An Assessment of Omega Dropwindsonde Data in Track Forecasts of Hurricane Debby (1982)

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Abstract

Omega dropwindsondes (ODWs) were released from two NOAA WP-3D aircraft to measure the environmental wind field in the middle and lower troposphere within 1000 km of the center of Hurricane Debby on 15 and 16 September 1982. The observations were coded in standard formats and transmitted from the aircraft to the National Hurricane Center (NHC) and the National Meteorological Center (NMC) before operational forecast deadlines. The ODW winds clearly indicated the location and strength of a midtropospheric trough in the westerlies that was the major synoptic-scale feature affecting Debby's motion. On 16 September, the dropwindsondes also identified a smaller scale cutoff low in the northern part of the trough. The cutoff low that was centered about 500 km to the north northwest of Debby affected the hurricane's motion from midday on the 16th to midday on the 17th.

The ODWs provided NHC with timely information that was used subjectively in determining the official forecasts of Debby's track. The potential of the ODWs to improve the track models that serve as guidance for the forecasters at NHC depends upon both the quality of the ODW data and the ability of the operational objective analyses to respond to the ODW data. In 1982, the objective analysis that initialized several of the track models was a spectral analysis with a global domain. At 500 mb, the scale of the wind circulations of Debby and the cutoff low was approximately 500 km. The global operational objective analysis did not resolve these important features. The ODW data can help to improve the objective guidance for the hurricane forecasters only if the operational objective analyses and the track models are designed to make use of the ODW information. To obtain the data needed to revise current models and to develop new models, ODW experiments are planned in the next few years when hurricanes threaten the Atlantic or Gulf coasts of the United States.

1. Introduction

In the last two decades, the population in many coastal areas that could be affected by tropical cyclones has increased rapidly. The ability to forecast tropical cyclones, however, has not kept pace with the resultant need for improved warnings and longer lead times. In a few particularly vulnerable areas of the United States, the time required for complete evacuation exceeds the state-of-the-art lead time of 12 hours of daylight provided by the forecaster's warnings. Although significant improvements in 24-hour forecasts of tropical cyclone tracks occurred from 1959 to 1966 in the Atlantic (Dunn *et al.*, 1968), the rate of improvement of the forecasts has decreased and average seasonal errors for 24-hour forecasts have possibly reached a plateau near 200 km (Neumann, 1981). A similar trend has been observed in the western Pacific, where average seasonal errors for 24-hour track forecasts decreased from 1966 to 1971 (Jarrell *et al.*, 1978); now, they are also approaching a value of about 200 km (Harrison and Fiorino, 1982). The inability to achieve further improvements has caused considerable concern among forecasters and research meteorologists as well as those government officials who are involved with community preparedness.

Although operational tropical cyclone track forecasting remains rather subjective, the forecaster's decision processes are influenced by a number of objective prediction models (Neumann and Pelisser, 1981). As the skill of these models improves, it seems likely that the average forecast errors of tropical cyclone motion will be reduced. The skill of the objective models depends to a large extent upon the quality and quantity of observations of the environmental flow around a storm. The data base currently available over the tropical and subtropical oceans consists of relatively dense coverage in the lowest 2 km, where surface observations are obtained from ships, and winds are determined from the motion of low clouds viewed by satellite. Coverage is also extensive in the layer from 9 to 12 km, where wind observations are derived from aircraft navigation systems and from high cloud motions that are observed by satellite. Few observations are available at the midtropospheric levels. George and Gray (1976) and Neumann (1979) have shown, however, that storm motion is best correlated with midtropospheric patterns of wind and geopotential height on the periphery of tropical cyclones. Neumann (1981) has argued that a major reason for the slower rate of improvement of track forecasts in recent years is that advances in satellite technology and dynamical modeling were offset by a decline in the quality of midtropospheric analyses in the tropics and subtropics that occurred during the late 60s and 70s. Neumann suggested that the decrease in quality of the analyses was due to the closing of several land and ship radiosonde stations, fewer observations from commercial aircraft as jets became more prevalent than prop aircraft, and the operational use of objective analyses rather than carefully prepared hand analyses.

Dynamical tropical cyclone models that are being used in the Atlantic and western Pacific basins have the potential for providing guidance that will lead to improved official forecasts (Hovermale and Livezey, 1977; Elsberry, 1979; Sanders *et al.*, 1980; Harrison and Fiorino, 1982). New formulations of statistical models proposed by Neumann (1983) and Sha-

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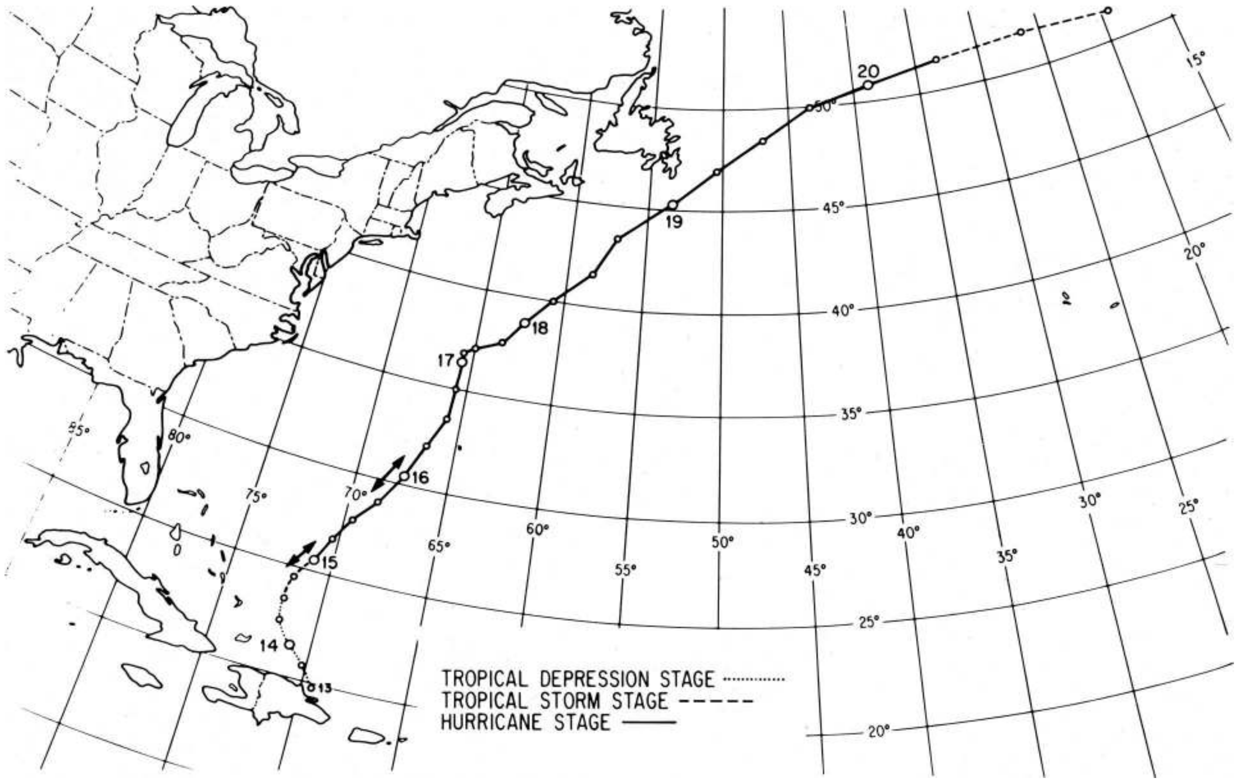

FIG. 1. Best track positions of Hurricane Debby. The positions are represented by open circles and have been plotted four times each day at 0000, 0600, 1200, and 1800 GMT. The date is indicated next to the location of the storm at 0000 GMT for that day; except on 13 September, when Debby first became a depression, it is plotted next to the 1200 GMT position. The approximate times of the two ODW experiments are indicated by the arrows.

piro and Neumann (1984) may also provide better guidance. Before the potential of the dynamical and statistical track models can be fully achieved, however, midtropospheric observations over the tropical and subtropical oceans must be improved. Some progress is being made toward reducing the data deficiencies through satellite remote-sensing techniques. These techniques are still under development for geostationary satellites, and it may be several years before they can contribute to improved operational track forecasts.

Currently, the ODW is the only instrument with proven capability for obtaining midtropospheric wind data in remote ocean areas. ODWs are launched from aircraft and measure wind, temperature, humidity, and pressure as the sondes fall to the ocean surface (Scribner and Smalley, 1981). They have been used in all of the field experiments of the Global Atmospheric Research Program (GARP), particularly during the special observing periods of the Global Weather Experiment (Julian, 1982).

In this paper, an experiment that used ODWs to determine the wind field in the middle and lower troposphere on the periphery of Hurricane Debby of 1982 is discussed. Observations were obtained from ODWs released from the two NOAA WP-3D aircraft in the middle or upper troposphere. The ODWs descended to the ocean surface by parachute at about 25 $mb \cdot min^{-1}$ ($\sim$300 $m \cdot min^{-1}$). Instruments on the sondes measured pressure, temperature, and relative humidity at one-second intervals and phase angles from eight worldwide Omega navigational stations at 10-second intervals. From the phase angles, the location of an ODW was determined by a computer on the aircraft. Winds were calculated from successive positions. The ODW data were transmitted from the aircraft to the National Hurricane Center (NHC) and the National Meteorological Center (NMC) during the flights. The impact of the data on the operational objective analyses, a statistical and a dynamical model, and the official hurricane forecasts is discussed. Important ODW characteristics and the general strategy for specifying aircraft flight tracks and releasing ODWs are also described.

2. Aircraft flights in Debby

The disturbance that ultimately became Debby formed over Africa in early September and tracked westward across the Atlantic with little change in strength. As the disturbance began to recurve north of Hispaniola on 14 September 1982, it was named Tropical Storm Debby. Debby continued to strengthen and reached hurricane intensity on 15 September as it headed toward the northeast (Fig. 1). Details of Debby's most important characteristics are contained in Clark's (1983) summary of the 1982 Atlantic hurricane season.

The design of optimum flight patterns depends upon tropical cyclone location and direction of motion, airport locations, aircraft speed and range, location of nearby radiosonde stations, ODW performance characteristics, and

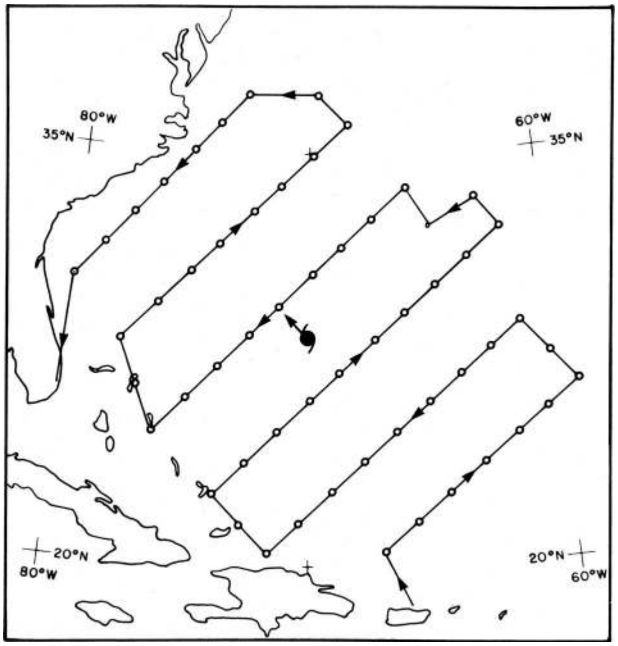

FIG. 2. Idealized flight pattern for dropwindsonde experiment that incorporates ideas discussed in the text. One aircraft starts in Bermuda and flies to Miami at the end of the mission. The second aircraft takes off from San Juan and completes its mission in Bermuda. The location of a hypothetical hurricane that is moving toward the northwest is at 28°N, 70°W. The locations of ODWs are represented by open circles.

operational and research uses of the observations. For research, it is desirable to have flight tracks that provide uniform coverage over as wide an oceanic area as possible. Since a tropical cyclone tends to be steered by the environmental current in which it is embedded (e.g., George and Gray, 1976), gradients of the wind field and thermodynamic variables perpendicular to the storm track are particularly important for determining storm motion. Thus, it is advantageous to orient tropical cyclone flight patterns with respect to the storm heading so that cross-track gradients can be measured in the least amount of time. Parallel flight legs were separated by about 335 km (3° latitude) and ODWs were released at intervals of 165 to 170 km (1.5° latitude) along the track. An example of an idealized flight pattern that incorporates these ideas and that uses two aircraft is shown in Fig. 2. The flight tracks do not pass through the center of a tropical cyclone because ODW data collected in the interior of a storm would probably be strongly influenced by convective scales, and because a U.S. Air Force reconnaissance aircraft is assumed to be in position to gather information on the tropical cyclone's intensity. To insure that the observations are as representative as possible of the synoptic scale, ODWs may be released up to three minutes before or after planned locations to minimize the influence of deep convection on the data.

Two ODW experiments were conducted at approximately 0000 GMT on 15 and 16 September, when Debby's minimum central pressure was 993 and 966 mb, respectively. The flight patterns flown are illustrated in Figs. 3a and 3b. On both days, two aircraft were used. On the first day, however, one of the aircraft was primarily collecting data in the inner core of the storm as part of other experiments. Consequently, the aircraft tracks on 15 September deviated considerably from those shown in Fig. 2. With only one aircraft dedicated to the ODW experiment, the pattern was designed to gather ODW data north, east, and west of the storm in areas where the ODWs supplemented the radiosondes at Bermuda and along the southeast coast of the United States. The flight tracks on 16 September more nearly resemble the idealized patterns. The differences between the patterns in Figs. 2 and 3b are largely due to constraints resulting from Debby's position and motion at 0000 GMT and the preflight location of both aircraft in Miami.

The takeoff time for the Debby flights was selected so that all of the data could be transmitted from the aircraft to NMC before the 0320 GMT cutoff time for the 0000 GMT global objective analysis. The aircraft missions were planned to last approximately nine hours. With 15 hours of crew rest, the patterns could be repeated on a second or third day and still be in proper phase with the operational schedule at NMC. During the Debby missions, the aircraft climbed to the 500 mb level soon after takeoff and gradually reached about 380 mb near the end of the flight as fuel was burned. At these altitudes, the aircraft have cruising speeds of about 165 $m \cdot s^{-1}$, so that the total range in nine hours is about 5300 km. With a fall speed of 300 $m \cdot min^{-1}$, ODWs launched from typical altitudes of 5.5 to 8.0 km reach the ocean surface in 18 to 27 minutes. The aircraft flies the 165 to 170 km between successive ODW launch points in about 17 minutes. Thus, only one or two ODWs from each aircraft need be in the air simultaneously. Since ODWs are designed to transmit data on one of three frequencies, those with one frequency can be reserved for quick launch as backups should it be impossible to compute realistic winds from one of the other sondes. Backup ODWs were used at about 10–15% of the launch points, because either Omega signals were not received on the aircraft or because their parachutes did not open.

During the Debby flights, wind, temperature, and humidity at mandatory pressure levels were coded in the standard dropwindsonde code and transmitted to NHC and NMC via the aircraft satellite data link that was described by Pifer *et al.* (1978). Flight-level observations in Reconnaissance Code (RECCO) format were also transmitted at 15 to 20 minute intervals. Almost all of the data were received in time to be used by the hurricane forecasters at NHC and to be included in the NMC objective analyses.

To obtain reliable wind estimates, the phase angles were smoothed using a three-minute filter. A wind computed from the filtered phase angles represents the average wind in a pressure interval of about 75 mb. Because of the filtering, winds are unavailable for the 35 to 40 mb layers just below the aircraft and just above the ocean surface.

The height of the sondes as a function of pressure is not a measured quantity. In principle, the height can be calculated from the hydrostatic equation using sonde pressure and thermodynamic data. No attempt was made, however, to compute heights during the Debby missions. Postflight integrations of the hydrostatic equation, downward from flight-level, produced estimates of surface pressure by successive ODWs that increased linearly with time. Comparison of these ODW surface pressures with the surface analyses pro-

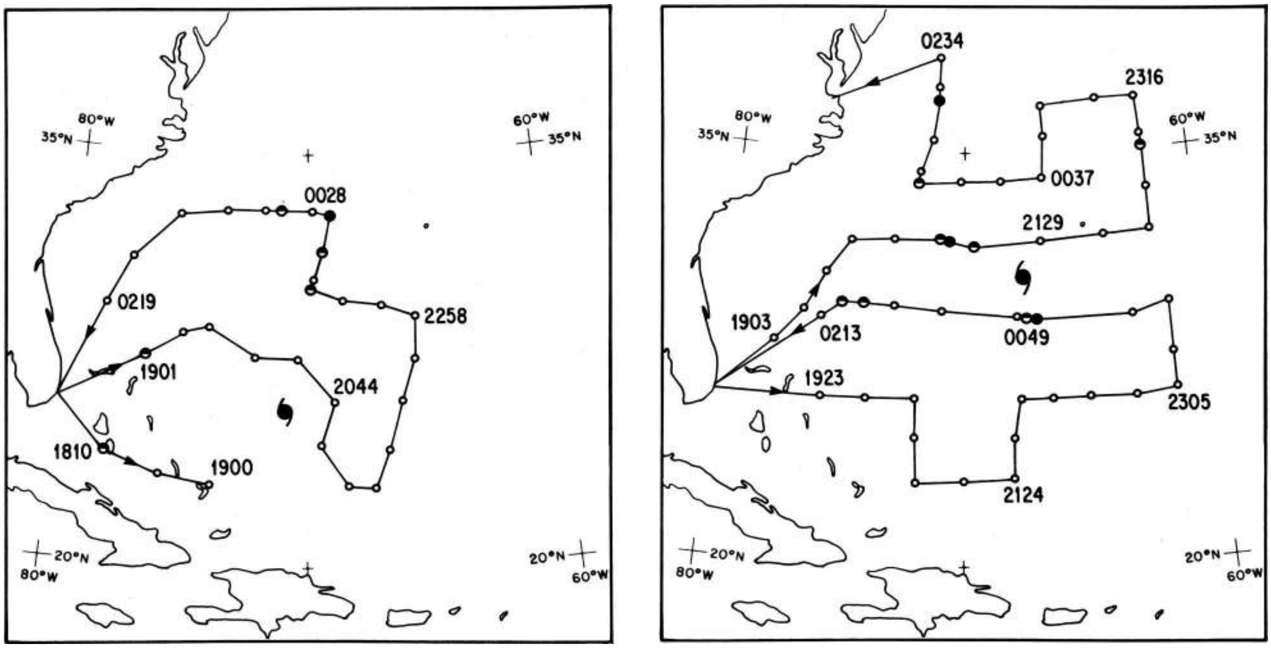

FIG. 3. Flight tracks for dropwindsonde experiments corresponding to the approximate map time of 0000 GMT on (a) 15 September and (b) 16 September 1982. The open circles indicate the location of each ODW that recorded winds and thermodynamic variables. The black circles indicate the location of sondes that failed. The circles with the top half darkened identify the location of ODWs that recorded only thermodynamic variables. The time in GMT of selected ODWs is shown. The hurricane symbol indicates Debby's location at 0000 GMT.

duced at NHC revealed that the linear trend was erroneous and was probably caused by a slight drift, with time, of the flight-level pressure sensor or radar altimeter. Upward integrations from the surface could not provide useful heights because ODW estimates of surface pressure have a typical root mean square error of about 6.5 mb (Franklin, 1983). In addition to this error, ODW surface pressure measurements frequently have a negative bias of about 7 mb (Julian, 1982). ODWs with the pressure bias were recognized during the flights and corrections were applied subjectively. As a result of these uncertainties in the pressure sensor, the temperature and humidity may have been slightly misaligned in the vertical. The winds were not significantly affected, since they represent averages over 75 mb.

The absence of reported heights of mandatory pressure levels during the flights may have affected the impact of the ODW data on the NMC objective analyses and, consequently, the forecast models. To assess the influence of including heights in the reported data, a set of heights, considered more reliable than those from the real-time flight data, was calculated. In the corrected flight-level data, the drift of the aircraft sensor was removed. Analyses computed with and without these heights are discussed in sections 4 and 5.

3. ODW analyses

The 500 mb analyses of ODW and radiosonde observations on 15 and 16 September are shown in Figs. 4a and 4b. All of the ODW observations that became part of the operational data base at NMC are plotted on the maps for 0000 GMT, even though the first ODW of each nine-hour flight was released about 1900 GMT on the previous day and the last was dropped about 0230 GMT. The locations of the ODWs that were released at times other than 0000 GMT have not been adjusted to account for storm motion. Flight level winds near 500 mb could have been added to the maps for the early parts of the flight tracks, but have been omitted to highlight the ODW winds. The 500 mb analyses show that the operational ODWs are capable of defining the synoptic-scale flow patterns on the periphery of a tropical cyclone. Some subsynoptic-scale features can also be identified.

On both days, the ODWs were received and plotted at NHC in time to be used subjectively in the preparation of the 0400 GMT official tropical cyclone forecasts. Before issuing their official forecast on the 15th, forecasters had to decide whether Debby would continue to recurve in advance of the trough in the westerlies, just to the east of the Carolinas, or whether it would be steered westward by the anticyclone over the southeastern United States. The ODWs clearly showed that the trough extended southward to 20°N and that Debby's circulation was embedded in the southwesterlies to the east of the trough (Fig. 4a). With this information, the forecasters were able to predict correctly that Debby would move northeastward (Clark, 1983).

The wind observations at 0000 GMT on the 16th indicate that the trough in the westerlies had strengthened considerably in the previous 24 hours. It appears that the part of the trough to the north northwest of Debby's center had either just cut off or was about to cut off from the westerly flow at 35° to 40°N. The close proximity (~500 km) of the center of

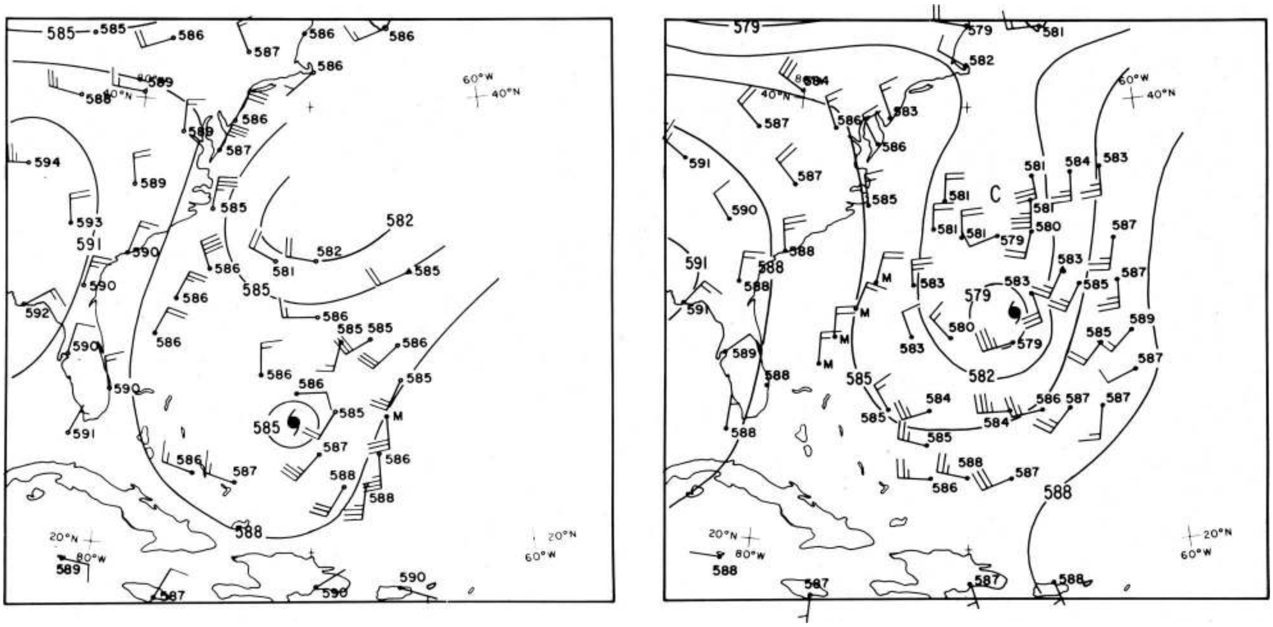

FIG. 4. 500 mb analyses at 0000 GMT on (a) 15 September and (b) 16 September 1982. Geopotential heights in decameters are shown to the right of the location of each wind observation. Height contours are at 30 m intervals. Missing heights are indicated by M. Wind speeds of 5 $m \cdot s^{-1}$ are represented by a full barb and speeds of 2.5 $m \cdot s^{-1}$ by a half barb. There is no barb for winds $\leq 1\ m \cdot s^{-1}$. Debby's location at 0000 GMT on the 15th and 16th is indicated by a hurricane symbol. The center of the cutoff low on the 16th is denoted by the letter C. The reported value of the 500 mb geopotential height at Bermuda for 0000 GMT on the 15th was 588 dam. The value of 585 dam shown in the figure was calculated from the hydrostatic equation with the operational thermodynamic observations. Bermuda's location is represented by a triangle.

this circulation to Debby suggests that the hurricane might begin to move in a counterclockwise direction around the cutoff low. Such a change was actually observed from 1200 GMT on the 16th to 0600 GMT on the 17th (Fig. 1).

4. Impact of the ODWs on operational objective analyses

Most of the operational objective track models that serve as guidance for the forecasters at NHC are initialized with NMC's operational objective analyses. The track models that are discussed in this paper use the NMC global analyses. The potential of the ODWs to improve the track models depends not only upon the quality of the ODW data, but also upon the ability of the operational objective analyses to resolve the scales of motion identified by the ODW data. The current global operational objective analysis at NMC uses a spectral method (Hough functions) developed by Flattery (1971). NMC plans to replace the spectral analysis with a global optimum interpolation (OI) scheme (Bergman, 1979) before the end of 1984. The ability of both analyses to respond to the ODW observations is examined in this section. The shortest wave resolved by the spectral analysis is 15° longitude (there are 24 Fourier components in the horizontal). The grid size of the OI is 330 km in the north–south direction and approximately 425 km in the east–west direction at the latitudes of Debby's location on the 15th and 16th. The OI has 30 wave rhomboidal truncation and was designed to have about the same resolution as the spectral analysis. The global objective analyses are updated at 0000, 0600, 1200, and 1800 GMT and use data taken within three hours of these times. Thus, ODWs released before 2100 GMT are incorporated in the 1800 GMT analysis. They only affect the 0000 GMT analysis to the extent that the six-hour forecast from 1800 GMT serves as the first guess for the 0000 GMT analysis.

To assess the impact of the ODW observations on both of NMC's global objective analyses, analyses for 0000 GMT on the 15th and 16th have been computed without ODW data, with the operational ODW data, and with the operational ODW data and geopotential heights at mandatory pressure levels. The geopotential heights were calculated with corrected flight-level data about two months after the experiment and have about the same accuracy that could be achieved in real time in future experiments. The objective analyses responded to the ODW observations in a similar manner on both days. Important points are illustrated with analyses from 16 September, when both aircraft were dedicated to the ODW mission.

The first guess analysis for 500 mb, shown in Fig. 5a, has a synoptic-scale trough near 70°W that extends from about 20° to 45°N. The trough line is in the same general location as the trough line indicated by the observations (Fig. 4b), but near 30°N, it is about 300 km too far to the west. Within the trough and west of Debby's center, there is a cutoff low. The hurricane circulation is not evident, and at the location of the hurricane, the 500 mb wind in the first guess is from the south southwest about 13 to 14 $m \cdot s^{-1}$. There is a col near 36°N, 68°W in approximately the same location as the small-scale cutoff low in Fig. 4b.

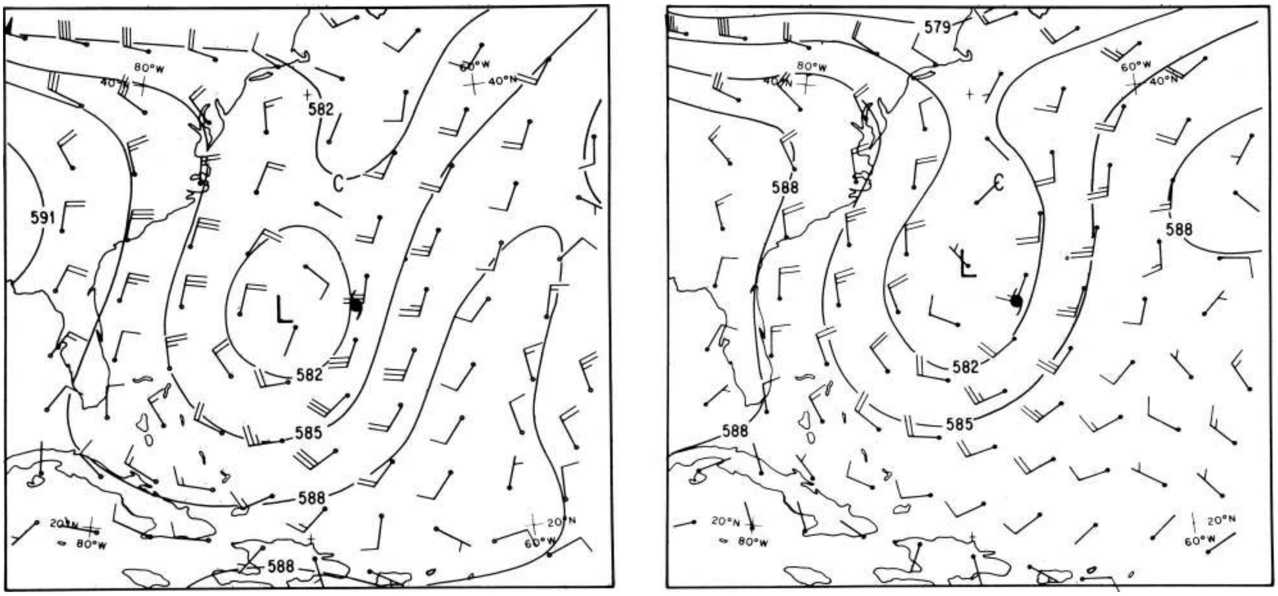

FIG. 5. 500 mb analyses at 0000 GMT on 16 September 1982 for (a) the first guess analysis and (b) the spectral analysis initialized with the operational ODW data and ODW geopotential heights computed 2 months after the experiment. The wind barbs are plotted at the grid points of the standard NMC grid. The letter C and the plotting convention for the winds and height contours are the same as in Fig. 4.

The spectral and OI analyses that were computed without any ODW observations in the data base improve the orientation and position of the synoptic-scale trough relative to the first guess (not shown). When the ODW observations are added to the data base, both objective analyses refine the analysis of the synoptic–scale trough in the area of the aircraft flights. Comparison of the spectral analysis in Fig. 5b with the subjectively-drawn analysis in Fig. 4b shows, however, that the objective analysis is unable to resolve either the hurricane circulation or the cutoff low in the northern part of the trough. At Debby's location, the 500 mb wind is from the south–southwest at 7 to 8 $m \cdot s^{-1}$, in better agreement with the instantaneous storm motion than the corresponding 500 mb wind in the first guess. The OI analysis with all of the ODW observations (not shown) is very similar to the spectral analysis. The inability of the objective analyses to resolve the mid-tropospheric hurricane circulation can be partially explained by the distribution of the ODW observations near Debby and the hurricane's relatively small scale. Unfortunately, the ODWs dropped in Debby's northwest quadrant did not work properly. Two of the three ODWs dropped about 250 to 400 km to the northwest of Debby's center (Fig. 3b) were able to measure only thermodynamic data. The third ODW failed to transmit any useful data to the aircraft. None of the observations from these ODWs was transmitted to NMC. In the absence of any observations in Debby's northwest quadrant, it is not surprising that the objective analyses are unable to resolve the hurricane circulation. The inability of the objective analyses to analyze the cutoff low near 36°N, 68°W cannot be attributed to lack of data. There were seven ODWs that helped to identify the circulation around the low. The low had a spatial scale of about 500 km, approximately the same as the scale of Debby's circulation. It appears that the analyses are unable to completely resolve features on this scale. Thus, Debby's circulation probably would not have been properly analyzed even if the ODW's that were dropped in the hurricane's northwest quadrant had functioned properly.

The general impression gathered from comparisons of hand–drawn and objective analyses is that the latter are relatively insensitive to the additional information provided by ODWs. The addition of the ODWs to the data base results in small changes on the synoptic scale in both the spectral and OI analyses. The two analyses are very similar within 1000 km of Debby's center; however, neither objective analysis is able to resolve spatial scales on the order of the cutoff low and Hurricane Debby.

5. Impact of ODWs on objective track models

In this section, the impact of the ODW observations on both an experimental statistical model that predicts storm motion based upon 500 mb heights and on NMC's operational dynamical track model—the movable fine mesh model (MFM) described by Hovermale and Livezey (1977)—is examined.

The experimental statistical model uses the stepwise screening regression technique to relate future tropical cyclone displacements to current 500 mb geopotential heights within a 15° latitude circle (1666 km) around the cyclone position. The screening was done on a grid of 2.5° latitude (278 km) spacing that has been rotated to conform with the cyclone motion over the past 12 hours. Developmental data consisted of operational NMC 500 mb analyses from 1962 to 1982. The model statistics do not consider cyclone motion

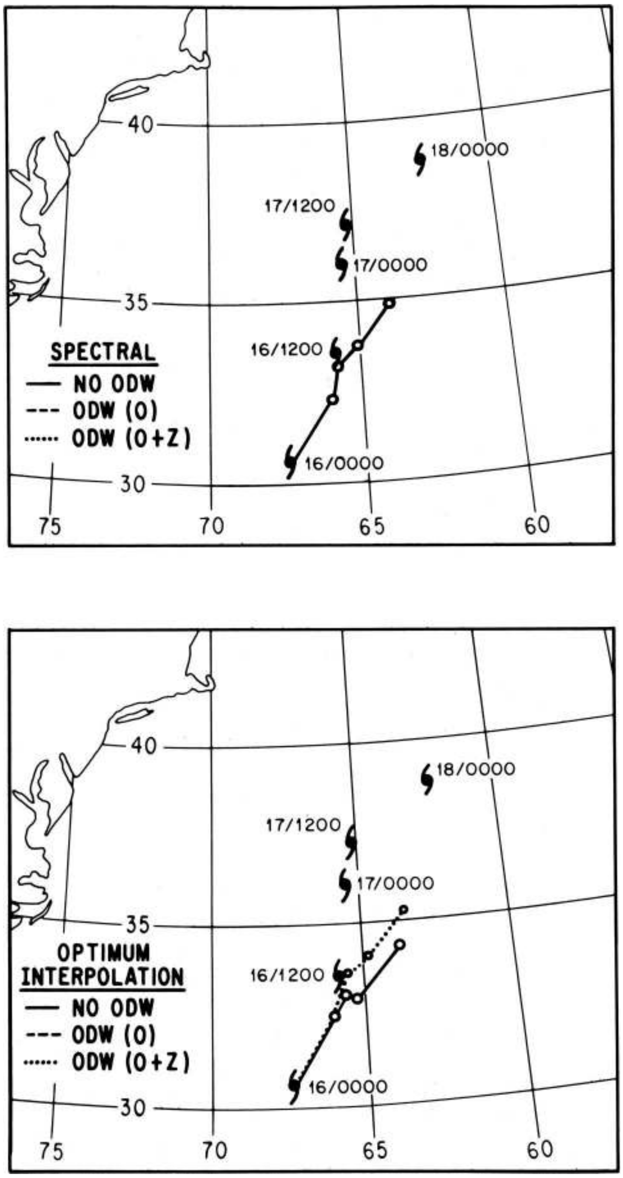

FIG. 6. Experimental statistical model forecasts from 12 to 48 hours of the track of Hurricane Debby for the initial time of 0000 GMT 16 September. The top part of the figure shows the forecasts when the experimental model was initialized with the spectral analysis. The bottom part shows track forecasts for the model when it was initialized with the OI. Debby's positions at 12-hour intervals are indicated by the hurricane symbols. ODW (O) indicates that the operational ODW data were used in the analysis. ODW (O + Z) indicates that the operational ODW data and the geopotential heights computed 2 months after the experiment were included in the analysis. The forecast tracks for the three different initializations of the spectral analysis are nearly the same and appear as a single line. The OI forecasts initialized with no ODW and ODW (O) are also virtually identical and are represented as a single line.

(other than in the orientation of the grid), forecast height fields, or climatology. The model is designed to test the sensitivity of the statistical method to improvements in initial geopotential height analyses on the synoptic scale around the cyclone. Fig. 6 shows forecast results from both the spectral and OI analyses for 0000 GMT on 16 September. Model results were computed with each analysis initialized in three ways: with no ODW data, with the operational ODW data, and with the operational ODW data plus heights. The correlations between the initial height field and subsequent cyclone displacement tend to decrease with time. For this reason, the forecast displacement at the longer time periods is largely determined by the mean motion of the tropical cyclones in the development sample. The forecast positions for the spectral analyses are nearly identical and appear as a single line in Fig. 6. The forecast positions based upon the OI analyses have slightly larger differences. The 48-hour forecast initialized with the OI analysis and the operational ODW data and heights is more than 50 km to the north of the 48-hour forecasts determined from all of the other analyses. The difference is not particularly large in view of the 500 km average length of the tracks of the six 48-hour forecasts shown in Fig. 6. The relatively small differences in the forecasts add further support to the conclusions in section 4 that the NMC analyses are rather similar and are not changed significantly by the ODW observations.

The MFM is a 10-level model with a 3000 km square domain and 60 km grid that can be centered on the location of a tropical cyclone. The model is initialized by interpolating either the spectral or OI analysis to the MFM grid. The analyses provide the large-scale flow for the tropical cyclone, but the minimum resolution of the objective analyses is relatively large compared with the MFM grid and the typical horizontal scale of a tropical cyclone. Because the global analyses cannot resolve the storm-scale circulation, an idealized three-dimensional flow generated by the MFM is used to represent the storm circulation. The kinematic and thermodynamic variables near the storm are determined by smoothing the large-scale variables in an array of 25×25 grid points that are centered on the storm and then superimposing the storm-scale variables. The tangential velocity of the storm circulation is a maximum about 100 km from the storm center and decreases to zero near 1000 km.

The MFM track forecasts are shown in Fig. 7 for 0000 GMT on the 16th. In all of the forecasts, the initial direction of the storm motion is more than 40° to the left of the observed storm motion. The MFM track forecasts are influenced by the cutoff low to the north–northwest of Debby. The storm motion is forecast to be in a northerly direction for the first 12 hours and then in a northeasterly direction from 24 to 48 hours. The addition of the operational ODW observations results in slower motion for 48 hours in the forecasts initialized by the spectral analysis and faster motion in the forecasts initialized by the OI. The difference in the 48-hour forecast positions for the forecasts initialized with the operational ODW observations in the two objective analyses is about 600 km. The ODW heights have a larger impact on the track forecast initialized with the OI than with the spectral.

In view of the earlier discussions on the similarity of the spectral and OI analyses near Debby, it appears that the MFM track forecasts are very sensitive to small variations in the initial analyses. Fiorino *et al.* (1982) also found substantial differences in MFM track forecasts when the heating rate of the cumulus parameterization or the size of the initial vortex is varied. Elsberry (1979) indicated that storm intensity in the MFM and some other tropical models is very sensitive to

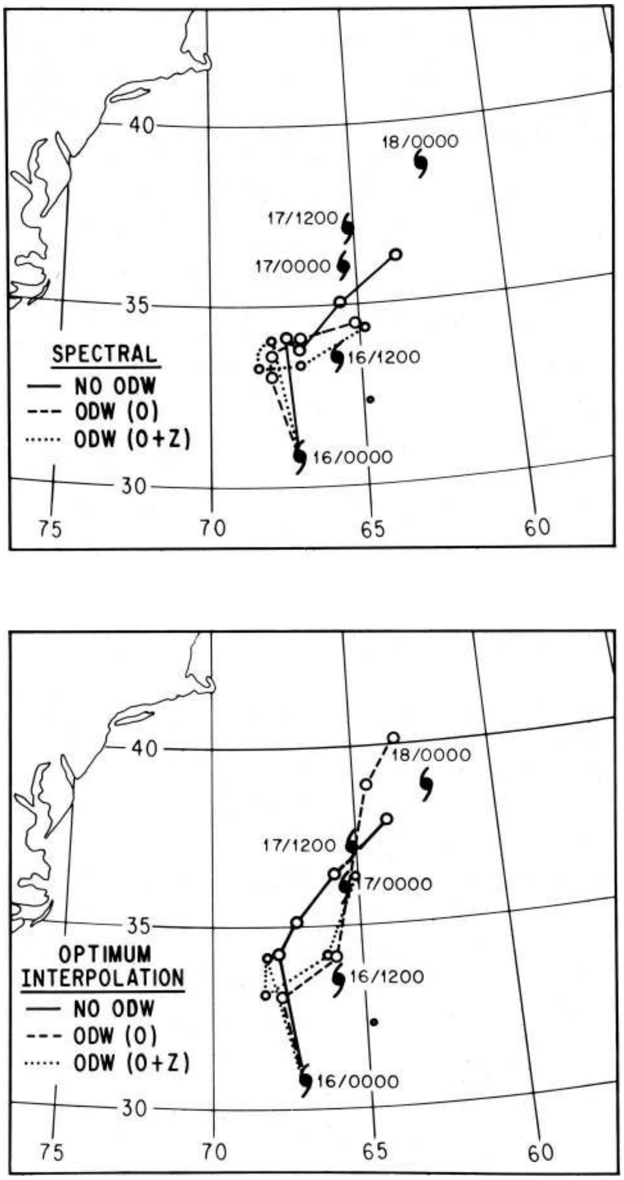

FIG. 7. Same as Fig. 6 except for the MFM.

small changes in humidity near the storm center and that unrealistic storm intensity may significantly affect the storm track. Humidity differences in the Debby objective analyses are relatively small. The precise reason for the substantial differences in the track forecasts is unknown. It is possible that some of the sensitivity in the Debby forecasts may be a result of the idealized initialization procedures that have been designed for hurricanes in data void regions. Work is in progress at NMC to develop a second initialization procedure for the MFM that would use the ODW data to generate the storm-scale circulation.

6. Concluding discussion

The first experiments designed to use ODWs to define the steering currents of mature tropical cyclones that threaten the coastal United States were conducted on the periphery of Hurricane Debby of 1982. In view of the large disparity in the MFM track forecasts that were initialized with the different data sets and objective analyses, the two Debby experiments represent a much too limited sample on which to assess improvements in operational track forecasts that might result from the ODW observations. Three conclusions, however, are apparent: 1) ODWs are capable of defining the important features of a hurricane's environmental flow in the middle and lower troposphere at radii of 150–1000 km from the center of a tropical cyclone. It is feasible to transmit the ODW observations in standard coded format to the NHC and NMC before forecast deadlines; 2) the data can provide useful information for hurricane forecasters to use subjectively. Based upon the ODW observations at 0000 GMT on 15 September, the forecasters were able to assess that Debby would continue to move northeastward for the next several hours (Clark, 1983). The ODWs at 0000 GMT on the 16th could have alerted the forecasters that Debby might turn more to the north and begin to move in a counterclockwise direction around the cutoff low; and 3) the spectral and OI objective analyses used at NMC to initialize several of NHC's storm track models were able to resolve the synoptic scale trough that encompassed Debby's circulation. The objective analyses did not resolve the smaller scale circulations of Hurricane Debby or the cutoff low. Although the spatial scale of the cutoff low was only about 500 km, it had a major influence on Debby's track from 1200 GMT on 16 September to 1200 GMT on 17 September. To achieve improved track forecasts with operational dynamical models, operational objective analyses must be capable of resolving circulation features of the environmental flow that have spatial scales typical of hurricanes. NMC is planning to implement, within two to three years, a regional objective analysis with a smaller minimum resolution that could be used to initialize many of NHC's hurricane track models. The regional analysis should be more capable of responding to hurricane-scale features than the present analyses.

The potential of ODW observations for reducing the errors of the objective hurricane track models can be compared with the expense of obtaining the observations. About 50 ODWs (at $500 each) and 18 hours of flight time (at $2000 per hour) were involved in the experiment on 16 September, so that the total cost of the experiment (excluding overtime, per diem, and the return flight from Virginia to Miami) was about $61,000. Hurricane warnings are usually issued 18 to 24 hours before landfall for a length of coastline averaging 555 km. The swath of damaging winds and tides caused by hurricanes that strike land, however, is generally less than 185 km. Thus, current forecasting skill results in an overwarning zone of approximately 370 km that is a tradeoff between maximizing warning lead time and keeping the warning area as small as possible. Neumann (1983) estimated that the preparedness and lost production cost incurred by the public in coastal areas included in hurricane warnings is about $46,500,000, or about $84,000 km^{-1} of coastline in 1981 dollars. With an adjustment for inflation, the corresponding value for 1982 is approximately $89,000 km^{-1}. If the ODW observations lead to improved objective guidance of storm motion when hurricanes threaten the U.S. coastline and forecasters are able to reduce the overwarning area by only 5% (~20 km), the cost involved in obtaining the ODW data would be well worth the expenditure.

When a hurricane is within 24 to 30 hours of the time of estimated landfall on the U.S. coastline, the NOAA research aircraft are required to gather data within 150 km of the storm center in support of NHC. ODW experiments, therefore, must be completed about 36 hours before landfall. The timing of the ODW experiments required to satisfy this commitment is nearly the same as the optimum timing of the experiments in the absence of the inner core flight. Neumann and Pelissier (1981) pointed out that storm track information from some of the operational track models is not available for interpretation by the hurricane forecasters until four to eight hours after the standard observation times of 0000 and 1200 GMT. Thus, all of the objective guidance based upon ODW experiments that are completed about 36 hours before landfall should be available during the critical time period, some 6 to 12 hours later, when forecasters must decide those specific areas to be included in hurricane warnings.

The ODW observations are being used in the development of more sophisticated dynamical models of tropical cyclones and as ground truth for testing methods of retrieving temperature and moisture profiles from radiometers on geostationary satellites. To achieve the potential of the ODW observations for improving track forecasts of tropical cyclones, more cases are needed. Based upon analyses of additional cases, we should be able to determine whether flight-level data only, in combination with satellite and conventional observations, are sufficient to resolve the environmental flow on the periphery of tropical cyclones. If flight-level data alone are inadequate to specify hurricane steering currents, the analyses should enable us to estimate optimum locations for ODW observations. On 24 and 25 September 1982, experiments similar to those conducted during Debby were flown on the periphery of eastern Pacific Tropical Storm Olivia, but these data have not yet been analyzed. Postprocessed ODW soundings from both the Debby and Olivia experiments are available on magnetic tape and can be obtained from the AOML/Hurricane Research Division (HRD). Resources are available for five or six ODW experiments on the periphery of mature hurricanes during the summer of 1984 and tentative plans have been made for additional experiments later in the 1980s.

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