The Impact of Omega Dropwindsondes on Operational Hurricane Track Forecast Models

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ABSTRACT

Since 1982, the Hurricane Research Division (HRD) has conducted a series of experiments with research aircraft to enhance the number of observations in the environment and the core of hurricanes threatening the United States. During these experiments, the National Oceanic and Atmospheric Administration WP-3D aircraft crews release Omega dropwindsondes (ODWs) at 15–20-min intervals along the flight track to obtain profiles of wind, temperature, and humidity between flight level and the sea surface. Data from the ODWs are transmitted back to the aircraft and then sent via satellite to the Tropical Prediction Center and the National Centers for Environmental Prediction (NCEP), where the observations become part of the operational database.

This paper tests the hypothesis that additional observations improve the objective track forecast models that provide operational guidance to the hurricane forecasters. The testing evaluates differences in forecast tracks from models run with and without the ODW data in a research mode at HRD, NCEP, and the Geophysical Fluid Dynamics Laboratory. The middle- and lower-tropospheric ODW data produce statistically significant reductions in 12–60-h mean forecast errors. The error reductions, which range from 16% to 30%, are at least as large as the accumulated improvement in operational forecasts achieved over the last 20–25 years. This breakthrough provides strong experimental evidence that more comprehensive observations in the hurricane environment and core will lead to immediate improvements in operational forecast guidance.

1. Introduction

During this century, improved forecasts and warnings, better communications, and increased public awareness have reduced the loss of life in the United States resulting from hurricanes. Over the past two decades, the improvement in forecast tracks in the Atlantic basin has averaged about 1% per year (McAdie and Lawrence 1993), while the population in hurricane-prone areas has increased by 3%–4% per year (Sheets 1990). Communities with limited escape routes now require much more time for preparation and evacuation than present warnings can reliably provide. Unless the rate of forecast improvements can be accelerated, the downward trend of hurricane casualties is not likely to continue.

Operational tropical cyclone forecasting is a subjective process that combines conventional, satellite, and reconnaissance observations with input from objective prediction models (e.g., Aberson and DeMaria 1994). Factors such as enhancements of the observing network, development of new data assimilation techniques, and improvement of model resolution and physics contribute to increased model accuracy and reliability and produce improved operational forecasts. When a hurricane poses a potential landfall threat, one key element of the warning process is the forecaster's assessment of the likely model errors. Therefore, as forecasters develop more confidence in their improved objective guidance,

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more accurate and/or precise warnings would be possible.

Accurate modeling of hurricane motion requires accurate representation of interactions that occur throughout the depth of the troposphere on a variety of scales; this initial representation is determined through data assimilation that combines observations with short-term model forecasts. Observations are much less dense over the tropical and subtropical oceans than over North America. Those oceanic observations that do exist are confined primarily to the lowest 2 km and the layer from 9 to 12 km. In the lower layer, ships report surface wind and thermodynamic observations and satellites provide surface and lower-tropospheric winds, and in the upper layer, wind observations are derived from high cloud motions determined by satellite and aircraft navigation systems. To date, however, the only oceanic sounding information comes from the occasional shipboard rawinsonde and thermodynamic retrievals from satellite radiances. Since thermodynamic observations have less influence on tropical analyses than winds (Kalnay et al. 1986), satellite soundings are currently of limited value for initial analyses in the Tropics. Other potential data platforms, such as unmanned aircraft, are several years away from providing sufficient observations at the midtropospheric levels, where the patterns of wind and geopotential height are best correlated with storm motion (George and Gray 1976; Neumann 1979; Franklin et al. 1996).

Burpee et al. (1984) hypothesized that enhancing wind and thermodynamic observations in the hurricane environment and core would improve the initial representation and model track forecasts of hurricanes. Since 1982, the Hurricane Research Division (HRD) has conducted a series of 18 experiments with research aircraft to enhance the observations. The aircraft crews deploy Omega dropwindsondes (ODWs) that measure vertical profiles of wind, temperature, and humidity between flight level and the sea surface. Franklin and DeMaria (1992) evaluated the impact of the ODW data from the first 14 experiments on a barotropic track model. This paper extends their results by examining hurricane track forecasts for the complete sample from three dynamic guidance models run with and without the ODW data in a research mode at the HRD, the National Centers for Environmental Prediction

TABLE 1. Synoptic flow experiments conducted in Atlantic tropical cyclones. The time is the nominal (standard) observation time for the experiment, and the storm strength (SS) is indicated by an H for hurricane or TS for tropical storm. Also shown are the number of aircraft participating in an experiment and the number of successful ODWs.

	Storm name	SS	Date/time (UTC)	Number of aircraft/number of ODWs
1	Debby	H	15 September 1982/0000	1/29
2	Debby	H	16 September 1982/0000	2/49
3	Josephine	TS	10 October 1984/0000	2/48
4	Josephine	H	11 October 1984/0000	2/46
5	Josephine	H	12 October 1984/0000	2/46
6	Gloria	H	25 September 1985/0000	2/53
7	Emily	TS	24 September 1987/0000	1/30
8	Emily	TS	25 September 1987/0000	2/53
9	Floyd	TS	11 October 1987/0000	2/53
10	Floyd	TS	12 October 1987/0000	1/29
11	Florence	TS	9 September 1988/0000	2/51
12	Hugo	H	20 September 1989/0000	1/24
13	Hugo	H	21 September 1989/0000	1/29
14	Jerry	TS	14 October 1989/1200	1/20
15	Bob[a]	H	18 August 1991/0000	1/14
16	Andrew	H	23 August 1992/0000	2/49
17	Emily	H	30 August 1993/0000	2/44
18	Emily	H	31 August 1993/0000	1/19

[a] Analysis archive was lost.

(NCEP), and the Geophysical Fluid Dynamics Laboratory (GFDL). Typical changes in the initial objective analyses resulting from the ODWs are described for the 500-mb flow near a hurricane.

2. Overview of ODW experiments

The HRD and the National Oceanic and Atmospheric Administration (NOAA) Aircraft Operations Center (AOC) have conducted 18 ODW experiments in 11 Atlantic tropical cyclones (Table 1). Nine of these storms made landfall, requiring the issuance of hurricane warnings. At the time of the research flights, 11 of the tropical cyclones were hurricanes and 7 were tropical storms. The sample includes major hurricanes Gloria (1985), Hugo (1989), and Andrew (1992), each of which was flown within about 48 h of landfall. Most (14) of the experiments were conducted in the western Atlantic in an area bounded by Cape Hatteras, Bermuda, and San Juan, with two experiments each in the Caribbean and the Gulf of Mexico. All of the storms were within 1200 km of the U.S. coastline at the time of the flights. Operational data for Hurricane Bob (1991) were lost due to archiving problems; this paper presents the results of the remaining 17 missions.

Each experiment involved flights by one or both WP-3D research aricraft, during which ODWs sampled the environment at approximately 150–200-km intervals along the flight track (Fig. 1). Each aircraft released 20–30 ODWs over the 9–10-h duration of the flights. Specific flight tracks were determined by the relative locations of the tropical cyclones and available airports, with occasional constraints imposed by earlier or anticipated WP-3D missions. As the WP-3D flight levels were typically between 400 and 500 mb, the soundings were confined to the lower and middle troposphere. HRD meteorologists on board the aircraft validated wind and thermodynamic data from the ODWs and then formatted the data into standard messages. The messages were then transmitted via satellite to the Tropical Prediction Center (TPC, formerly the National Hurricane Center) and the NCEP for real-time subjective interpretation by the forecasters and by data assimilation, respectively. In particular, the operational ODW observations from the two most recent experiments in 1993's Hurricane Emily (Table 1) played a substantial role in the forecast and warnings process at the TPC (Burpee et al. 1994).

Figure 1 shows the flight tracks and 500-mb ODW winds for the two-aircraft experiment in Hurricane Debby at 0000 UTC 16 September 1982. Burpee et al. (1984) pointed out that the ODWs accurately located the position and strength of the midtropospheric trough in the westerlies that was the major synoptic-scale feature affecting Debby's motion. The ODWs also identified a cutoff low in the northern part of the trough that was centered about 500 km to the north-northwest of Debby. This feature affected the hurricane's motion from 1200 UTC on 16 September to 1800 UTC on 17 September. Because the researchers and crew members lacked experience using ODWs in areas of organized convection, the flight tracks avoided Debby's center. This design strategy was used from 1982 to 1984; since then, the experiment has usually included at least one aircraft that traversed the storm center. During penetrations of the cyclone core, crew members released ODWs at somewhat smaller intervals than those on a storm's periphery. Figure 2 of Franklin et al. (1993) illustrates the flight tracks for the ODW experiment in Hurricane Gloria, during which both aircraft penetrated the hurricane center.

3. Initial procedures and analysis

Global observations from the NCEP's "final" archived datasets were used in the NCEP Global Data Assimilation System (GDAS) as configured when this

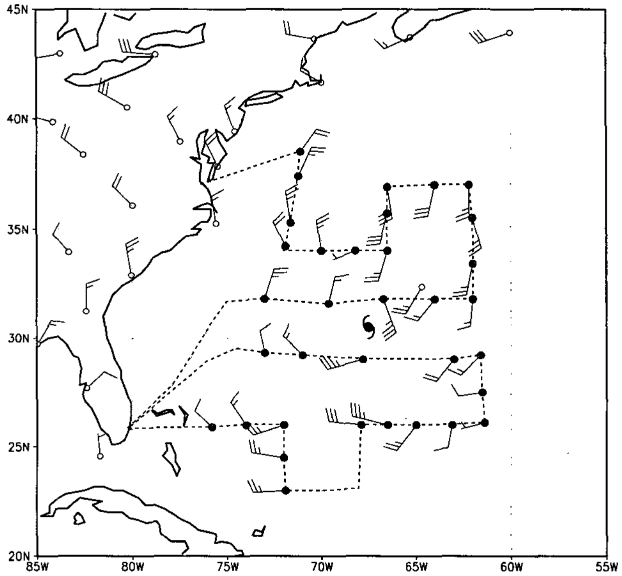

FIG. 1. Two-aircraft flight tracks (dashed lines) and 500-mb rawinsonde (○) and ODW (●) wind observations for Hurricane Debby at 0000 UTC 16 September 1982. Full, half, and no-wind barbs indicate speeds of 5, 2.5, and < 1 m s^{-1}, respectively.

study began in 1991. The observations consist of rawinsondes, conventional aircraft reports, temperature soundings from polar-orbiting satellites (SATEMS), cloud track winds from geostationary satellites, surface marine observations, and reports of surface pressure and specific humidity. For storms during the period 1982–84, observations (except SATEMS) were obtained from the National Center for Atmospheric Research (NCAR) (R. Jenne 1991, personal communication), while the SATEMS were obtained from National Environmental Satellite Data and Information Service archives.

The NCEP GDAS consists of a global model, an analysis procedure, a quality control algorithm, and a synthetic data (wind bogusing) procedure for tropical cyclones. The global model is the operational version in place in 1991. The horizontal resolution is spectral triangular 126 (T126) with a Gaussian grid of 190 × 384 (approximately 1° latitude × 1° longitude). The vertical domain spans the surface to 22 mb with 18 unequally spaced levels in a sigma (normalized pressure) coordinate. Physical parameterizations include horizontal and vertical diffusion, gravity wave drag, shortwave and longwave radiation, penetrative cumulus convection, shallow convection, and surface fluxes of momentum, heat, and moisture. Details are in Kanamitsu (1989), Kalnay et al. (1990), and Kanamitsu et al. (1991).

The global analysis is the spectral statistical interpolation (SSI) (Parrish and Derber 1992) as configured for operational use in June 1991. Every 6 h, at 0000, 0600, 1200, and 1800 UTC, observations of wind, temperature, specific humidity, and surface pressure are combined with model-generated background fields using a three-dimensional variational, multivariate formalism. The background fields are 6-h forecasts from the previous analysis time. The quality control algorithm uses optimal interpolation and hierarchical decision making (Woollen 1991) to evaluate the representativeness and accuracy of all wind, temperature, and specific humidity observations before input to the analysis.

The synthetic data procedure (Lord 1991) creates wind observations representative of a tropical cyclone with the operationally estimated intensity and storm position. Observations are generated at mandatory pressure levels from 1000 to 300 mb and cover an area within 300 km of the storm center. Synthetic wind data are not subject to quality control, and experience has shown them to be a reasonable match to observations in the vicinity of the storm. ODWs in the vicinity of the storm have a substantial impact on the synthetic winds.

The GDAS was used to "spin up" the archived NCEP model fields for a period of 3–4 days prior to the time when the ODWs were inserted. During this spinup period, operational ODW and WP-3D flight-level observations were removed from the database to provide a clean control ("no ODW") assimilation. The 3–4-day assimilation period is required to prevent dynamic imbalances from degrading the initial state and subsequent forecasts. These imbalances occur because the archived fields are from either spectral coefficients of a coarser resolution (T80) model or from fields at 2.5° latitude × 2.5° longitude resolution on mandatory pressure surfaces. In the latter case, the model fields are interpolated to sigma levels using a surface pressure field interpolated to the T126 orography. During the first day of the spinup, a normal mode initialization (Ballish et al. 1992) was applied to the analysis to damp gravity wave noise due to the interpolation procedures. Normal mode initialization is not necessary with the SSI and, therefore, was not used at other times. After the spinup period, the ODW data were inserted or omitted for the ODW or no ODW analyses and forecasts, respectively. Postprocessed ODW data (Franklin 1987) rather than operational data were used in these experiments to account for improvements in data processing and communications procedures developed since the experiments began.[1]

Figure 2a shows the 1000–100-mb deep-layer mean GDAS wind analysis, including the ODWs in the assimilation, for Hurricane Debby at 0000 UTC 16 September 1982. The wind analysis includes the synoptic-scale trough and the cutoff low sampled by the ODWs. Burpee et al. (1984) showed that the operational global analyses of the early 1980s were unable to resolve the cutoff low. The analysis differences, ODW minus no ODW, in the deep-layer mean winds (Fig. 2b) are 2–3 m s^{-1} to the north and northeast of the storm's initial position. The cyclonic flow in the difference field immediately north and west of Debby reflects an improved depiction of the trough and cutoff low by the ODWs in the GDAS analysis. This example demonstrates the potential of the ODW data to resolve small-scale features in the hurricane

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[1] Numerous technical issues have limited the ability of the operational GDAS to ingest large numbers of operational ODW soundings; however, these problems have largely been resolved over the years.

environment. More frequently, the ODWs produced relatively subtle adjustments to the large-scale environmental wind analyses, on the order of 1–2 m s^{-1}.

4. Results

The impact of the ODWs for the 17-case ensemble is evaluated by using three of the best guidance models that were available in the early 1990s (Aberson and DeMaria 1994): the HRD's barotropic model (VICBAR) (DeMaria et al. 1992), the NCEP's global spectral model (GSM) (Lord 1993), and the GFDL hurricane model (Bender et al. 1993). The initial condition of each model is determined in the following ways: the GSM uses GDAS directly, VICBAR combines the GDAS with a reanalysis over the storm environment and then adds a vortex bogus, and the GFDL model also modifies the GDAS analysis near the storm center with its own vortex specification scheme (Kurihara et al. 1995). Neither the VICBAR nor the GFDL models use the ODW data in their vortex generation schemes.

A simple measure of the overall ODW impact is obtained by averaging the forecast positions from the three guidance models to form a "consensus" forecast (CON3). CON3 forecast positions are calculated at 12-h intervals from 12 to 72 h for both the control (no ODW) and ODW forecasts. Consensus is used because it is often regarded as a better overall predictor than any one forecast model. In this sample, the VICBAR, GSM, and GFDL models perform about equally for the first 36–48 h. At 60 and 72 h, the GFDL model is substantially more accurate than the other CON3 models. Individual model performance, however, does not affect the calculation of the consensus fore-

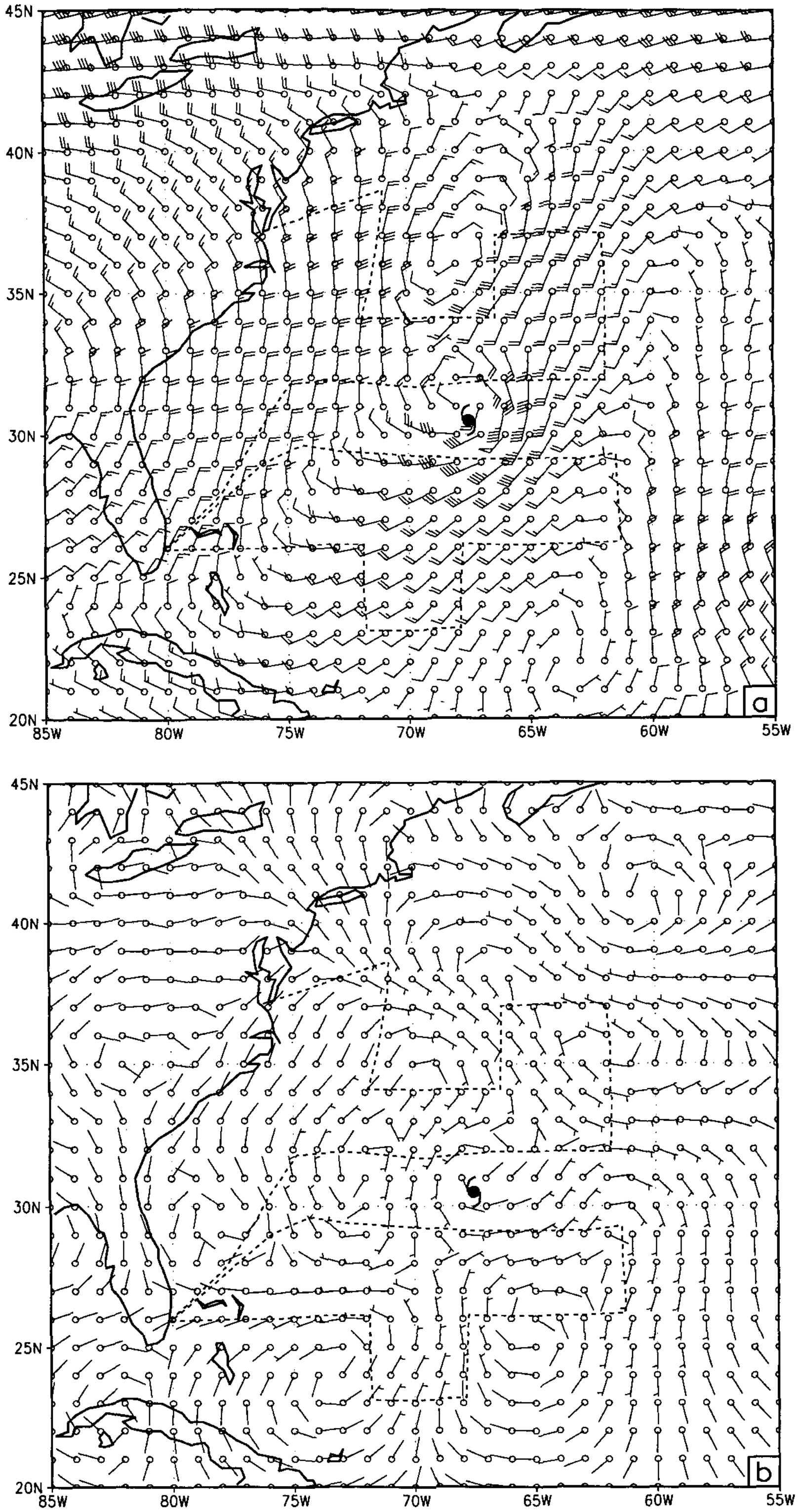

FIG. 2. Deep-layer (1000–100 mb) mean wind analyses from the GDAS at intervals of 1° latitude and longitude for Hurricane Debby at 0000 UTC 16 September 1982. The analysis with ODW data is shown in (a), and the difference between analyses with and without the ODW data is shown in (b). The plotting convention for the winds is the same as in Fig. 1. The flight tracks are indicated by the dashed lines.

cast, which consists of equal contributions from the three models.

Figure 3 shows the mean errors for the control and ODW CON3 forecasts relative to CLIPER (Neumann 1972), a statistical regression model using only climatology and persistence as predictors. Each forecast error is the great-circle distance between the forecast and the corresponding best track position. The relative error is the percentage difference of a forecast error compared to that of CLIPER and represents the skill of a forecast. Forecasts with positive skill have smaller errors than CLIPER and, therefore, negative relative errors. The relative errors of the control CON3 forecasts are 44%–54% less than those of CLIPER at forecast intervals from 24 to 72 h and are smaller than the average errors, relative to CLIPER, for the operational track models examined by Aberson and DeMaria (1994) for the period of 1989–93. Thus, the control CON3 forecasts are very good by state-of-the-art standards. The average ODW CON3 track forecasts from 24–72 h, however, indicate even greater skill, improving upon the control predictions by 21%–30% (34–106 km). The ODW CON3 forecast has smaller errors than the control 82%, 75%, and 71% of the time at 24, 48, and 72 h, respectively. It is worth noting that the mean difference in the initial positions is less than 2 km. The improved forecasts, therefore, result from an improved description of the hurricane environment by the ODWs.

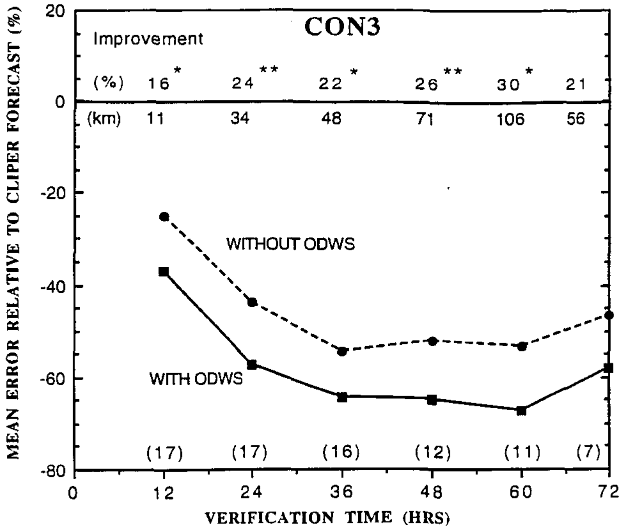

FIG. 3. The average relative errors (in percent) of the CON3 forecasts with and without the ODWs. The numbers just above the zero-skill line are the percentages of improvement of the forecast tracks with ODWs, relative to those without ODWs, where the single- and double-asterisk superscripts indicate significance of this improvement at the 95% and 99% significance level, respectively. Numbers just below the zero-skill line are the average track improvements in kilometers, and those in parentheses at the bottom are the number of cases for each forecast interval.

To evaluate the statistical significance of the differences, it is necessary to estimate the serial correlation between forecasts for the same storm because several of the experiments are separated by 24 h (Table 1); Neumann et al. (1977) indicate that independence of tropical cyclone track characteristics may not be fully attained with separations less than 30 h. Aberson and DeMaria (1994) determined that track forecasts with a more recent version of VICBAR are uncorrelated if they are separated by at least 15–21 h. They used 24 h for the calculation of the effective sample size for their significance tests. In this paper, statistical significance is estimated using the paired-*t* test described by Franklin and DeMaria (1992), and the effective sample size is determined with the more conservative 30-h criterion. With this procedure, the ODW CON3 improvements, relative to the controls, are statistically significant at the 95% level at 12, 36, and 60 h and at the 99% level at 24 and 48 h. The 72-h ODW CON3 improvements, with a sample size of only seven cases, fail to attain statistical significance.

As an example of the forecast improvements resulting from the ODWs, Fig. 4 compares NHC's "best track," determined by poststorm analysis, and the CON3 control and ODW forecasts for the 72 h following the Debby experiment on 16 September 1982. Debby turned toward the north about 12 h after the initial time in response to the cutoff low. The greater southeasterly flow to the northeast of Debby in the initial analysis with ODWs (Fig. 2b) is consistent with, and probably accounts for, Debby's turn to the north in the ODW CON3 track forecast. The CON3 control track forecast maintained Debby's motion toward the north-northeast with minimal, if any, interaction with the cutoff low. The track forecast improvements resulting from this case, in which the ODWs helped resolve a small-scale environmental feature, are about 200 km from 48 to 72 h and are among the largest in the sample. For any given storm, the scale of the relevant steering features is probably a key factor in determining the potential influence of the ODWs. Other factors that may affect the amount of improvement include distance from the conventional rawinsonde network and the degree of baroclinity or wind shear in the storm environment. However, the sample of cases is too small to verify this.

Track forecast differences between ODW and control runs were also calculated for a five-model consensus (CON5), which is an average of the track forecasts for the GFDL, GSM, VICBAR, NHC90, and the quasi-Lagrangian model (QLM). The NHC90 is a statistical–dynamical model (McAdie 1991) based upon a regression procedure that does not utilize the ODW data directly, and the QLM (Mathur 1991) was replaced by the GFDL model at the beginning of the 1995 season. The relative errors of the control CON5 forecasts are 30%–40% smaller than those of CLIPER at forecast intervals from 24 to 48 h and are comparable with the best forecasts in the Atlantic basin by individual models from 1989 to 1993 (Aberson and DeMaria 1994). The average ODW CON5 forecasts from 24 to 48 h improve the control forecasts by 16%–23% or by 28–74 km. The error reductions are statistically significant at the 95% level at 24 h and the 99% level for the 36 and 48 h track forecasts (not shown). The improvements due to the ODWs in CON5 are smaller than those for CON3. This result indicates that the ODWs have a larger impact in reducing the errors of the current operational dynamical models than in the previous generation models.

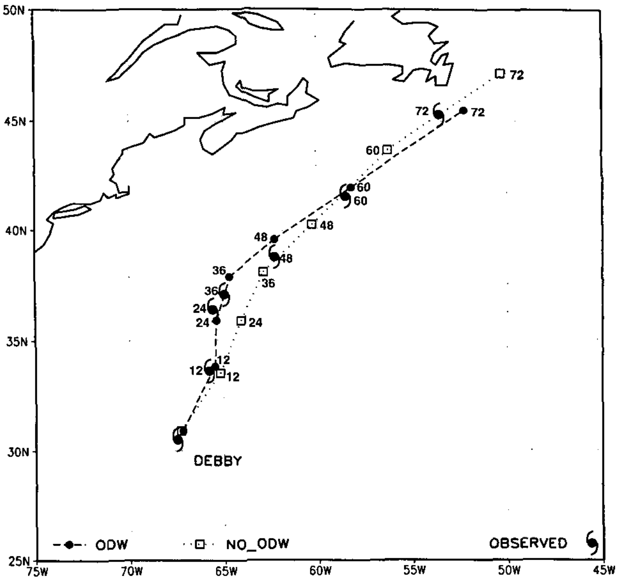

FIG. 4. ODW (dashed line) and no-ODW (dotted line) CON3 track forecasts for Hurricane Debby from 0000 UTC 16 September 1982. Forecast tracks and actual positions (hurricane symbols) are shown at 12-h intervals.

5. Concluding discussion

ODWs are an effective, high quality data source for improving initial wind and thermodynamic analyses of hurricanes and their near environment in oceanic areas with few in situ observations. ODW data gathered by the WP-3D aircraft from 1982 to 1993 have produced statistically significant reductions in 12–60-h model track errors, relative to control runs. At these forecast intervals, which include the decision point for issuing of hurricane warnings, the average error reductions in the consensus forecasts (CON3) from three dynamical models varied from 16% to 30%. The improvements are at least as large as the accumulated improvement in operational forecasts achieved over the 22-yr period from 1970 to 1991 (McAdie and Lawrence 1993) and represent a major breakthrough in hurricane forecasting capability.

While routine operational use of ODWs would increase reconnaissance costs, these costs would be more than offset by savings from the resultant increase in forecast skill. Burpee et al. (1984) and Franklin and DeMaria (1992) compared the expenses of a two-aircraft ODW experiment with total preparation costs for residents of an area included in a hurricane warning. Their estimates of the experimental costs are similar to those incurred on the most recent mission with two aircraft in Hurricane Emily on 30 August 1993. That experiment used 44 ODWs, including failures, at $642 per ODW and 9 h of flight time for each of the two WP-3D aircraft at $2800 per hour. The total cost of obtaining the ODW data was about $80,000, excluding overtime and related travel.

Hurricane warnings are usually issued 18–24 h before landfall for a length of coastline averaging 555 km. The swath of damaging winds and tides caused by hurricanes striking land, however, is generally less than 185 km. Thus, current forecasting skill results in an overwarning zone of approximately 370 km that represents a tradeoff between maximizing warning lead time and keeping the warning area as small as possible. Sheets (1990) estimated that average preparation costs incurred by the public are about $90,000 for each kilometer along the coastline included in a warning, noting that this estimate does not include economic losses due to lost sales, productivity, etc. A more recent analysis by the TPC estimates that preparation costs are currently about $346,000 per kilometer of coastline warned (J. Jarrell 1995, personal communication). If forecasters can develop confidence in the forecast track models initialized with the ODW data and reduce the overwarned area by only 5% (18–19 km), the average savings in warning response costs will exceed the cost of obtaining the observations by about a factor of 80. If a smaller warning zone allows a large city such as Miami or New Orleans to avoid a hurricane warning, the savings would be far greater.

Improvements in track forecasting that allow the TPC to issue hurricane warnings two 12-h periods of daylight before landfall would allow even greater cost savings. Such forecasts would permit coastal residents more time to secure homes and move mobile assets to safety. Research efforts are aimed at making 48-h forecasts as accurate as today's 24-h forecasts, which would permit the longer lead times with no increase in overwarning. Recent increases in onboard computing capability have enhanced the accuracy of real-time ODW data (Griffin et al. 1992). In 1996, a new, more accurate design of dropwindsonde will be available. At that time, the quality of the operational dropwindsonde data should exceed the quality of the postprocessed data that were used in this study. NOAA recently purchased a Gulfstream IV jet airplane that is being instrumented to deploy dropwindsondes around hurricanes to support the TPC's operational requirements. The jet is expected to be ready for flights during the 1996 Atlantic hurricane season. Coordinated flights of the jet with the WP-3D research aircraft will provide unprecedented data coverage.

The jet will obtain upper-tropospheric sounding data for the first time that may also be useful for understanding and predicting intensity change, an area where operational forecasts have little or no skill. Recent research (DeMaria and Kaplan 1994) has shown that upper-tropospheric eddy angular momentum transports can be used to forecast hurricane intensity. Soundings from the jet will resolve these transports with far greater precision than is currently possible.

In NCEP's current analysis scheme, radiances from polar-orbiting satellites are used instead of retrieved soundings; radiances from the Geostationary Operational Environmental Satellites will also be incorporated in the future. This approach is a more accurate and theoretically consistent usage of satellite information and enhances the ability of the analysis to combine satellite and conventional data. Through this improvement, dropwindsondes in the otherwise data-sparse hurricane environment not only improve the analysis directly, but also increase the value of satellite observations.

The collection of dropwindsonde data in the hurricane core and environment is a viable, cost-effective means of reducing the errors of operational hurricane forecasts. The model results and prospects for improved real-time dropwindsonde data provide strong experimental evidence that the acquisition of more comprehensive data will lead to improvements in the operational hurricane track guidance. Additional improvements in track forecasts will require the development of objective analysis schemes that can assimilate high-density observations into model-compatible initial conditions and a new generation of track models.

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