangential velocity, radial velocity, temperature, mixing ratio, and D-values. The vertical velocity analyses are featured in this paper as being of greatest interest. Analyses of three hurricanes: Inez (1966), Debbie (1969), and Ginger (1971), are presented and compared.

2. Objective analysis procedure

The computer programs used to analyze the data fields operate in two steps. First, the vertical motions are computed, as described in Section 3, from the basic one-second interval data, using time steps of 6 s (about 600 m flight distance). Since the vertical velocities therefore represent averages over 6 s, all the fields are converted to 6 s block averages and stored for use in the analysis portion of the program. (In order to accommodate the large number of observations in the available computer memory, the parameters are interpolated in time to yield one value every 10 s in the analysis part of the program.) The analysis of the meteorological fields are then performed using these time-averaged values along the aircraft flight path as observational data points. Vertical velocities are not computed for those portions of the path where the aircraft executed turning maneuvers, as they are unreliable in those locations. From Fig. 1, it is evident that the data distribution typically decreases in spatial density with increasing distance from the center of the storm.

Since virtually all of the obviously erroneous data are eliminated in the processing of the raw measurements, no routine is incorporated in the program for checking and eliminating bad data. An error checking routine could easily be incorporated if desired.

The meteorological fields are analyzed at points on a 25 by 25 Cartesian grid of 5.0 n mi spacing which is centered on the storm. Alignment of the grid is with the local directions of latitude and longitude. Thus, the analysis grid covers the storm out to a radius of at least 60 n mi. An initial estimate of the value $f_{ij}$ to be analyzed at the $(ij)$th grid point is computed by the formula

$$f_{ij} = \frac{\sum w_{ijk} f_k}{\sum w_{ijk}}$$  \hspace{1cm} (1)

where the $f_k$ are the observational data along the aircraft flight path and the $w_{ijk}$ are weights that determine the relative influence of each observation on the resulting analyzed grid point value $f_{ij}$. A functional relationship is used to determine these weights. Once the initial analysis is completed, the same formula is used to make successive corrections to the analyzed value in the manner of Cressman (1959). (In Cressman's method, an independent source, usually a forecast, is used to determine the initial estimate of the meteorological field at the grid points.)

In order to select a form of the weighting function that weights the data points in such a manner as to give the "best possible" analysis of the storm, various forms were tried, and the results were compared with carefully performed manual analyses. On the basis of these comparisons, the form selected for the weighting function is, in polar coordinates,

$$w_{ijk} = \left( \frac{D_{ij}^2 \sin \phi - (D_{ij}^2 - d_{ijk}^2) \cos \phi}{D_{ij}^2 + d_{ijk}^2} \right)$$  \hspace{1cm} (2a)

if $(r_k - r_i)^2 < D_{ij}^2$, and

$$w_{ijk} = 0$$  \hspace{1cm} (2b)

if $(r_k - r_i)^2 \geq D_{ij}^2$, where

$$D_{ij}^2 = hr_{ij}$$  \hspace{1cm} (3a)

$$d_{ijk}^2 = (r_k - r_i)^2 + r_{ij}^2 (\theta_k - \theta_{ij})^2$$  \hspace{1cm} (3b)

FIG. 1. Path of DC-6 flight at 2.5 km level in Hurricane Inez, 28 September 1966.

FIG. 2. Coordinate system for objective analysis formulae.
and

$$\phi_{ijk} = \tan^{-1}\left(\frac{r_{ij}\theta_k - \theta_{ij}}{|r_k - r_{ij}|}\right).$$

(3c)

In the above expressions, \( h \) is the grid spacing, \( r_{ij} \) the radial distance, and \( \theta_{ij} \) the azimuthal angle of the \((ij)\)th grid point from the center of the storm; similarly, \( r_k \) and \( \theta_k \) refer to the coordinates of the observational data point (Fig. 2).

The quantities \( d_{ijk} \) and \( \phi_{ijk} \) are the “distance” and “direction,” respectively, as measured in \( r, \theta \) coordinates, of the \((k)\)th data point from the \((ij)\)th grid point. Thus, the direction as well as the distance of each data point from the \((ij)\)th grid point enters into the determination of each weight \( w_{ijk} \). A directionally dependent weighting function was used by Endlich and Mancuso (1968) for analysis of jet maxima. In the present scheme, their concept of giving greater weight to observations along the direction of streamflow as compared to observations in a direction normal to the streamflow has been applied to the predominantly circular flow about the center of a tropical cyclone.

The weighting function (2a) combines high resolution in the radial direction (\( \sin \phi = 0 \)) with a high degree of circular symmetry in the tangential direction (\( \cos \phi = 0 \)).

Figure 3 shows isopleths of equal weight \( w_{ijk} \) as given by (2a) or (2b) for the analysis at a single grid point located 20 n mi east of the storm center. All data points found within an annulus of width \( 2D_{ij} \) about the center of the storm, with mid-line radius equal to \( r_{ij} \), are given positive weights. Data points located outside of this annulus are given zero weight. For the example shown, the half-width \( D_{ij} \) is 10 n mi (3a). The width of the annulus is made to increase for larger \( r_{ij} \) at a rate proportional to \( (r_{ij})^{-1} \). This broadening of the annulus, and hence more nearly circular isopleths of weight at larger radii, is consistent with the approximate dependence of tangential wind speed \( V_\theta \) on radial distance from storm center,

$$V_\theta \sim Cr^{-1},$$

(4)

as given by Riehl (1963) for tropical cyclones. If aircraft data for only a single radial flight leg are available, the analysis method will give a circularly symmetric storm, normally the preferred solution in the absence of other information.

After the initial estimate of the analysis has been obtained at each grid point, the corresponding analysis estimate at each of the observation locations along the flight path is determined by means of bilinear interpolation from the analyzed values at the nearest four grid points. In general, this interpolated value will not correspond to the value \( f_k \) actually observed but will differ by an amount \( \Delta f_k \), which may be called the residual “error” of the analyzed field at the \((k)\)th observation point.

Next, the field of residuals \( \Delta f_k \) thus obtained is analyzed using (2a) or (2b) in order to obtain a first correction \( (\Delta f_{ijk})^1 \) for the value of \( f_{ijk} \) at each grid point. Addition of this correction to the initial estimate yields a second, improved estimate of \( f_{ijk} \). New residuals at the
observation points may then be determined, and so forth. In general,

$$(f_{i0})^{n+1} = (f_{i0})^n + (\Delta f_{i0})^n, \quad n = 1, 2, \ldots$$  \hspace{1cm} (5)

Successive iterations are continued until convergence is reached, or

$$\left| (\Delta f_{i0})^n \right| < \left| (\Delta f_{i0})^{n-1} \right| < \delta, \quad \nu \neq 1,$$ \hspace{1cm} (6)

where $\delta$ is an acceptable level of analysis error.

In runs performed on Hurricane Inez (1966), satisfactory convergence was obtained after two corrective iterations over most of the grid domain, the exceptions being along the boundaries and in the corners beyond 60 n mi radius. The lack of convergence in the outermost portions of the grid can probably be attributed to the fact that there were few or no observations available at these large radii, and hence the interpolation formula was attempting to perform an analysis with a very limited and poorly distributed set of observational data in these regions. A smoothing routine, which averages the values at radii of 60 n mi and beyond, is used to ensure convergence at these radii; however, the resulting analysis cannot be considered as depicting storm structure accurately at these large radii.

Radial profiles of meteorological variables were obtained by taking all observations $f_{i0}$, ordering them by radial distance $r_i$ from the center, and applying the following one-dimensional weighted interpolation formula to get values $f_i$ at radii $r_i$ with radial interval $b$ of 1.0 n mi:

$$f_i = \sum_k w_{ik} f_{ik} / \sum_k w_{ik},$$ \hspace{1cm} (7)

where

$$w_{ik} = \left\{ h_{ri} - (r_i - r_k)^2 \right\} / \left\{ h_{ri} + (r_i - r_k)^2 \right\},$$ \hspace{1cm} (8a)

if $r_i = r_k < h_{ri}$, and

$$w_{ik} = 0,$$ \hspace{1cm} (8b)

if $r_i - r_k \geq h_{ri}$.

Only radial profiles of vertical velocity thus obtained are shown in this paper.

3. Vertical motion computations

Vertical velocities are computed from the aircraft flight data using the relation (Gray, 1965)

$$W_e = V_t (\alpha_d - \beta_d) + W_p,$$ \hspace{1cm} (9)

where $W_e$ is the convective vertical velocity of the air, $V_t$ the true air speed of the aircraft, $W_p$ the vertical velocity, $\alpha_d$ the deviation of the angle of attack from its equilibrium value $\alpha_e$, and $\beta_d$ the deviation of the pitch angle from its equilibrium value $\beta_e$. The angle of attack $\alpha$ is defined as the inclination of the longitudinal axis of the aircraft from the plane of the relative wind vector (including its vertical component) in the plane bisecting the aircraft fuselage, whereas the pitch angle $\beta$ is defined as the inclination of the longitudinal axis from the horizontal plane, on the same bisecting plane. The equilibrium values $\alpha_e$ and $\beta_e$ of these angles are considered to be identical (Gray, 1965), and represent values appropriate to smooth air with no convective updrafts or downdrafts.

The pitch angle $\beta$ and the true air speed $V_t$ are measured directly, and the aircraft vertical velocity $W_p$ is determined by differentiation of the aircraft altitude as measured by a rapid response radio altimeter. In order to determine $\beta_d$, hence also $\alpha_d$ and $\beta_e$, the net value of the vertical motion $W_e$ is assumed to be zero (to within the accuracy permitted by the system error) over some long flight interval $T_L$. Then

$$\beta_e = \frac{1}{T} \int_{-T_L/2}^{+T_L/2} \beta dT.$$ \hspace{1cm} (10)

The angle of attack $\alpha$ was not measured directly on flights through Inez, but nevertheless, $\alpha_d$ can be expressed as a function of other parameters in the aircraft lift equations (Carlson and Sheets, 1971). Gray (1965) has shown that $\alpha_d$ is usually negligibly small when averaged over 10 s intervals. Carlson and Sheets on the other hand have shown that inclusion of $\alpha_d$ in (9) slightly improves the computed draft speeds in cumulus clouds. The angle of attack has been included in the present vertical motion computations, but its effect on the results is probably small.

It is evident that real short term fluctuations in $\beta_e$, as well as long term variations in this quantity over time scales exceeding $T_L$, cannot be accounted for in the computations of $W_e$. It is unlikely, however, that any mechanical system involving aircraft can satisfactorily measure vertical velocities on scales greater than tens of miles. Variations in $\beta_e$ are probably rather gradual unless deliberate pilot maneuvers, involving power setting changes or sharp turns, are employed. It is our opinion that the relative error in $W_e$ is substantially less than 1 m s$^{-1}$ when the aircraft is flying in turbulent conditions but without power setting changes or significant changes in direction. Unfortunately, the aircraft is likely to deviate from such ideal conditions under certain critical situations, such as in penetrating the eye wall cloud. Indications are, however, that deliberate power setting changes will not drastically alter the character of the vertical motions (Carlson and Sheets, 1971).

In hurricanes, the scales of motion of primary interest to synopticians concerned with the total storm structure and energy budget are considerably larger than the width of individual cumulonimbus clouds. In a 100 mi straight line pass through the eye of a storm, an aircraft will likely encounter a large number of updrafts and downdrafts. Observations of radar echoes, such as those of Black et al. (1972), show that individual

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1Recently, an angle of attack vane has been mounted on the RFF aircraft, enabling $\alpha$ to be directly measured.
precipitation cells tend to rotate cyclonically with a speed comparable to that of the wind averaged over the vertical extent of the cell. The observations also show that major asymmetries tend to persist for long periods, suggesting the positional stability of major convergence and divergence patterns. These patterns become clearly manifest when the data are smoothed or composited in some objective fashion. We will subsequently refer to these larger scale patterns as the hurricane band scale as opposed to the individual cumulus scale.

The dimensions of the band scale may be tens of miles across and encompass a region within which there is a general ascending area surrounded by a region favored by descent. An example of such a band is the eye wall cloud or an outer spiral cloud band. Evidence of such band structure can be seen in the aircraft vertical motion profiles along a single straight line segment. Figure 4 shows computed traces of \( W_z \) for a pair of aircraft flights flown by two DC-6's toward the west from near the center of tropical storm Felice, 15 September 1970. These tracks were made almost simultaneously and within a few miles of each other, but at different levels. Individual updrafts and downdrafts are clearly evident in the vertical motion traces of Fig. 4, appearing as rapidly oscillating features; these scales of motion are poorly correlated between the two records. It is also evident that the broader features of these vertical motion profiles are quite similar and, indeed, the correlation between the records is high when they are both smoothed to remove the high frequency motions.

The two vertical velocity profiles show two areas of enhanced updrafts, corresponding to an average upward motion and higher echo tops, near 20 and 45 n mi from the storm center. The inner band corresponds to an eye wall cloud although Felice was not a particularly well organized storm and had winds of less than 60 kt (30 m s\(^{-1}\)).

It can be argued that the band scale may correspond not to real cloud and updraft features but to artificially induced changes in the response of the aircraft as it tries to maneuver through turbulent regions. In effect, \( \beta_s \) will behave erratically when the aircraft undergoes sharp banking in a turn or when the pilot changes his
power setting with the throttle. However, the similarity in the two profiles of $w_z$ shown in Fig. 4 does imply that our measurements have physical significance. Moreover, in comparing vertical motion profiles, we also find that similar profiles are computed when the measurements are stratified according to whether the
aircraft is heading toward or away from the eye, although the expected pilot response would be different in each case.

4. Analyses of three hurricanes

Objective analyses of vertical velocity and other parameters were carried out for three hurricanes: Inez (1966—2 days), Debbie (1969—1 day), and Ginger (1971—2 days). Inez was an extremely intense hurricane of relatively small diameter, Debbie a moderately intense hurricane of somewhat broader dimensions, and Ginger a marginal hurricane of large diameter but relatively poor organization.

a. Hurricane Inez: 28 September 1966

The meteorological history of Hurricane Inez has been given by Sugg (1967), and Hawkins and Rubsam (1967) have described this storm as a classic micro-hurricane. On 28 September, Inez was located about 100 mi south of Puerto Rico with central pressure of 927 mb and maximum gust speeds estimated to be almost 100 m s⁻¹. Aircraft radar showed the eye diameter to be only 8 to 10 n mi (15–18 km). The storm had intensified considerably in the previous 24 hours.

Research flights were made by a pair of instrumented DC-6 aircraft at four levels in the storm on 28 September. One DC-6 flew at approximately 0.5 and 2.5 km, the other at 3.5 and 5.5 km altitude. A complete set of six analyses is shown in Fig. 5 for the lowest level. The concentric circles are drawn at intervals of 10 n mi (18.5 km) from the center of the storm. Figure 5 shows strongest updrafts concentrated in a ring at approximately 10 n mi from the center with maximum updraft exceeding 2 m s⁻¹ in the northwest quadrant. (Inez was moving towards the west-northwest on 28 September.)

![Diagram](image-url)
Fig. 7. Radial profiles for four levels of vertical motion versus radius from hurricane center. The solid line refers to the aircraft-determined vertical motions and the dashed line is with the correction for large-scale continuity, the value $\bar{W}$ in the top of Fig. 8. Maximum tangential winds taken from the radial analyses of the parameter are indicated at the radius at which they were found.

This ring of upward motion coincides with the location of the eye wall as identified by the aircraft radar. The analysis shows marked descent (1.0 m s$^{-1}$) within the eye, and also weaker subsidence in large areas of the storm beyond about 30 n mi radius.

The tangential velocity analysis (Fig. 5) shows maximum speeds of greater than 60 m s$^{-1}$ to the east of the storm center. Maximum speeds in excess of 80 m s$^{-1}$ were analyzed at the 2.5 km level (not shown). Figure 5 shows the radial inflow to be expected at this lower level in the storm; however, some marked asymmetries are present in the analysis. The tangential and radial wind analyses are similar in appearance to those of Shea and Gray (1973), which are composites of several storms. It is doubtful that the horizontal wind directions measured by the aircraft are of sufficient accuracy to allow the radial wind field to be used for convergence calculations as a check on the analyzed vertical motions. The typical structure of a hurricane is shown in the temperature, mixing ratio, and $D$-value analyses of Fig. 5.

The ring of ascent in the eye wall cloud region, along with pronounced descent in the eye and weaker descent at larger radii, is also evident at the upper three levels. In Fig. 6 these features are evident at the 3.5 km level. A nearly complete ring of subsidence at 20 to 30 n mi radius surrounds the updraft associated with the eye wall. Figure 6 shows tangential wind, temperature, and mixing ratio analyses at 3.5 km. These analyses may be compared with their counterparts at 0.5 km (Fig. 5).

Because the vertical motion computation essentially ignores scales of motion greater than about 40 n mi across, the method of determining vertical velocities from aircraft data can lead to significant underestimates of the strength of updrafts and to overestimates of the descending motions. Miller (1964) used budget study calculations to show that a mean ascent of about 0.6 m s$^{-1}$ occurred over an annulus between 10 and 40 mi from the center of Hurricane Donna (1960). Similarly, an approximate mass budget has been calculated for Hurricane Inez by using the mean radial motion profile for the lowest (0.5 km) flight level and by assuming that the flow in the boundary layer is maximum inward at the surface, decreases linearly to zero at 1.0 km, and remains zero above that level. The mean ascent $\bar{W}$ over an annulus of width 40 mi, centered on the radial distance of the aircraft, was computed at successive radial distances for each of the four flight levels. The values of $\bar{W}$ thus determined may be added to the aircraft-determined vertical motions $W_e$, hereafter referred to as the convective vertical velocity, in order to obtain a corrected value $\bar{W}$ of the vertical motion that should correspond more closely to the true vertical motion.

The mean radial profiles of vertical motion (Fig. 7) show both the convective component $W_e$ (solid line) and the corrected value $\bar{W} = W_e + W_c$ (dashed line). The correction for mean ascent is small compared to values of $W_e$ in the eye wall region, but does result in decreasing the strength of the central downdraft while increasing the updraft in the eye wall. The profiles show great similarity between levels, especially in the eye wall region. The strongest updraft at each level coincides closely with location of maximum tangential wind at that level. The eye wall updraft is
greatest at the 2.5 km level (where the tangential wind is also maximum) and has a corrected value of about 3.7 m s^{-1}. The downdraft in the eye is fairly uniform with corrected values of about 1.5 m s^{-1} at the upper three levels but with maximum corrected downdraft of approximately 2.0 m s^{-1} at the 0.5 km level. At the upper three levels, a zone of weaker downward motions is indicated between 10 and 20 n mi radius, outside the eye wall cloud. This feature is most pronounced at the 2.5 km level, where corrected mean downdraft of 1.0 m s^{-1} occurs, and may be part of a compensatory flow pattern for the intense convective updrafts present in the nearby eye wall cloud region.

Figure 8 is a composite radius-height analysis of the convective vertical motion \( W_c \) which has been constructed from the four mean radial profiles of Fig. 7. Also shown are the corrections for large-scale convergence \( \bar{W} \) at each level at the top of the figure and, for the maximum eye downdraft and eye wall updraft, the uncorrected and corrected vertical profiles at the right-hand margin of the figure.

Eyewitness accounts (H. F. Hawkins, personal communication) and movies of the eye of Inez on this day indicate that the eye was relatively calm and cloud-free at the higher three flight levels, but that considerable cloudiness and turbulence was encountered at the lowest (0.5 km) level. Moreover, some of these clouds were characterized as being decidedly convective in nature. These observations cast some doubt upon the magnitude of downdraft obtained by our analysis at the lowest level. However, the steep vertical lapse rate of absolute humidity observed in the eye is consistent with strong subsidence in this very intense storm.

Descent of this magnitude in the eye is also not indicated by the numerical hurricane models currently being developed at NHRL (Rosenthal, 1971; R. Jones, private communication). The asymmetric model of R. Jones generates a maximum descent of about 0.5 m s^{-1}. Both the symmetric and asymmetric models give eye wall ascent rates of a few meters per second in magnitude, in agreement with our result. Gray and Shea's (1973) composite of real hurricane data taken from several storms also shows subsidence in the eye of about 0.5 m s^{-1}, along with ascent of about equal magnitude in the eye wall. Hurricane Inez, being an especially intense storm, probably had appreciably
Fig. 9. Same as Fig. 5 but for Hurricane Inez on 27 September 1966 at 3.5 km, 1616 to 1956 GMT, and for the vertical velocity, tangential velocity, temperature, and D-values.

Fig. 10. Same as Fig. 7 but for three levels on 27 September 1966.

stronger ascent and descent rates than the average in Gray and Shea’s composite.

b. Hurricane Inez: 27 September 1966

Inez had not yet reached its full strength on the 27th, although it was already an intense and compact hurricane. On this day, the storm passed directly over the island of Guadeloupe (17°N, 61°W), where surface winds in excess of 40 m s⁻¹ were reported. The proximity of the storm to land prevented execution of a flight at the 0.5 km level; otherwise, the three levels flown by DC-6 aircraft were the same as those of the 28th.

The convective vertical motions (Figs. 9 and 10) were less than those of the 28th at the 2.5 and 5.5 km levels but approached those of the 28th at the 3.5 km level. (No correction for mean vertical motion has been made in these figures.) In Fig. 9, maximum ascent of nearly 4 m s⁻¹ at the 3.5 km level is shown in the vertical velocity analysis just south of the eye, in close proximity to the maximum tangential winds of 49 m s⁻¹
at this level. A warm core is evident in the temperature analysis (Fig. 9), but the central value is about 2°C less than on the 28th (Fig. 6). The height gradient (Fig. 9) is weaker than on the 28th as expected.

3. Hurricane Debbie: 20 August 1969

This storm has received much attention in the literature because of the Project STORMFURY seeding experiments that were carried out in the eye wall cloud region on 18 and 20 August (Gentry, 1970; Hawkins, 1971; Black et al., 1972). On 20 August, only one of the DC-6 aircraft was properly equipped to measure and record the necessary parameters for computing vertical velocities. This aircraft flew a series of 10 passes through the eye of the storm at about 3.5 km (650 mb). Eight of these passes were from northeast to southwest, while the remaining two were from southeast to northwest (the direction of storm movement).

Minimum sea level pressure in Debbie on 20 August was 950 mb, thus Debbie was not as intense a storm as Inez on 28 September. Also, the eye of Debbie was 12 mi in diameter and therefore larger than the eye of Inez. Most of the passes were flown between the second and fifth seedings. Changes in the storm structure, as noted by Hawkins (1971), were judged not to have been very

Fig. 11. Same as Fig. 9 but for Hurricane Debbie, 20 August 1969, at approximately 3.5 km, 1357 to 1946 GMT. The four fields are the same as in Fig. 9.

Fig. 12. Same as Fig. 7 but for the 3.5 km level in Hurricane Debbie.
great during this interval, and it is likely that the analyses presented here are fairly representative of the unseeded state. However, the complex structure of the eye reported by Hawkins and Black et al. is not evident in the analyses because of the time scale of the composites and the 5.0 n mi grid spacing used.

The essential features of Hurricane Debbie are shown in Fig. 11. Tangential winds and vertical motions have an almost circularly symmetric distribution but with slightly higher speeds in the southern quadrant. Maximum upward vertical velocities in the eye wall are only slightly more than 1 m s⁻¹, but there is evidence of substantial descending motion in the eye (Fig. 12) although no correction for mean vertical motion has been applied. Although the vertical and horizontal motions in Debbie are weaker than those in Inez, the vertical motion profiles are very similar in character, with strongest updraft coinciding closely with the radius of maximum wind speed. Surprisingly, the eye of Debbie on 20 August is just as warm (temperature analysis, Fig. 11) as the eye of Inez on 28 September. Similar vertical motion profiles (not shown) were obtained for Debbie on 18 August.

d. Hurricane Ginger: 26 and 28 September 1971

Hurricane Ginger was a large, diffuse storm of marginal hurricane intensity. Cloud seeding experiments were conducted in this storm on 26 and 28 September, but since a well-defined eye wall cloud structure was absent, the seeding operations were carried out in spiral bands at distances greater than 60 n mi from the center. A description of the meteorological history of this storm and an analysis of the seeding operations have been made by Hawkins et al. (1972).

Minimum sea level pressure in Ginger was 976 mb on 26 September and 980 mb on 28 September. Movement of the storm was westward on 26 September but
northwestward two days later. On each of these days, DC-6 aircraft flew three series of radial passes through the center. Changes in storm structure due to seeding were judged to have been slight.

Analyses prepared from the 1.6 km flight on the afternoon of 26 September are shown in Fig. 13. Both maximum updrafts and tangential winds are found at 40 to 50 n mi radius, indicating the unusually large size of the poorly defined eye. The maximum wind speeds only slightly exceed 30 m s⁻¹. The pattern of subsidence in the central part of Ginger shows marked asymmetry, with greatest descent of 0.5 m s⁻¹ displaced 20 n mi southwest of the presumed center of the storm. The ascent pattern is also highly asymmetric, with maximum updraft of 0.7 m s⁻¹ located 55 n mi southwest of the storm center (vertical velocity analysis, Fig. 13). The temperature analysis shows a rather weak warm core structure.

Mean radial profiles of vertical motion (Fig. 14) for Ginger show the relative weakness of this storm as compared to Inez or Debbie. It is interesting to note that the radius of maximum updraft has increased by approximately 15 n mi between 26 September and 28 September. The radius of maximum tangential winds also increased by about this amount between the two days.

5. Summary and conclusion

We have developed a computer program package which uses NOAA DC-6 aircraft data to produce a set of analyzed data fields for tropical cyclones. It is likely that these analyses do not show the details of storm structure that could be obtained by a painstaking hand analysis. The objective analyses do appear, however, to have sufficient accuracy to permit use in many types of dynamical computations and diagnostic studies. They provide a useful set of analyses for comparison with numerical models which simulate the structure and dynamics of tropical cyclones. Moreover, these analyses can be generated at modest expense and in a relatively short time once the aircraft data tapes have undergone their initial processing. More detailed analyses of selected areas of a tropical cyclone may be produced by reducing the analysis grid spacing; we have done this experimentally for 1.0 n mi grid spacing.

A unique feature of the set of six analyses is the vertical velocity analysis. In tropical cyclones, systematic vertical velocity profiles become evident when the small-scale fluctuations are eliminated by smoothing and compositing of the data. The cumulus updrafts and downdrafts appear to be superimposed upon a larger band scale of motion that is more stable and coherent in time than the individual cloud features. The most persistent features of this band scale motion are the annular ring of ascent associated with the eye wall and the descent both within the eye and just outside of the eye wall cloud area. Maximum ascent and descent rates for band scale motions reach a few meters per second in very intense hurricanes. The radius of maximum updraft coincides very closely with the radius of maximum tangential winds in the mean radial profiles of the three storms we have investigated, but maximum vertical and tangential motions are not always found in the same quadrant of these storms.

The analyses of horizontal motion, temperature, mixing ratio, and D-values show the typical structure of tropical cyclones while also indicating the major asymmetries present in individual storms and the variation in size and intensity among storms.

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