A Real-Time Hurricane Surface Wind Forecasting Model: Formulation and Verification

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ABSTRACT

A real-time hurricane wind forecast model is developed by 1) incorporating an asymmetric effect into the Holland hurricane wind model; 2) using the National Oceanic and Atmospheric Administration (NOAA)/ National Hurricane Center's (NHC) hurricane forecast guidance for prognostic modeling; and 3) assimilating the National Data Buoy Center (NDBC) real-time buoy data into the model's initial wind field. The method is validated using all 2003 and 2004 Atlantic and Gulf of Mexico hurricanes. The results show that 6- and 12-h forecast winds using the asymmetric hurricane wind model are statistically more accurate than using a symmetric wind model. Detailed case studies were conducted for four historical hurricanes, namely, Floyd (1999), Gordon (2000), Lily (2002), and Isabel (2003). Although the asymmetric model performed generally better than the symmetric model, the improvement in hurricane wind forecasts produced by the asymmetric model varied significantly for different storms. In some cases, optimizing the symmetric model using observations available at initial time and forecast mean radius of maximum wind can produce comparable wind accuracy measured in terms of rms error of wind speed. However, in order to describe the asymmetric structure of hurricane winds, an asymmetric model is needed.

1. Introduction

Hurricane-induced storm surge and flooding remain a severe threat to coastal communities despite progress made over the past several decades on improved hurricane track and intensity forecasts. The accuracy of a storm surge forecast depends not only on the track and intensity, but also on the distribution of the forecast wind field. A variety of numerical and statistical models have been developed for forecasting (e.g., Holland 1980; Jelesnianski et al. 1992) and hindcasting hurricane wind fields (e.g., Powell and Houston 1998; Houston et al. 1999). The extensive resources needed in the use of full physics mesoscale models have kept them from being adopted in routine operational forecasts of hurricane winds. Instead, simple parameterized models are widely used in the simulations of hurricane wind fields and for providing hurricane forcing for storm surge forecasting. Early studies (Depperman 1947; Hughes 1952; Riehl 1954, chapter 11) used a modified Rankine vortex to approximate the structure of a generic tropical cyclone (TC). The deficiency of the modified Rankine vortex model is that it requires accurate measurements of the radius of maximum winds, and the vortex is axisymmetric. Schleomer (1954) suggested a parametric model that relates the wind field to the pressure field. However, Schleomer's model markedly underestimates the radial extent of hurricane winds. Holland (1980) suggested further modifications to Schleomer's (1954) formulation, using U.S. Army Corps of Engineers data in the Florida area. Holland's model assumes that for a generic TC, the surface pressure field follows a modified rectangular hyperbola, as a function of radius, to give

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$$P(r) = P_c + (P_n - P_c)\exp^{-(R_{\max}/r)^B}, \quad (1)$$

and the tangential wind field is given by the pressure field via cyclostrophic balance,

$$V(r) = \left[\frac{B}{\rho_a}\left(\frac{R_{\max}}{r}\right)^B (P_n - P_c)\exp^{-(R_{\max}/r)^B} + \left(\frac{rf}{2}\right)^2\right]^{1/2} - \frac{rf}{2}, \quad (2)$$

where $P(r)$ is the surface pressure at a distance of r from the hurricane center, P_n the ambient surface pressure, P_c the hurricane central surface pressure, $R_{\max}$ the radius of maximum wind (RMW), B a hurricane-shape parameter, f the Coriolis parameter, and $V(r)$ the velocity at a distance r from the hurricane center. For hurricanes at low latitudes, the terms associated with the Coriolis parameter, f, are neglected.

In Holland's model, there is no need to know the RMW in order to compute the maximum wind because of the cyclostrophic balance. However, in order to describe the structure of the wind field, RMW must be known. The parameter B (ranging from 1 to 2.5), which represents the vortex's shape and size, must be specified. When the parameter B is poorly specified, the errors of the calculated wind field can be significant. One way to estimate B is to develop a statistical relationship between B and the hurricane center pressure drop in a specific region (Jakobsen and Madsen 2004). Such an approach is useful for modeling historical hurricanes, but offers only limited improvement over the original Holland model.

The Holland model is an axisymmetric model, meaning that the asymmetric structure of a hurricane cannot be represented by the model no matter how B is determined. On the other hand, it is well known that an actual hurricane is rarely axisymmetric. Within the same hurricane, the differences in wind speeds at different azimuthal directions can be substantial. Highly asymmetric structures in a landfalling hurricane often lead to large errors in storm surge forecasting (Houston et al. 1999).

Georgiou (1985) introduced a more sophisticated model to overcome some of these limitations:

$$V = V_{\text{holland}} + 0.5V_t \operatorname{Sin}(\beta), \quad (3)$$

where V_t is the hurricane translation speed and β is the angle from the direction of the hurricane movement. In addition to the cyclone movement included in Eq. (3), various other factors can contribute to the asymmetric structure of a hurricane, such as friction (Shapiro 1983), vertical shear, and environmental conditions (Wang and Holland 1996), the near discontinuity of the surface friction and the latent heat flux (Chen and Yau 2003), and the β effect (Ross and Kurihara 1992). There is no consensus on how these factors should be incorporated into parametric hurricane models.

On the other hand, in recent years other resources have been made available in the public domain such as the TC forecast guidance issued by the National Hurricane Center (NHC) of the National Oceanic and Atmospheric Administration (NOAA), observations from buoy stations, and the near–real time hurricane surface wind analysis provided by Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division (HRD; referred to as the HRD winds, hereafter) that may be used to initialize hurricane winds and validate wind forecasts.

The NHC issues 120-h TC track and intensity forecasts (the wind structure forecasts are limited to 72 h) four times a day for all storms in the North Atlantic and the North Pacific east of 140°W (http://www.nhc.noaa.gov). The track forecasts include the latitude and longitude (to the nearest tenth of a degree) of the storm center, and the intensity forecasts include the maximum sustained (1-min average) surface wind (to the nearest 5 kt) at 12, 24, 36, 48, and 72 h. The storm structure is depicted by the radial extent of the 34-, 50-, and 64-kt winds in four quadrants (northeast, southeast, southwest, and northwest). These radii represent the maximum radial extent of winds of a given threshold in each of the four quadrants surrounding the storm. Forecasts of these wind radii are issued four times a day out to 36 h. The 50-kt wind radii are also forecast at 48 and 72 h. The TC intensity models used by the NHC include the Statistical Hurricane Intensity Forecast (SHIFOR) (Jarvinen and Neumann 1979), the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria and Kaplan 1994), and the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model. The NHC forecast guidance is useful in hurricane warning and evacuation processes. However, the NHC forecast guidance has not been effectively utilized for storm surge forecasting because of a number of limiting factors, such as the still relatively large mean track error and the lack of a convenient method to incorporate the NHC forecast guidance into gridded hurricane wind forecasts.

In this study, an algorithm to produce near–real time forecasts of hurricane wind fields is developed by using the NHC hurricane forecast guidance and real-time buoy observations. Near–real time HRD surface wind analysis and buoy wind observations are used to validate model forecasts. The method is described in section 2. A statistical analysis of the model error relative to the traditional Holland model was carried out for all 2003 and 2004 hurricanes. Case studies were also carried out for four recent hurricanes, namely, Floyd (1999), Gordon (2000), Lily (2002), and Isabel (2003). In the case study, the wind fields computed with the new asymmetric wind model (AWM) were compared with those produced by the Holland model (HM), optimized Holland model (OHM), buoy observations, and HRD wind analyses. The results and discussions are presented in section 3. A case study of how to quantify uncertainty in the simulated wind field is explained in section 4. A summary of the conclusions is provided in section 5.

2. Method

The objective of this study is to develop a near–real time hurricane wind forecast system by incorporating the asymmetric representation of a hurricane wind field into the well-known and very utilitarian HM, based on available real-time observations and analyses as well as the NHC hurricane forecast guidance, to provide optimized asymmetric hurricane wind forecasts.

The National Data Buoy Center (NDBC) maintains automated reporting stations in the Gulf of Mexico, in coastal areas, in portions of the Atlantic and Pacific Oceans, and in the Great Lakes. These data acquisition systems collect real-time meteorological and oceanographic measurements for operations and for research purposes. Moored buoy and Coastal-Marine Automated Network (C-MAN) stations routinely acquire, store, and transmit data every hour. Data obtained operationally include sea level pressure, wind speed and direction, peak wind, and air temperature. Sea surface temperature and wave spectra data are measured by all moored buoys and a limited number of C-MAN stations. Relative humidity is measured at several stations. Ocean currents and salinity are measured at a few coastal stations. The buoy stations whose data are used in this study are listed in the appendix.

The HRD wind analysis uses virtually all available surface weather observations (e.g., ships, buoys, coastal platforms, surface aviation reports, reconnaissance aircraft data adjusted to the surface). Observational data are downloaded on a regular schedule and then processed to fit the analysis framework. This includes the data sent by NOAA P3 and G4 research aircraft during the HRD hurricane field program, the Step Frequency Microwave Radiometer measurements of surface winds, as well as U.S. Air Force Reserves (AFRES) C-130 reconnaissance aircraft, remotely sensed winds from the polar-orbiting Special Sensor Microwave Imager (SSM/I) and European Remote Sensing Satellite (ERS), the Quick Scatterometer (QuikSCAT) platform and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager satellites, and Geostationary Operational Environmental Satellite (GOES) cloud drift winds derived from tracking low-level near-infrared cloud imagery from these geostationary satellites. Available data are composited relative to the storm over a 4–6-h period. All data are quality controlled and processed to conform to a common framework for height (10 m or 33 ft), exposure (marine or open terrain over land), and averaging period (maximum sustained 1-min wind speed) using accepted methods from micrometeorology and wind engineering (Powell et al. 1996; Powell and Houston 1996). Note that the HRD wind analyses are highly variable in accuracy, depending on the quality and quantity of the observations used, and on the appropriateness of the underlying assumptions used to manipulate the observations. In particular, analyses conducted without the benefit of Stepped Frequency Microwave Radiometer data may be in error locally by 10–15 m s^{-1} or more. Despite these deficiencies, they remain the best available near–real time gridded hurricane wind analyses (J. L. Franklin 2003, personal communication).

We use the forecasting of the Hurricane Isabel (2003) wind field at 0000 UTC 18 September as an example to illustrate the asymmetric hurricane wind forecasting system. First, NHC hurricane forecast guidance issued at 1500 UTC 17 September 2003 (as listed below) is retrieved from the NHC:

FORECAST VALID 18/0000UTC 31.4N 73.5W.
MAX WIND 95 KT . . . GUSTS 115 KT.
64 KT . . . 100NE 80SE 60SW 90NW.
50 KT . . . 125NE 100SE 80SW 125NW.
34 KT . . . 275NE 250SE 150SW 200NW.

The forecast is effective at 0000 UTC 18 September. The forecast storm center is at 31.4°N, 73.5°W. The 1-min average maximum sustained surface wind is 95 kt with gusts up to 115 kt. The storm structure is characterized by the radial extent of the 34-, 50-, and 64-kt wind in four quadrants (northeast, southeast, southwest, and northwest) relative to the storm center.

To incorporate the NHC forecast guidance into the Holland model, R_{max} in Eq. (2) is modified to become a function of the azimuthal angle (θ):

$$R_{\max}(\theta) = P_1\theta^{n-1} + P_2\theta^{n-2} + \cdots + P_{n-1}\theta + P_n, \tag{4}$$

$$P(r, \theta) = P_c + (P_n - P_c)\exp^{-[R_{\max}(\theta)/r]^B}, \tag{5}$$

$$V_{\text{Aholland}} = \left[\frac{B}{\rho_a}\left(\frac{R_{\max}(\theta)}{r}\right)^B (P_n - P_c)\exp^{-[R_{\max}(\theta)/r]^B} + \left(\frac{rf}{2}\right)^2\right]^{1/2} - \frac{rf}{2}, \tag{6}$$

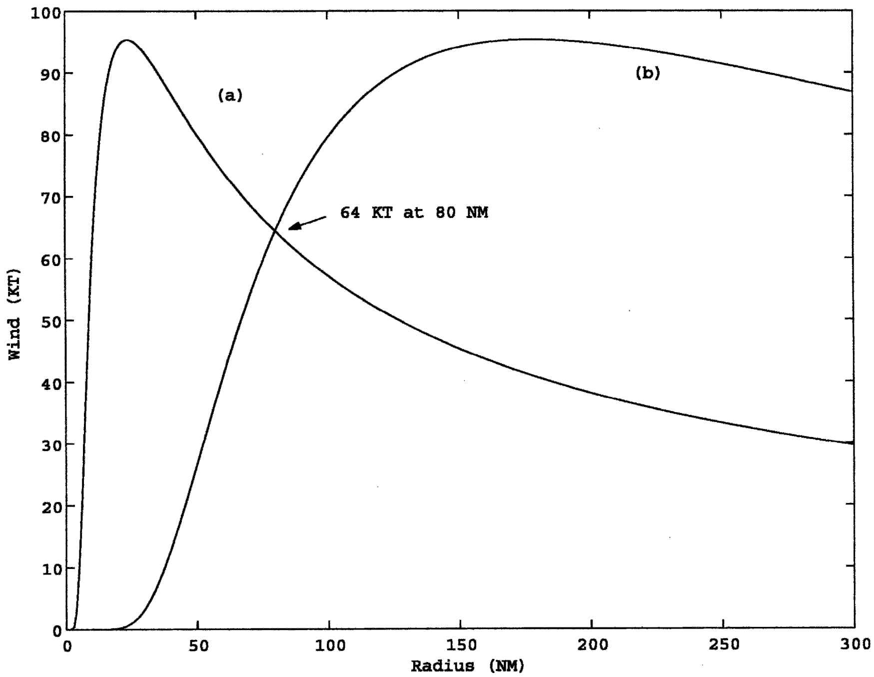

FIG. 1. Hurricane Isabel wind profiles (kt) in the southeast quadrant: (a) curve is for R_{max} = 23.70 n mi; (b) curve is for R_{max} = 176.20 n mi.

where P is the atmospheric pressure, P_c the hurricane center pressure, P_n the environmental pressure, $V_{Aholland}$ the wind speed, ρ_a the air density, and f the Coriolis parameter.

From Eq. (2) we can determine the initial values of B using V_{max}, P_n, and P_c at the initial time (1500 UTC 17 September 2003):

$$B_0 = \frac{V_{max}^2 \rho_a e}{P_n - P_c}, \tag{7}$$

where V_{max} is hurricane maximum wind speed, and e = 2.7183. Then, the NHC forecast guidance is used to curve fit the polynomial [Eq. (4)] to obtain R_{max} as a function of θ. Note that in Eq. (2), when values of V(r) and r are given, R_{max} has two solutions in each of the four quadrants. For example, in the NHC forecast for 0000 UTC 18 September listed above, in the southeast quadrant, the radius of the 64-kt wind is 80 n mi. Equation (2) can be solved based upon this information and the two corresponding R_{max} solutions are 23.7 and 176.2 n mi, respectively (Fig. 1). However, only the smaller value is the physical solution since the NHC forecast indicates that 64-kt winds occur within 80 n mi of the storm center in the southeast quadrant. The R_{max} values computed for the four quadrants for the 0000 UTC 18 September forecast are 29.62, 23.70, 18.96, and 29.62 n mi for the northeast, southeast, southwest, and northwest quadrants, respectively. Next, the coefficients of the fourth-order polynomial [Eq. (4)] are obtained by a polynomial curve fitting of the R_{max} values. For the Hurricane Isabel case, the coefficients at 0000 UTC 18 September are estimated as follows:

$$n = 5,$$

$$P_1 = -2.56(10^{-8}),$$

$$P_2 = 2.17(10^{-5}),$$

$$P_3 = -5.70(10^{-3}),$$

$$P_4 = 4.83(10^{-1}),$$

$$P_5 = 17.6.$$

The same procedure is used to compute P_1 to P_5 at the initial time (1500 UTC 17 September 2003). Secondary optimization of the initial wind field using the NDBC buoy winds is performed whenever there are functioning buoys within the analysis domain. The optimal values of the parameters (B and P_i, i = 1–5) for the initial wind field are those that minimize the following root-mean-square (rms) error function:

$$\sqrt{\sum_{n=1}^{N} [\mathbf{V}(B, P_{1-5}) - \mathbf{V}_{buoy}]^2}, \tag{8}$$

where N is the number of functioning buoy stations within the analysis domain. If there is no working buoy within the analysis domain, secondary optimization of the initial wind field is not performed. Finally, the hurricane wind field at time T between the initial time T_0 (in this case 1500 UTC 17 September) and NHC forecast guidance valid for T_1 (in this case, 0000 UTC 18 September) is linearly interpolated. Similarly, hurricane wind fields at T_2 can be computed using NHC forecast guidance valid for T_2, and the wind fields at any time between T_1 and T_2 are linearly interpolated. This forecast process can continue until the end of the NHC forecast guidance period. Note that, since buoy observations are used to optimize the initial wind field, in the event that no operational buoy falls within the analysis domain, the model-simulated initial wind asymmetry only reflects the contribution from the NHC initial estimation of the wind radii in each quadrant. The number of buoy observations or the lack of them may affect the accuracy of the initial wind analysis and the interpolated wind between the initial time (T_0) and the nearest NHC forecast time (T_1). However whether or not buoy observations are available at the initial time does not affect the wind forecast at or beyond T_1 since only the parameters in the NHC forecast guidance are used in the computation of the forecast wind field at or beyond T_1, which does not rely on the initial wind field. This is because parametric hurricane wind models such the Holland model are essentially balanced models that do not involve tendency (*d/dt*) calculation.

The NHC forecast guidance provides the radius of the 34-, 50-, and 64-kt winds in four quadrants. It does not provide information on the wind distribution in regions where the wind speed is greater than 64 kt. However, because severe storm surge and flooding damages are often associated with peak winds, the parameters obtained with the method described above may sometimes still underestimate the effects of the wind asymmetries near the radius of maximum winds. To improve the wind forecast in the vicinity of $R_{\max}$, we introduce the following formula:

$$V = A(\theta)V_{\text{holland}}(B, R_{\max}), \tag{9}$$

where B is the same as in that in Eq. (6), $R_{\max}$ is the average of $R_{\max}(\theta)$in Eq. (6), $A(\theta) = [R_{\max}(\theta)/R_{\max}]^{\alpha}$, and $\alpha = B/2$. By using Eq. (9), the asymmetric wind structure represented by $R_{\max}(\theta)$is translated into coefficient $A(\theta)$, which reproduces not only the asymmetric shape but also the asymmetric distribution of the maximum wind speed.

The pressure profile used by the original Holland (1980) model does not describe the surface (10 m) wind but may be used to estimate a gradient or cyclostrophic wind. The wind fields obtained directly from the Holland model apply at the top of the surface layer. Theoretically, surface friction in marine waters must be included when converting Holland winds to surface winds. However, in practice the Holland model is only needed for mapping wind distribution. The actual magnitude of the wind speed is usually determined empirically by fitting the radial profile of hurricane wind speed using observed surface (10 m) maximum sustained wind speed. Thus, the effect of surface friction is implicitly included during the optimization processes [Eq. (9)].

3. Results and discussions

In this section, we present the results for model validation. We begin with an extensive statistical validation by conducting 144 hurricane wind hindcasts for all 2003 and 2004 Atlantic and Gulf of Mexico hurricanes except those whose buoy observations or HRD surface wind analysis were incomplete (for validation purposes), or whose NHC forecast guidance were too few to produce valid $R_{\max}$ in all four quadrants. For all cases, 6- and 12-h wind forecasts are made. A 6-h (12 h) wind forecast utilizes NHC storm track and intensity forecast guidance that is validated 6 (12 h) from the time when the wind forecast is made. Note that, although NHC forecast guidance contains hurricane track and intensity information at 12-h intervals, the forecast is updated at least four times a day. Thus, the NHC hurricane forecast guidance is available at 6-h intervals. For example, let $t = 0$ represent the current time, then a 12-h forecast guidance issued $t = -6$ h provides information at $t = 6$ h, a 12-h forecast guidance issued at $t = 0$ gives information at $t = 12$ h, etc.

In the following, both 6- and 12-h forecast results are presented. The forecast results using the AWM, HM, and OHM models are compared against the buoy data as well as HRD surface wind analyses. The average rms errors estimated by using the buoy data are 4.4, 4.4, 7.9, and 4.9 m s^{-1} for the AWM 6-h, AWM 12-h, HM 6-h, and OHM 6-h forecasts, respectively. The average rms errors estimated by using the HRD wind analyses are 3.4, 3.3, 9.9, and 4.8 m s^{-1} for the AWM 6-h, AWM 12-h, HM 6-h, and OHM 6-h forecasts, respectively. Thus, both AWM 6- and 12-h forecasts are generally in closer agreement with buoy observations and HRD surface wind analyses than the 6-h forecasts computed by the HM and the OHM.

Next, consider the forecast error in more detail for four historical hurricanes, namely, Floyd (1999), Gordon (2000), Lily (2002), and Isabel (2003). These four cases are chosen because there are more complete buoy

TABLE 1. Comparison of the maximum wind speed differences (m s^{-1}) from buoy station measurements using different models: (a) AWM 6-h prediction; (b) AWM 12-h prediction; (c) HM 6-h prediction; and (d) OHM 6-h prediction.

Storm/buoy	(a)	(b)	(c)	(d)
Floyd/44014	−2.57	−1.79	−3.62	−6.83
Floyd/FPSN7	−1.22	0.77	5.21	5.83
Floyd/BUZM3	3.70	2.13	−7.18	−10.44
Floyd/CLKN7	0.22	−5.43	1.43	−2.95
Floyd/VENF1	4.00	5.70	17.82	8.57
Gordon/DPIA1	−0.01	−0.59	0.11	−2.13
Gordon/SANF1	−1.79	−1.29	4.39	3.26
Gordon/42041	−0.97	−0.38	3.89	2.60
Gordon/LONF1	−0.71	−0.58	5.73	4.56
Gordon/SPGF1	1.83	1.81	8.15	6.93
Isabel/44014	4.52	2.36	3.85	2.18
Isabel/44025	−1.04	−1.21	1.34	−1.94
Isabel/CHLV2	0.61	0.14	0.89	−0.07
Isabel/41001	0.37	1.63	2.80	−0.55
Isabel/DUCN7	4.42	2.46	1.70	1.82
Lily/DRYF1	−1.73	−1.73	8.15	5.65
Lily/LONF1	−0.33	−0.60	8.40	5.52
Lily/SANF1	−1.54	−2.02	7.44	4.67
Lily/SMKF1	−1.00	−1.31	7.89	4.95
Lily/BURL1	1.94	1.60	9.27	5.77
Mean rms error	2.26	2.33	6.93	5.18

observations and HRD surface wind analysis available for these cases (for validation purposes). Forecasts were made for these four historical hurricanes using the asymmetric hurricane wind model described in section 2. Comparisons of the difference in the hurricane maximum wind speed between the buoy measurements and forecasts using different hurricane wind models are shown in Table 1. When the hurricane center is far away from a buoy station, the winds measured by the buoy reflect primarily the ambient winds. To focus on the validation of hurricane wind fields, only the difference between the buoy measurements and the forecasts valid for local peak winds are presented. Note that both the 6- and 12-h forecasts are updated hourly. The advantage of the asymmetric model is clearly demonstrated. As shown in Table 1, the overall rms error for (a) 6-h and (b) 12-h forecasts using the asymmetric model was 2.26 and 2.33 m s^{-1}, respectively, considerably smaller than that of the 6-h forecast using the (c) Holland model (6.93 m s^{-1}) and the (d) optimized Holland model (5.18 m s^{-1}).

Forecasts for Hurricane Floyd were made from 2100 UTC 7 September to 0900 UTC 17 September, a 228-h period. Figure 2 shows the time series of Floyd's winds at buoy stations FPSN7, CLKN7, VENF1, and 44014. For each panel, five time series are shown: 1) buoy data; 2) the HM-derived wind; 3) the OHM-derived wind; 4) the new AWM 6-h; and 5) the AWM 12-h forecast results. The wind speed at each hour is the forecast result using the NHC forecast guidance available 6 and 12 h prior to the forecast time. The buoy data are adjusted to a standard 10-m height based on Large and Pond (1981).

The hurricane tracks, hurricane center minimum pressures, and the maximum wind speed used in the axisymmetric HM runs were the same as those used in the AWM. In the axisymmetric HM runs without optimization, B was set to 1.0, as in the Sea, Lake, and Overland Surges from Hurricanes model (Jelesnianski et al. 1992), and R_{max} was specified based on climatological values suggested by Hsu and Yan (1998) and the NHC forecast guidance available 6 h before the forecast validation time. For the OHM runs, the parameters B and R_{max} were optimized using the NHC forecast guidance available 6 h before the forecast validation time.

Figure 2 shows that wind forecasts from the AWM showed better agreement with buoy measurements than those forecast from the HM. As shown in Figs. 2a–c, the HM overestimated the maximum wind speed, while in Fig. 2d, it underestimated the maximum wind speed. The rms error for the 6- and 12-h forecasts using the AWM are 3.07 and 4.19 m s^{-1}, respectively, whereas the rms for the Holland model reached 10.14 m s^{-1} (without optimization) and 8.22 m s^{-1} (with optimization; Table 1). For all buoy stations, the Holland model tended to overestimate the wind speed before the peak wind. Compared to the HM, the OHM improved the forecast overall. Thus, although optimization can lead to some improvement in hurricane wind forecasts using the axisymmetric Holland model, the optimization using the asymmetric model provided the best hurricane wind forecasts.

Figure 3 shows the two-dimensional wind fields of Floyd at 1300 UTC 11 September. The five panels of the figure are, respectively, (a) the wind field of HRD surface wind analysis; (b) the AWM 6-h forecast; (c) the AWM 12-h forecast; (d) the HM 6-h forecast; and (e) the OHM 6-h forecast. It is shown that the AWM 6- and 12-h forecasts were able to capture the main characteristics of the asymmetric structure and the intensity of the hurricane winds. Stronger winds appear in the northeast quadrant, consistent with the HRD hurricane wind analyses. The average rms error from the HRD surface wind analysis is 4.18 and 5.45 m s^{-1} for the asymmetric model's 6- and 12-h forecasts, and 8.29 and 6.77 m s^{-1} for the HM 6-h and OHM 6-h forecasts, respectively (Table 2). The HM described neither the magnitude nor the asymmetric structure of the HRD data correctly. The OHM depicted hurricane wind strength better than the HM, but because it cannot de-

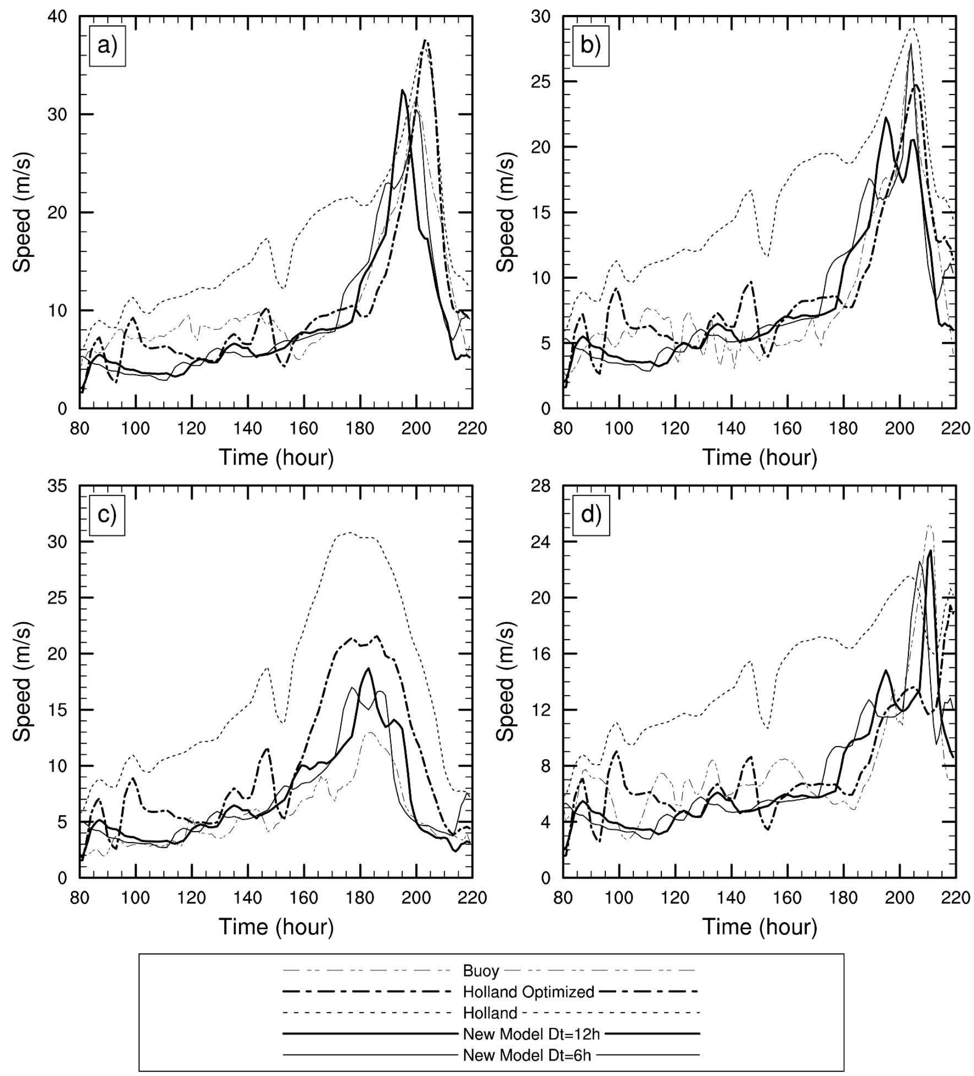

FIG. 2. Time series of wind speed during Hurricane Floyd (1999) at NDBC buoy station (a) FPSN7; (b) CLKN7; (c) VENF1; and (d) 44014.

scribe the hurricane asymmetric wind structure, its rms error is larger than those of the AWM 6- and 12-h forecasts.

For the Floyd case the optimization on the axisymmetric Holland model had mixed effects (Tables 1 and 2). For the other three hurricanes simulated in this study, the performances of the AWM are similar to that of Floyd, except that in all three cases, the OHM produced better results than those of the axisymmetric HM. As an example, forecasts for Gordon (2000) were made from 1500 UTC 14 September to 1500 UTC 18 September. Figure 4 shows the time series of the forecast and buoy winds for Hurricane Gordon at buoy stations SANF1, 42041, and 42041. The rms error for the 6- and 12-h forecasts using the AWM are 1.41 and 1.20 m s^{-1}, respectively, whereas the rms error for the HM and OHM reached 5.78 and 4.72 m s^{-1}, respectively (Table 1). Figure 5 shows the two-dimensional wind field of Gordon at 1330 UTC 17 September. The average rms difference from the HRD surface wind analysis is 7.64 and 7.36 m s^{-1} for the AWM 6- and 12-h forecasts, but 11.50 and 10.07 m s^{-1} for the HM and OHM, respectively (Table 2).

Forecasts for Isabel (2003) were made from 1300 UTC 6 September to 1500 UTC 19 September. Figure 6 shows the time series of Hurricane Isabel winds at NDBC buoy stations 44025, 44014, CHLV2, and 41001. The rms error for the 6- and 12-h forecasts using the AWM are 3.22 and 1.98 m s^{-1}, respectively, whereas the rms error for the HM and OHM reached 2.65 and 1.70 m s^{-1}, respectively (Table 1). In this case, the HM and OHM results for the maximum wind speed were

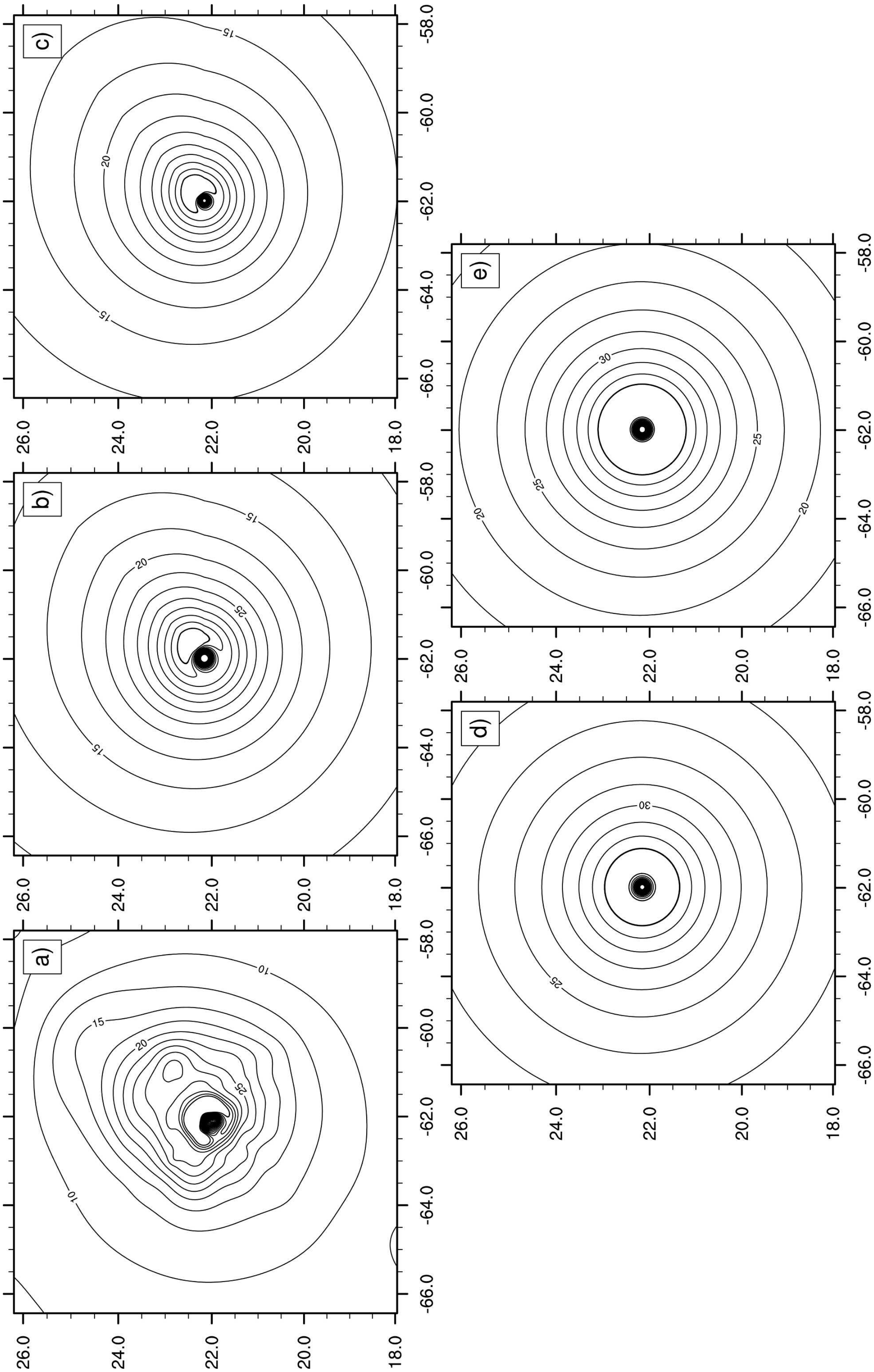

FIG. 3. Two-dimensional wind structures of Floyd (1999) at 1330 UTC 11 Sep: (a) HRD wind analysis; (b) new asymmetric model forecast (Δt = 6 h); (c) new asymmetric model forecast (Δt = 12 h); (d) nonoptimized Holland model; and (e) optimized Holland model.

TABLE 2. Comparison of the rms errors (m s^{-1}) from the HRD wind analysis using different methods: (a) rms error of AWM 6-h prediction; (b) rms error of ASM 12-h prediction; (c) rms error of HM 6-h prediction; and (d) rms error of OHM 6-h prediction.

Hurricane/time	(a)	(b)	(c)	(d)
Floyd/1330 UTC 11 Sep 1999	3.77	4.37	11.12	11.06
Floyd/0130 UTC 12 Sep 1999	3.57	3.38	7.12	4.44
Floyd/1930 UTC 13 Sep 1999	4.39	7.61	4.01	6.33
Floyd/0730 UTC 15 Sep 1999	5.02	6.45	10.94	5.28
Gordon/1630 UTC 17 Sep 2000	9.55	7.55	11.48	9.48
Gordon/1330 UTC 17 Sep 2000	5.38	7.85	12.34	11.97
Gordon/1930 UTC 17 Sep2000	7.99	6.70	10.68	8.79
Isabel/1730 UTC 11 Sep 2003	4.32	4.28	14.07	8.81
Isabel/0730 UTC 13 Sep 2003	2.59	3.09	12.67	3.91
Isabel/0730 UTC 14 Sep 2003	4.66	3.15	11.84	3.76
Lily/0130 UTC 28 Sep 2002	2.29	3.50	4.12	3.50
Lily/1930 UTC 28 Sep 2002	1.88	3.16	5.35	4.14
Lily/2356 UTC 28 Sep 2002	2.77	2.87	5.71	4.65

about the same as that from the AWM wind 6-h forecast. However, the HM overestimated the hurricane winds overall. Figure 7 shows the two-dimensional wind field of Isabel at 0730 UTC 14 September. The average rms error is 3.85 and 3.50 m s^{-1} for the AWM 6- and 12-h forecasts, but 12.85 m s^{-1} for the HM and 5.49 m s^{-1} for the OHM (Table 2).

Forecasts for Hurricane Lily (2002) were made from 2100 UTC 21 September to 0900 UTC 4 October. Figure 8 shows the time series of Hurricane Lily winds at NDBC buoy stations DRYF1, LONF1, and SANF1. The rms error for the 6- and 12-h forecasts using the AWM are 1.59 and 1.71 m s^{-1}, respectively, whereas the rms error for the HM and OHM 6-h forecast reached 9.22 and 5.91 m s^{-1}, respectively (Table 1). Figure 9 shows the two-dimensional wind field of Hurricane Lily at 0130 UTC 28 September. The rms error is 2.31 and 3.17 m s^{-1} for the AWM 6- and 12-h forecasts, compared with 5.05 and 4.09 m s^{-1} for the HM and OHM, respectively (Table 2).

4. Quantifying uncertainty

The previous section noted that forecast quality of the asymmetric model depends on the quality of the NHC forecast guidance. In general, there are systematic and random errors present in all of the observed and forecast data that are used to optimize the axisymmetric and asymmetric wind models. It is important to take into account the resulting uncertainty in the optimization methods used to estimate the parameters in the original Holland model (B, R_{max}) and the proposed asymmetric model [B, $R_{max}(\theta)$]. Using Hurricane Floyd as a case study, statistical methods were used to quantify this uncertainty. First, the Holland model is reparameterized to account for the constraint, $1 < B < 2.5$ by rewriting the model using a new parameter β, where β is defined as follows:

$$B = 1.5\frac{e^{\beta}}{1 + e^{\beta}} + 1. \quad (10)$$

Estimates for β can then be used to estimate B using (10). The estimated values as well as the standard error values for the B and R_{max} parameters can be found using the method of nonlinear least squares (NLS).

The standard error estimates provide a measure of

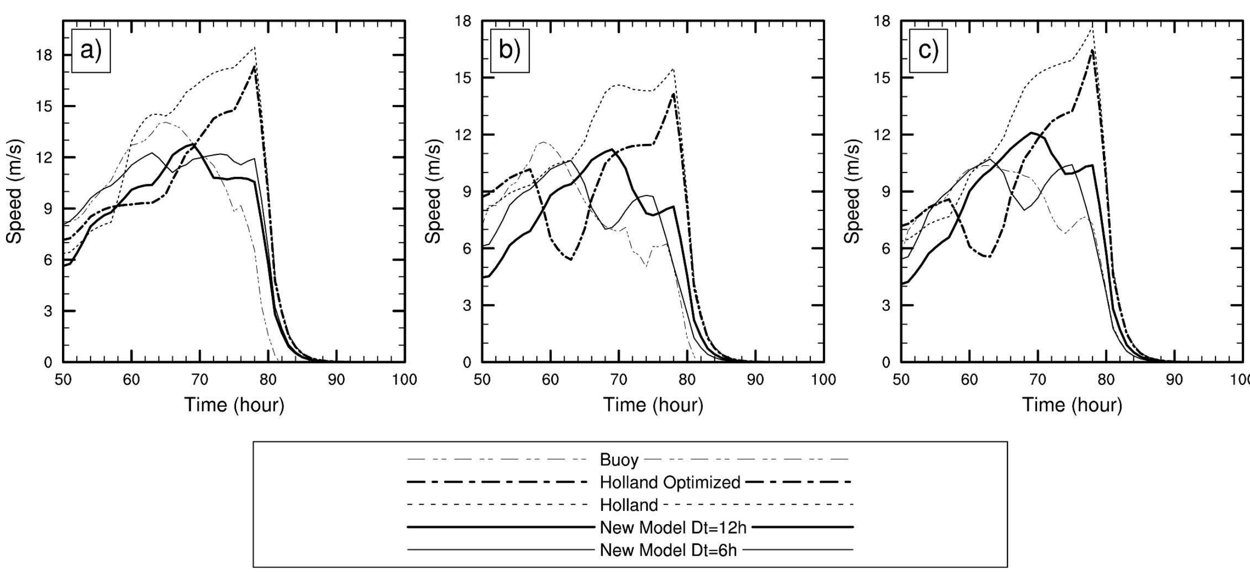

FIG. 4. Time series of wind speed during Hurricane Gordon (2000) at NDBC buoy station (a) SANF1; (b) 42041; and (c) DPIA1.

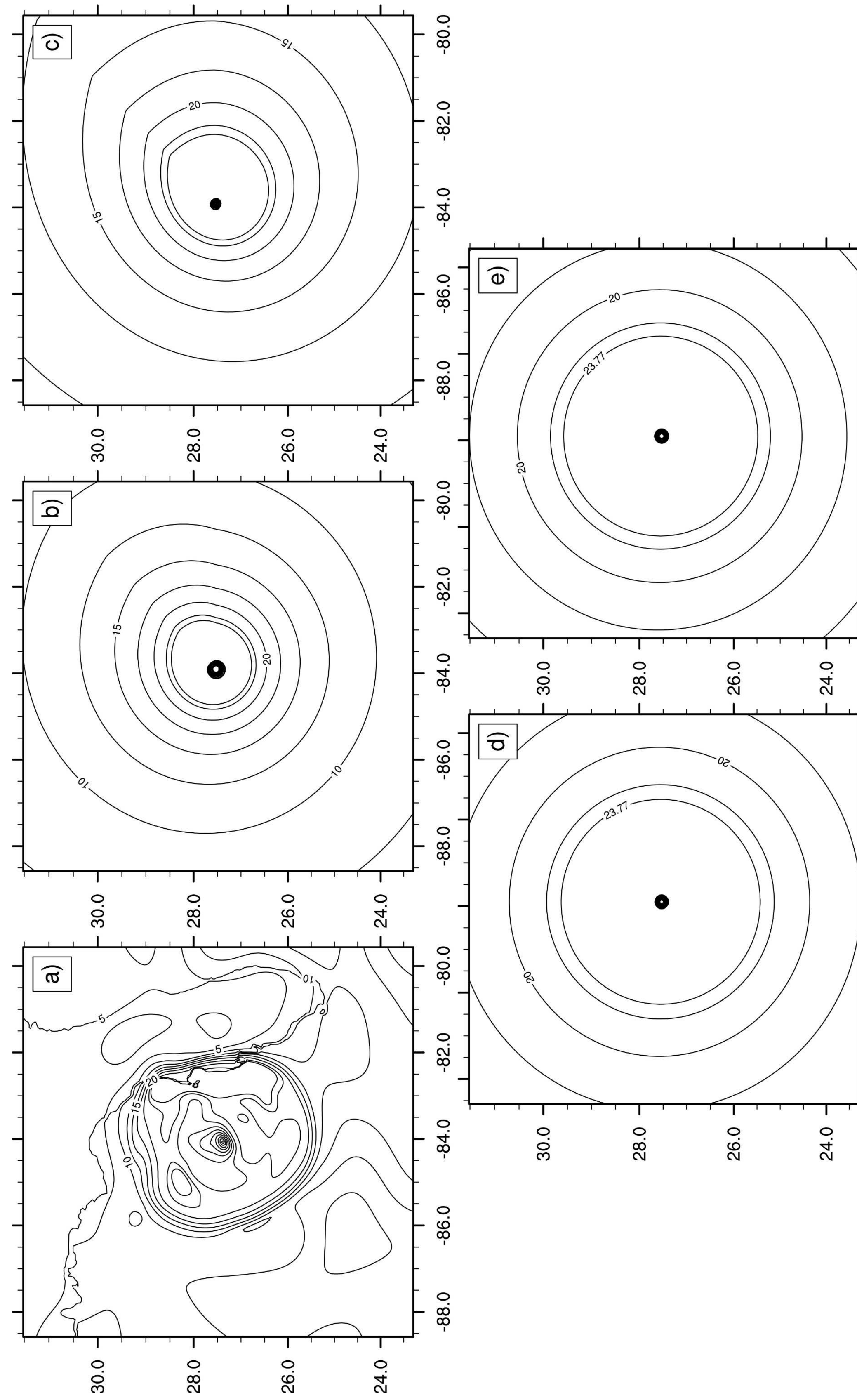

FIG. 5. Same as in Fig. 3, but for Gordon (2000) at 1330 UTC 17 Sep.

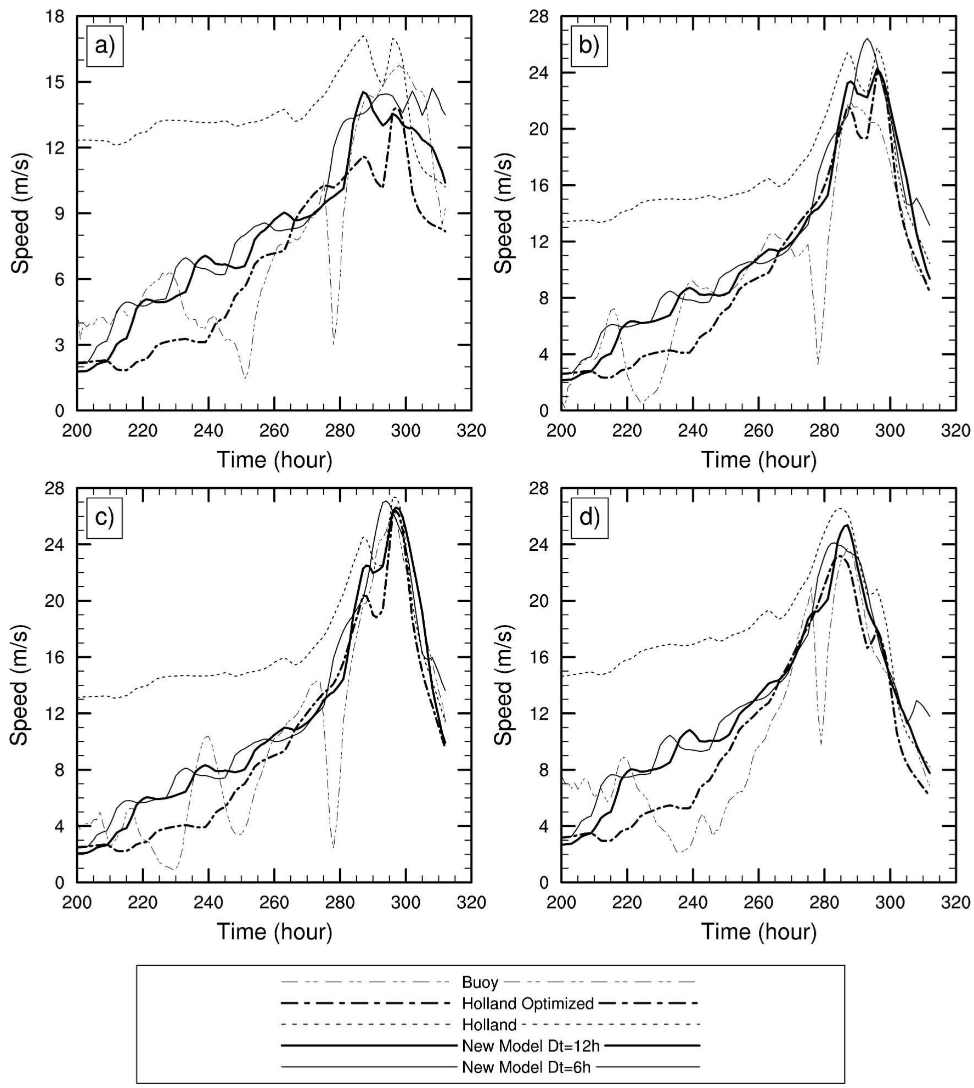

FIG. 6. Time series of wind speed during Hurricane Isabel (2003) at NDBC buoy station (a) 44025; (b) 44014; (c) CHLV2; and (d) 41001.

uncertainty associated with the estimated values for each parameter. For example, for the axisymmetric model the R_{max} estimates based on the NHC data at seven different time periods from 0130 UTC 14 September to 0700 UTC 16 September ranged from 12.5 to 16.25 n mi with standard errors ranging from 2.6 to 3.6 n mi. In contrast, the estimates of R_{max} in the four quadrants (northeast, northwest, southwest, and southeast) used to construct the asymmetric model ranged from 11.5 to 41.5 n mi across the four quadrants with standard errors ranging from 0.5 to 8.1 n mi. The estimates for the two parameters of the axisymmetric Holland model are based on the NHC reported maximum radial extent for sustained winds of 34-, 50-, and 64-kt winds in each quadrant surrounding the storm as well as additional buoy observations. Essentially the NHC data are information about three locations within each quadrant. The standard errors for the parameter estimates quantify how well the model was able to fit these data points. As a result, the extra parameters of the asymmetric model within each quadrant are estimated using fewer observations, and this additional uncertainty in the estimates is reflected in the larger standard error values. Thus, if only a small number of observational data points (such as in the case of buoy observations) are available, dividing these data points into four different quadrants actually increases the uncertainty in the error estimates.

Monitoring the standard errors of each estimate for R_{max} can help in a real-time situation when we may

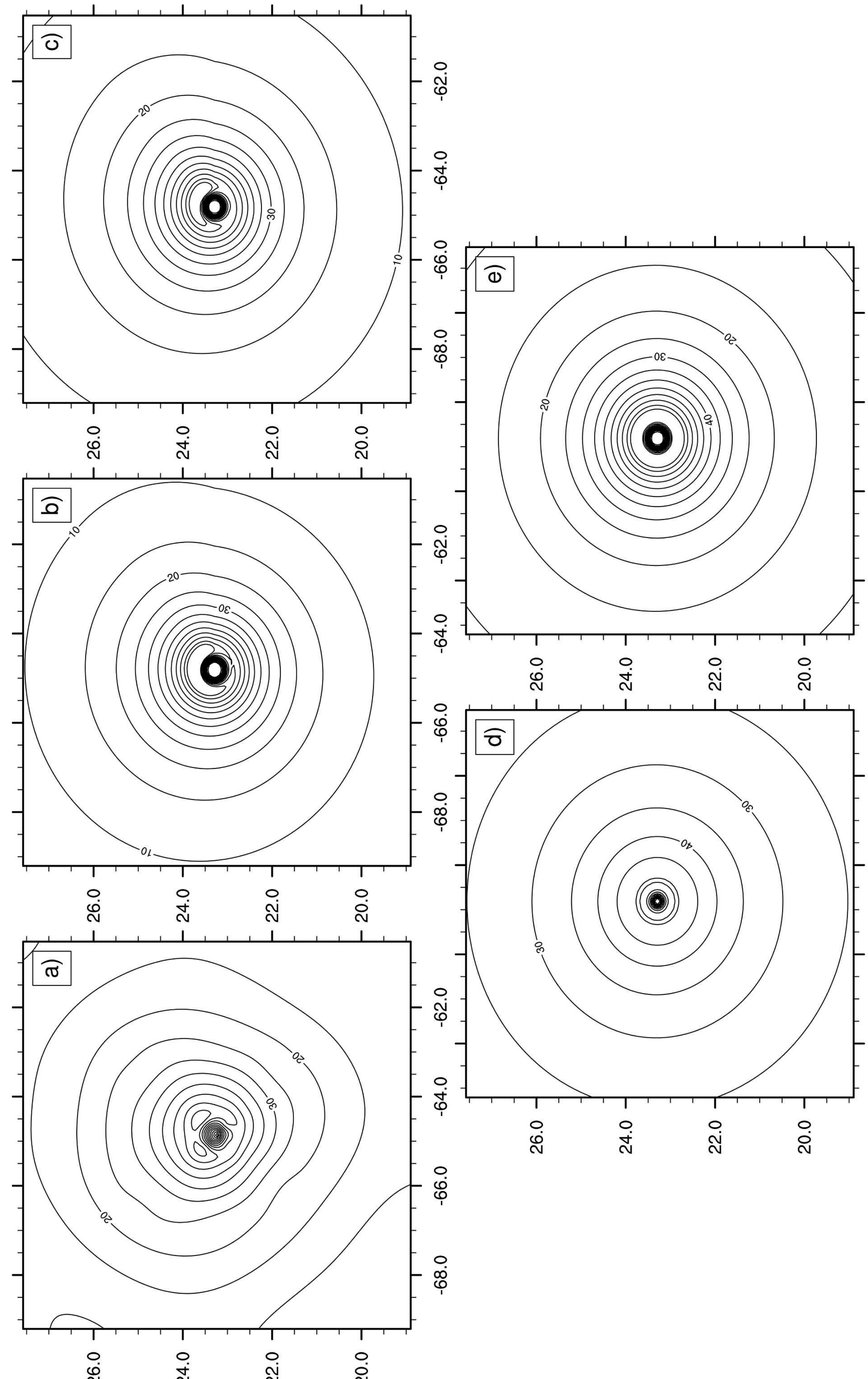

FIG. 7. Same as in Fig. 3, but for Isabel at 0730 UTC 14 Sep 2003.

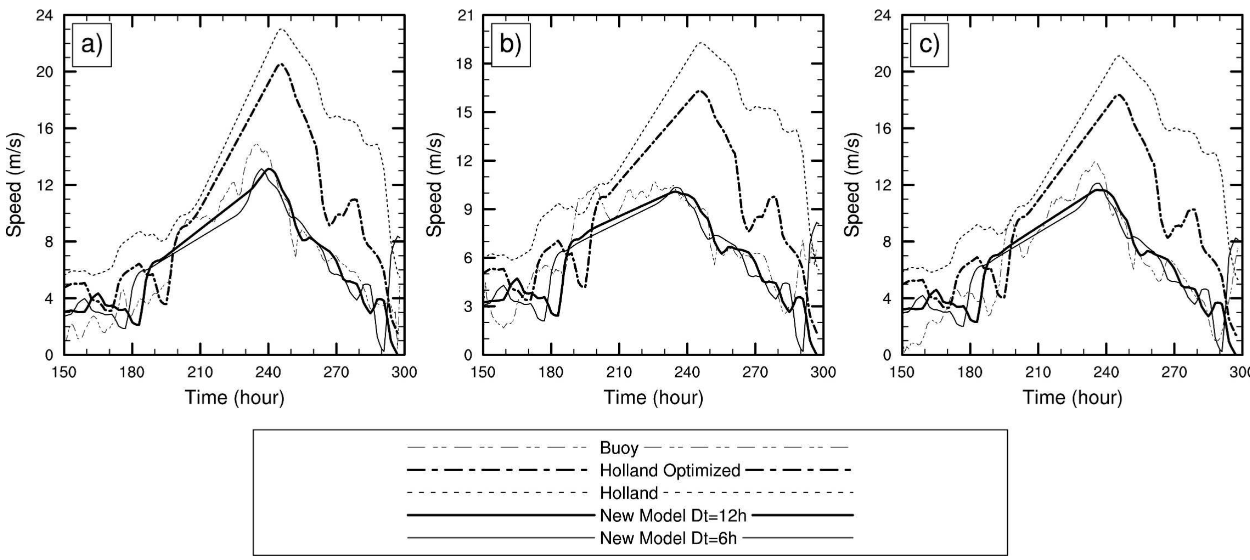

FIG. 8. Time series of wind speed during Hurricane Lily (2002) at NDBC buoy station (a) DRYF1; (b) LONF1; and (c) SANF1.

wish to decide if the axisymmetric or the asymmetric Holland model is more appropriate. As an example, Table 3 shows the nonlinear least square estimates and standard errors for the R_{max} parameter in the four quadrants of Hurricane Floyd for 0600 UTC 14 September and 1200 UTC 16 September. The HRD wind fields on 14 September show Hurricane Floyd had not yet made landfall along the U.S. coast and was still fairly organized with some evidence of stronger winds in the northeast and southeast quadrants. On 16 September Floyd had made landfall and had begun to weaken and the structure of the storm was much less organized. Thus it is expected that the differences in the estimates for R_{max} in the four quadrants will be more pronounced during this later time period. From Table 3, we see that for 14 September there is not a significant difference between the estimates for R_{max} in the different quadrants when the standard errors, which are relatively large, are considered. However for 16 September the standard errors are smaller, suggesting the new asymmetric model is more appropriate to account for these differences in the four quadrants.

The standard errors from the nonlinear least square estimation are based on the assumption that the residuals, or observed values minus fitted values, are independent and have homogeneous variance. For future analysis the estimation methods described here could be improved by taking into account the spatial correlation in the wind field. A generalized nonlinear least squares approach would account for errors that are correlated and/or have unequal variance but would also be more computationally demanding.

Another source of uncertainty in the analysis is the use of the HRD winds to evaluate the Holland model and new asymmetric model. Since the HRD winds are not direct measurements of the wind but rather a reanalysis of several different observation sources there are measurement errors as well as additional biases in this data. However the HRD winds incorporate observations from aircraft and so can give a better sense of the asymmetry of the storm than the buoys, which are scattered along the coast and can provide only limited information about the spatial features of the hurricane.

As a final comparison, data from Hurricane Floyd were used to compare the HRD data to the observed buoy winds to get a sense of the magnitude of the difference in the wind speed values from these two sources. To compare the buoy and HRD observations the buoy data are first adjusted to 10-m height and then interpolated in time and space. The buoy observations are hourly and the HRD winds were reported every 3 h. The buoy observations were interpolated temporally to the reporting time for the HRD winds. Additionally the buoy locations were interpolated in space to the closest HRD grid point. This was only done for buoy locations that fell within the HRD domain for any given time since the HRD reports a wind field only for a region around the center of the storm. This interpolation was done for 14 buoy locations during a period from 15 to 16 September 1999 for Hurricane Floyd when the storm moved up the eastern coast and eventually made landfall.

Combining the data from all sites for all of the time periods, 95% of the differences between the buoy and HRD wind speed observations (buoy − HRD) fell between −7.8 and 5.9 m s^{-1}, and the average difference

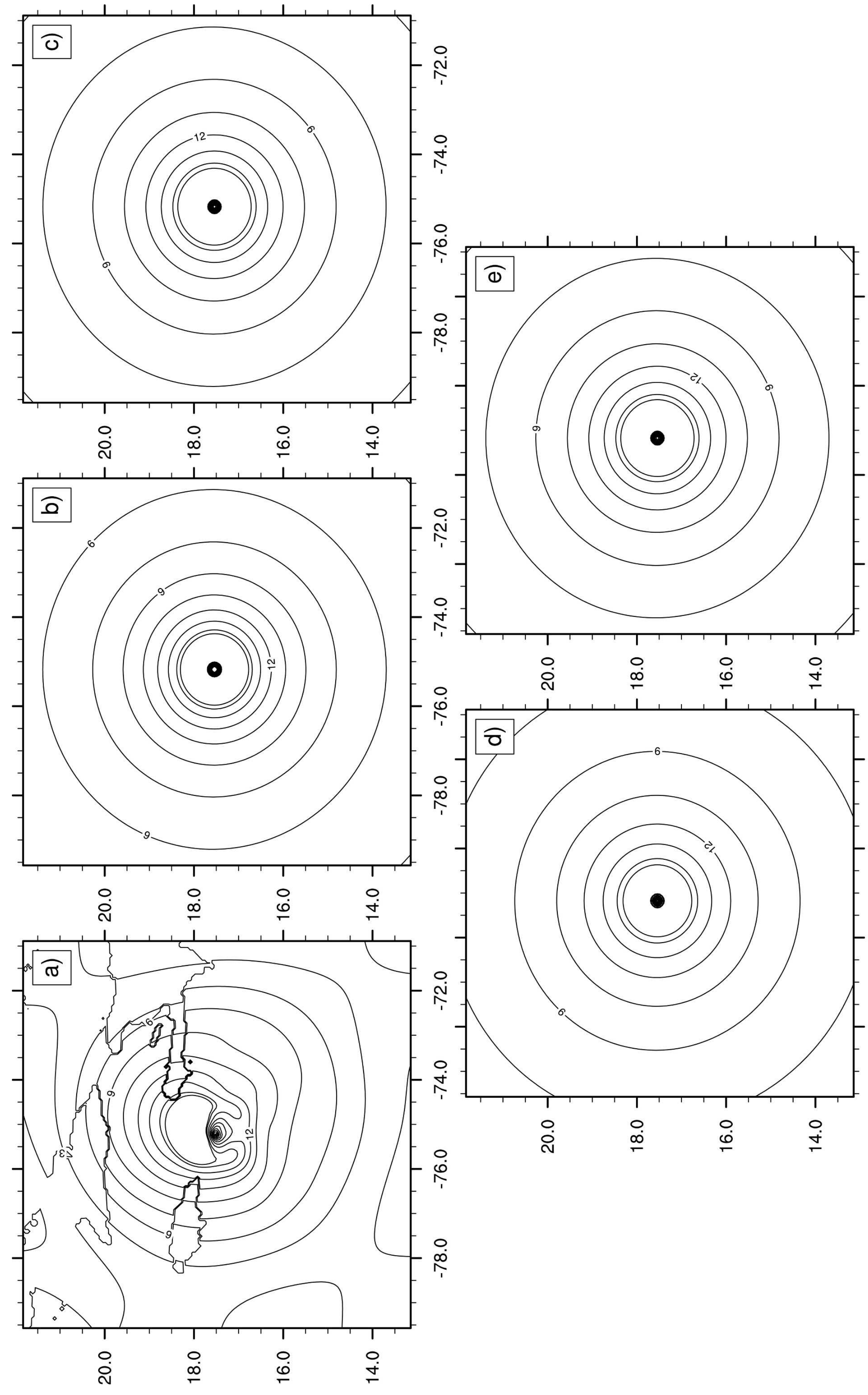

FIG. 9. Same as in Fig. 3, but for Lily at 0130 UTC 28 Sep 2002.

TABLE 3. Estimates of the R_{max} parameter (n mi) and standard errors (SEs) obtained using nonlinear least squares.

0600 UTC 14 Sep			1200 UTC 16 Sep		
Quadrant	R_{max}	SE	Quadrant	R_{max}	SE
NE	26.6	6.0	NE	41.5	2.5
NW	22.4	6.9	NW	10.7	1.4
SW	13.6	3.2	SW	11.9	0.6
SE	16.5	5.0	SE	32.8	1.5

between the buoy and HRD wind speed observations (buoy − HRD) was −0.9 m s^{-1} with a standard deviation of 3.7 m s^{-1}. The largest differences were approximately −10 m s^{-1} when the HRD winds are larger than the buoy winds. Looking at these differences across time the largest differences between the HRD and buoy observations occurred when the hurricane made landfall. At this point the HRD reported higher wind speeds at locations closest to the center of the storm. Also across all the time periods the difference in the two sources of data is largest for locations to the northeast of the storm center. Thus, despite the fact that buoy observations are included in HRD wind analysis, buoy observations and HRD winds still show large uncertainly. The uncertainty in observations presents a challenge in the validation of hurricane wind forecasts.

5. Conclusions

An asymmetric wind model is developed by incorporating an asymmetry term into the Holland model. This new asymmetric Holland model is further enhanced by using various near–real time data that are available to optimize the parameters in the model. Six- and twelve-hour forecasts of the wind fields for Hurricanes Floyd (1999), Gordon (2000), Lily (2002), and Isabel (2003) using this new model are compared against both the NDBC buoy data and HRD surface wind analysis, and the results are quite promising. Furthermore, the scheme developed within may be used to forecast and hindcast hurricane wind fields. It can be applied in numerical simulations of storm surge and waves induced by hurricanes. An automated real-time wind forecast system has been developed using this algorithm.

It should be noted that the accuracy of the forecast wind from the AWM strongly depends on the accuracy of the forecast (track and wind radii) guidance issued by the NHC. The AWM model provides a method to make use of the NHC forecast guidance, especially regarding the wind structure. The AWM translates the text of NHC forecast guidance of the four-quadrant radii of the 34-, 50-, and 64-kt wind speed and other real-time surface wind data into gridded wind forecasts that can be used by storm surge and wave modelers. It should be noted that real-time forecasting of hurricane winds is not only a challenge in making the forecasts due to errors and uncertainties in hurricane track and intensity forecasts, but also a challenge in quantifying the uncertainty in the forecasts due to uncertainties in hurricane wind analysis.

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APPENDIX

List of NDBC Buoy Stations Used for Four Different Hurricane Cases

a. Floyd (1999)

FPSN7 41001 41002 41004 41008 41009 41010 42036 44004 44005 44007 44008 44009 44011 44013 44014 44025 ABAN6 AL SN6 BUZM3 CDRF1 CHLV2 CLKN7 DBLN6 DRYF1 DSLN7 DUCN7 FBIS1 FWYF1 IOSN3 KTNF1 LKWF1 LONF1 MDRM1 MISM1 MLRF1 SANF 1 SAUF1 SMKF1 SPGF1 SUPN6 THIN6 TPLM2 VENF1

b. Gordon (2000)

41004 41008 41009 41010 42001 42003 42007 42036 42039 42040 42041 42042 42054 BURL1 CDRF1 CSBF1 DPIA1 DRYF1 FB IS1 FPSN7 FWYF1 GDIL1 KTNF1 LKWF1 LONF1 MLRF1 SANF1 SAUF1 SMKF1 SPGF1 VENF1

c. Lily (2002)

42001 42002 42003 42007 42019 42020 42035 42036 42039 42040 42041 BURL1 CSBF1 DPIA1 DRYF1 FWYF1 GDIL1 LONF1 ML RF1 PTAT2 SANF1 SMKF1 SRST2 VENF1

d. Isabel (2003)

41001 41002 41008 41010 41025 44009 44014 44017 44025 45002 45003 45005 45007 45008 45012 ABAN6 ALSN6 CHLV2 CL KN7 DBLN6 DSLN7 DUCN7 FBIS1 FPSN7 LSCM4 SBIO1 SUPN6 THIN6 TPLM2

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