9.4 An asymmetric hurricane wind model for storm surge and wave forecasting

Shaowu Bao*, Lian Xie, Leonard J. Pietrafesa
North Carolina State University, Raleigh, NC

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; Skamaroc et al. 2005) and hind-casting 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 and inundation forecasting. Holland's model (Holland 1980) assumes that for a generic tropical cyclone (TC), surface pressure field follows a modified rectangular hyperbola, as a function of radius, to give:

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

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

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

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.

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. However, 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). Various factors can contribute to the asymmetric structure of a hurricane, such as hurricane's system motion (Georgiou 1985), 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.

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 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.

*Corresponding author address: Shaowu Bao, NCSU/MEAS, Box 8208, Raleigh, NC 27695-8208. Email: sbao@ncsu.edu

2 Method

We use the forecasting of Hurricane Isabel (2003) wind field on September 18 0000 UTC as an example to illustrate the asymmetric hurricane forecasting system. First, NHC TC forecast guidance issued at 1500 UTC SEPT 17 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 September 18 0000UTC. The forecast storm center is at 31.4N 73.5W. The 1-minute 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.

In order 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:

$$R_{\max}(\theta) = P_1\theta^{n-1} + P_2\theta^{n-2} + ... + P_{n-1}\theta + P_n \tag{3}$$

$$P(r,\theta) = P_c + (P_n - P_c)\exp^{-(R_{\max}(\theta)/r)^B} \tag{4}$$

$$V(r) = \left[\frac{B}{\rho_a}\left(\frac{R_{\max}(\theta)}{r}\right)^B (P_n - P_c)\exp^{-(R_{\max}(\theta)/r)^B} + \left(\frac{rf}{2}\right)^2\right]^{1/2} - \frac{rf}{2} \tag{5}$$

where P is the atmospheric pressure, P_c is the hurricane center pressure, P_n is the environment pressure, $V(r)$ is the wind speed, ρ_a the atmosphere density, and f the Coriolis parameter.

From Eq. 5 we determine the initial values of B using V_{max}, P_n and P_c at the initial time (1500UTC, Sept 17, 2003):

$$B_0 = \frac{V_{\max}^2\rho_a e}{P_{n-}P_c} \tag{6}$$

where $V_{max} = V(r = R_{max})$, $e = 2.7183$.

Then, the NHC forecast guidance is used to curve-fit the polynomial (Eq. 3) to obtain R_{max} as a function of θ For example, in the NHC forecast for 0000UTC Sept 18 listed above, in the southeast quadrant, the radius of the 64 kt wind is 80 NM. Eq. 2 can be solved based upon this information and the corresponding R_{max} solution is 23.7 NM. The R_{max} values computed for the four quadrants for the 0000UTC Sept 18 forecast are 29.62, 23.70, 18.96, 29.62 NM for the northeast, southeast, southwest and northwest quadrants, respectively. Next, the coefficients of the 4th order polynomial (Eq. 3) are obtained by a polynomial curve-fitting of the R_{max} values. For the hurricane Isabel case, the coefficients at 0000UTC Sept 18 are estimated as follows:

$n = 5$

$P_1 = -2.5610^{-10}$

$P_2 = 2.1710 - 7$

$P_3 = -5.7010 - 5$

$P_4 = 4.8310 - 3$

$P_5 = 0.176$

The same procedure is used to compute to at the initial time (1500UTC, Sept 17 2003).

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, 6h and 12h wind forecasts are made. A 6h (12h) wind forecast utilizes NHC storm track and intensity forecast guidance that is validated 6h (12h) from the time when the wind forecast is made.

In the following, both 6h and 12h 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 m/s, 4.4 m/s, 7.9 m/s and 4.9 m/s for the AWM 6h, AWM12h, HM 6h and OHM 6h forecasts, respectively. The average RMS errors estimated by using the HRD wind analyses are 3.4 m/s, 3.3 m/s, 9.9m/s and 4.8 m/s for the AWM 6h, AWM12h, HM 6h and OHM 6h forecasts, respectively. Thus, both AWM 6h and 12h forecasts are generally in closer agreement with buoy observations and HRD surface wind analyses than the 6h forecasts computed by the HM and the OHM.

Next, consider the forecast error in more details 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 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 6h and 12h forecasts are updated hourly. The advantage of the asymmetric model is clearly demonstrated. As shown in Table 1, the overall RMS error for 6h (a) and 12h (b) forecasts using the asymmetric model was 2.26 m/s and 2.33 m/s, respectively, considerably smaller than that of the 6h forecast using the Holland model (c) (6.93 m/s) and the optimized Holland model (d) (5.18 m/s).

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
RMS Error	2.27	2.33	6.93	5.18

Table 1: Comparison of the maximum wind speed differences (in m/s) from buoy station measurements using different models: (a) new model 6h prediction (b) new model 12h prediction (c) non-optimized axisymmetric Holland model (d) optimized axisymmetric Holland model

Forecasts for Hurricane Floyd were made from 2100UTC September 7 to 0900UTC September 17, a 228-hour period. Figure 1 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 asymmetric wind model (AWM) 6h; and 5) the AWM 12h forecast results. The wind speed

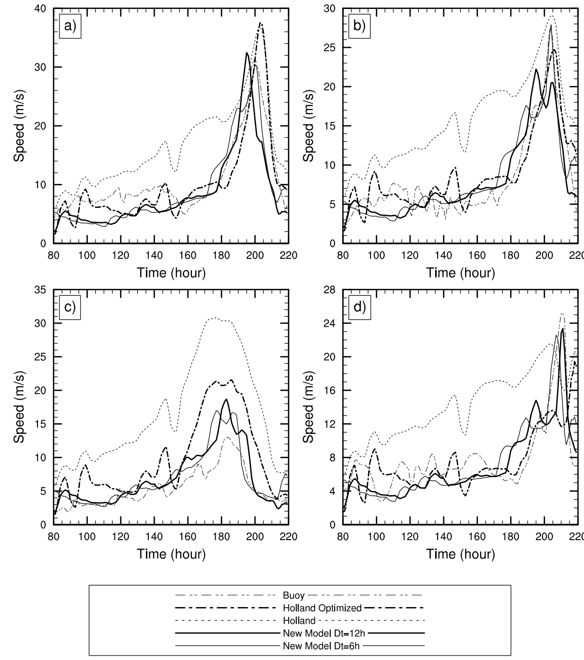

Figure 1: Time Series of wind speed during hurricane Floyd (1999) at NDBC buoy station a) FPSN7 b) CLKN7 c) VENF1 and d) 44014

at each hour is the forecast result using the NHC forecast guidance available 6h and 12h 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 SLOSH 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 were optimized using the NHC forecast guidance available 6 hours before the forecast validation time.

Figure 1 shows that wind forecasts from the AWM showed better agreement with buoy measurements than those forecast from the HM. As shown in Fig. 1 a), b) and c), the HM overestimated the maximum wind speed, while in Fig. 1 d, it underestimated the maximum wind speed. The RMS error for the 6h and 12h forecasts using the AWM are 3.07 m/s and 4.19 m/s, respectively, whereas the RMS for the Holland model reached 10.14 m/s (without optimization) and 8.22 m/s (with optimization) (Table 1). For all buoy stations, the Holland model tended to overestimate the wind speed before the peak

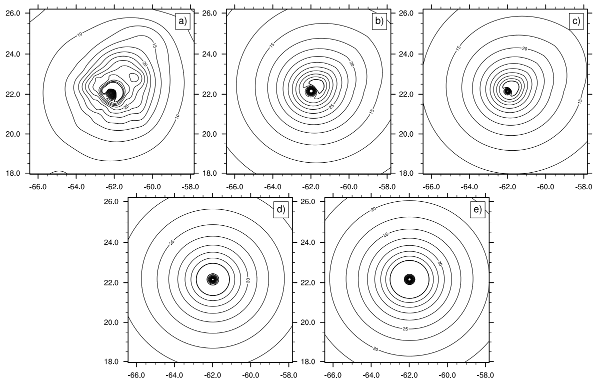

Figure 2: Two dimensional wind structures of Floyd (1999) at Sept-11-13:30 a) HRD wind analysis b) New asymmetric model forecast (Dt=6h) c) New asymmetric model forecast (Dt=12h) d) non-optimized Holland model e) optimized Holland model

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 2 shows the two-dimensional wind fields of Floyd at September 11-1300UTC. The five panels of the figure are, respectively, a) the wind field of HRD surface wind analysis; b) the AWM 6h forecast; c) the AWM 12hr forecast; d) the HM 6h forecast; and e) the OHM 6h forecast. It is shown that the AWM 6 h and 12 Hurricane 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 m/s and 5.45 m/s for the asymmetric model's 6h and 12h forecasts, 8.29 m/s and 6.77 for the HM 6h 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 describe the hurricane asymmetric wind structure, its RMS error is larger than those of the AWM 6h and 12h forecasts.

Hurricane/Time	a	b	c	d
Floyd1999_0911_13_30	3.77	4.37	11.12	11.06
Floyd1999_0912_01_30	3.57	3.38	7.12	4.44
Floyd1999_0913_19_30	4.39	7.61	4.01	6.33
Floyd1999_0915_07_30	5.02	6.45	10.94	5.28
Gordon2000_0917_16_30	9.55	7.55	11.48	9.48
Gordon2000_0917_13_30	5.38	7.85	12.34	11.97
Gordon2000_0917_19_30	7.99	6.70	10.68	8.79
Isabel2003_0911_17_30	4.32	4.28	14.07	8.81
Isabel2003_0913_07_30	2.59	3.09	12.67	3.91
Isabel2003_0914_07_30	4.66	3.15	11.84	3.76
Lily2002_0928_01_30	2.29	3.50	4.12	3.50
Lily2002_0928_19_30	1.88	3.16	5.35	4.14
Lili2002_0928_23_56	2.77	2.87	5.71	4.65

Table 2: Comparison of the root mean square errors (m/s) from the HRD wind analysis using different methods: (a) new model 6h prediction (b) new model 12h prediction (c) non-optimized axisymmetric Holland model (d) optimized axisymmetric Holland model

4 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. 6h and 12h forecasts of the wind fields for hurricane 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 4-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.

5 Acknowledgement

This study is supported by the Carolina Coastal Ocean Observation and Prediction System (Caro-Coops) project under NOAA Grant No. NA16RP2543 via the National Ocean Service, through Charleston Coastal Services Center. Caro-COOPS is a partnership between the University of South Carolina and North Carolina State University.

References

Chen, Y. and M. K. Yau, 2003: Asymmetric structures in a simulated landfalling hurricane. *J.A.S.*, **60**(18), 2294–2312.

Georgiou, P., 1985: *Design Wind Speeds in Tropical Cyclone Prone Regions*. Ph.D. thesis, University of Western Ontario.

Holland, G. J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Monthly Weather Review*, **108**, 1212–1218.

Houston, S. H., W. A. Shaffer, M. D. Powell and J. Chen, 1999: Comparisons of HRD and SLOSH surface wind fields in hurricanes: Implications for storm surge modeling. *Weather and Forecasting*, **14**(5), 671–686.

Hsu, S. A. and Z. Yan, 1998: A note on the radius of maximum wind for hurricanes. *Journal of coastal research*, **14**(2), 667–668.

Jelesnianski, C., J. Chen and W. Shaffer, 1992: Slosh: sea, lake and overland surges from hurricane. Technical report, National Weather Service, silver springs, MD.

Large, W. G. and S. Pond, 1981: Open ocean momentum flux measurements in moderate to strong winds. *J. Phys. Oceanogr.*, **11**, 324–336.

Powell, M. D. and S. H. Houston, 1998: Surface wind fields of 1995 hurricanes erin, opal, luis, marilyn, and roxanne at landfall. *Monthly Weather Review*, **126**(5), 1259–1273.

Ross, R. J. and Y. Kurihara, 1992: A simplified scheme to simulate asymmetries due to the beta effect in barotropic vortices. *Journal of the Atmospheric Sciences*, **49**(17), 1620–1628.

Shapiro, L., 1983: The asymmetric boundary layer flow under a translating hurricane. *J. ATMOS. SCI.*, **40**(8), 1984–1998.

Skamaroc, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang and J. G. Powers, 2005: A description of theadvanced research wrf version 2. Technical Report NCAR/TN468+STR, NCAR, Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, Corolado, USA.

Wang, Y. and G. J. Holland, 1996: Tropical cyclone motion and evolution in vertical shear. *Journal of the Atmospheric Sciences*, **53**(22), 3313 3332.

Xie, L., S. Bao, L. Pietrafesa, K. Foley and M. Fuentes, 2005: A real-time hurricane surface wind forecasting model: Formulation and verification. *Monthly Weather Review*, (in press).