Statistical Models of Holland Pressure Profile Parameter and Radius to Maximum Winds of Hurricanes from Flight-Level Pressure and H*Wind Data

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ABSTRACT

In many hurricane risk models the inclusion of the Holland *B* parameter plays an important role in the risk prediction methodology. This paper presents an analysis of the relationship between *B* and a nondimensional intensity parameter. The nondimensional parameter includes the strong negative correlation of *B* with increasing hurricane size [as defined by the radius to maximum winds (RMW)] and latitude as well as a positive correlation with sea surface temperature. A weak positive correlation between central pressure deficit and *B* is also included in the single parameter term. Alternate statistical models relating *B* to RMW and latitude are also developed. Estimates of *B* are derived using pressure data collected during hurricane reconnaissance flights, coupled with additional information derived from the Hurricane Research Division's H*Wind snapshots of hurricane wind fields. The reconnaissance data incorporate flights encompassing the time period 1977 through 2001, but the analysis was limited to include only those data collected at the 700-hPa-or-higher level. Statistical models relating RMW to latitude and central pressure derived from the dataset are compared to those derived for U.S. landfalling storms during the period 1900–2005. The authors find that for the Gulf of Mexico, using only the landfall hurricanes, the data suggest that there is no inverse relationship between RMW and the central pressure deficit. The RMW data also demonstrate that Gulf of Mexico hurricanes are, on average, smaller than Atlantic Ocean hurricanes. A qualitative examination of the variation of *B*, central pressure, and radius to maximum winds as a function of time suggests that along the Gulf of Mexico coastline (excluding southwest Florida), during the final 6–24 h before landfall, the hurricanes weaken as characterized by both an increase in central pressure and the radius to maximum winds and a decrease in *B*. This weakening characteristic of landfalling storms is not evident for hurricanes making landfall elsewhere along the U.S. coastline.

1. Introduction

Hurricane risk models are commonly used for estimating insurance risk (e.g., Powell et al. 2005; Vickery et al. 2006), for providing information on wind speeds for the design of buildings in the United States (American National Standards Institute 1982; American Society of Civil Engineers 1990, through to the present), the Caribbean (Caribbean Community Secretariat 1986), and Australia (Standards Association of Australia 1989), or for use in estimating design storm surge values. The simulation methodologies are described in detail in reports and in the peer-reviewed literature (e.g., Batts et al. 1980; Georgiou 1985; Vickery et al. 2000; Powell et al. 2005; James and Mason 2005; Lee and Rosowsky 2007). One of the components used within a hurricane risk model is a hurricane wind field model. In most hurricane risk applications the primary inputs to the hurricane wind field model include a representation of surface pressure field (defined using a minimum of a radius and a central pressure deficit) and a system translation speed. The surface level pressure field is used to drive a wind field model to obtain estimates of the wind speeds at the top of the boundary layer (assumed to be about 500 m in most cases), and then coupled with a boundary layer model to finally arrive at estimates of the surface level wind field, as defined by wind speeds and directions at any location within the model hurricane. These wind field model inputs are simulated using statistical models derived from historical data to develop thousands of years of simulated hurricanes. Historical information on central pressure is usually obtained from sources including the National Hurricane Center (NHC) database (HURDAT; Jar-

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vinen et al. 1984) and the Tropical Prediction Center publication (Blake et al. 2007 and predecessors). Information for the storm radius [usually defined by the radius to maximum winds (RMW)] is usually derived from the National Weather Service (NWS) 38 publication (Ho et al. 1987), supplemented with additional information derived from the Hurricane Research Division's H*Wind (Powell et al. 1998) snapshots of hurricane wind fields.

In some hurricane risk models an additional term, commonly referred to as the Holland B parameter, is used to define the pressure field and plays an important role in the risk prediction methodology (e.g., Vickery et al. 2000; Powell et al. 2005).

Holland (1980) describes the radial distribution of surface pressure in a hurricane in the form

$$p(r) = p_0 + \Delta p \exp - \left(\frac{A}{r^B}\right), \tag{1}$$

where $p(r)$ is the surface pressure at a distance r from the storm center, p_0 is the central pressure, Δp is the difference between the peripheral pressure and the central pressure, A is the location parameter, and B is Holland's pressure profile parameter. Holland (1980) showed that RMW $= A^{1/B}$, and thus (1) can be expressed as

$$p(r) = p_0 + \Delta p \exp - \left(\frac{\mathrm{RMW}}{r}\right)^B. \tag{2}$$

The gradient balance velocity V_G for a stationary storm is thus

$$V_G = \left\{\left(\frac{\mathrm{RMW}}{r}\right)^B \frac{B\Delta p \exp\left[-\left(\frac{\mathrm{RMW}}{r}\right)^B\right]}{\rho} + \frac{r^2 f^2}{4}\right\}^{1/2} - \frac{fr}{2}, \tag{3}$$

where ρ is the density of air and f is the Coriolis parameter. The maximum wind speed at the RMW is

$$V_{G\max} \approx \sqrt{\frac{B\Delta p}{e\rho}}. \tag{4}$$

In parametric hurricane wind field models where the input surface pressure field is defined by two parameters (Δp and a radius), the maximum wind speed in the simulated hurricane is proportional to $\sqrt{\Delta p}$, whereas with the introduction of the additional term, B, the maximum wind speed in the simulated hurricane is proportional to $\sqrt{B\Delta p}$. Figure 1 presents example pressure profiles and gradient speed wind profiles associated with (1)–(3).

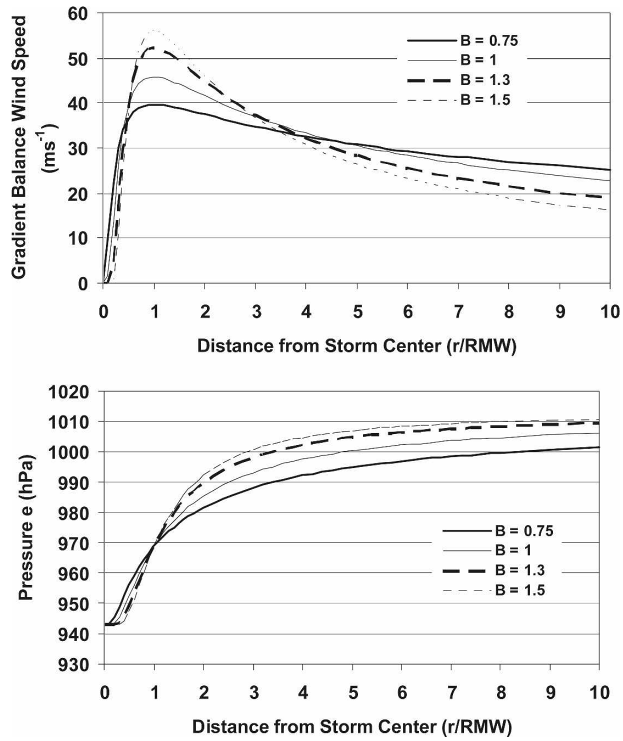

FIG. 1. Effect of B on (top) gradient balance wind speed and (bottom) pressure vs distance from storm center.

It is noteworthy that modeling the surface pressure field using an equation in the form of (2) is a significant improvement over modeling the pressure field with empirical models described by only two parameters. The approach still has limitations, as discussed for example in Thompson and Cardone (1996), Willoughby and Rahn (2004), Willoughby et al. (2006), and Vickery et al. (2008); the use of a single value of B (or RMW) does not reproduce the azimuthal and radial variations in the pressure fields (and hence wind fields) that are often found in real hurricanes.

Thus, while the use of (2) has limitations, when incorporated within a hurricane simulation model, the approach allows for the modeling of both Hurricane Katrina–like storms ($p_0 \sim 920$ hPa, $V_{\max} \sim 110$ kt) and Hurricane Charley–like storms, ($p_0 \sim 942$ hPa, $V_{\max} \sim 125$ kt), where $V_{\max}$ is the estimated maximum 1-min average wind speed at a height of 10 m over water as defined by the NHC. The omission of B does not allow for the variation in the maximum wind speed observed in real hurricanes for a given Δp (all else being equal).

Modeling B as a random variable within a hurricane simulation model was first introduced by Vickery et al. (2000). They estimated B using a subset of the reconnaissance aircraft dataset used here, by fitting a variation of (4) to the wind speeds from flights flown at heights of 3000 m and less and 1500 m and less and settled on a model based on the 1500 m and less estimates of B. Their fits were performed over the range [0.5RMW, 1.5RMW], and they modeled B as a function of RMW and Δp using

$$B = 1.38 - 0.001\,84\Delta p + 0.003\,09\mathrm{RMW}; \quad r^2 = 0.026. \tag{5}$$

Willoughby and Rahn (2004) used the same flight-level dataset used here to estimate B, deriving their estimates of B by minimizing a cost function incorporating both wind speed and pressure (as defined by geopotential height). Willoughby and Rahn (2004) developed statistical models for B and RMW in the form

$$B = 1.0036 + 0.0173V_{F\max} + 0.0313\ln(\mathrm{RMW}) + 0.0087\psi; \quad r^2 = 0.51, \quad \sigma_B = 0.25 \quad \text{and} \tag{6}$$

$$\ln(\mathrm{RMW}) = 3.94 - 0.0223V_{F\max} + 0.0281\psi; \quad r^2 = 0.297; \quad \sigma_{\ln\mathrm{RMW}} = 0.441, \tag{7}$$

where $V_{F\max}$ is the maximum flight-level wind speed and ψ is latitude. Unfortunately, an equation in the form of (6) cannot be used in hurricane risk models where wind speeds are outputs of the models, not inputs. Powell et al. (2005) obtained the B values computed by Willoughby and Rahn (2004) and developed a model for B in the form

$$B = 1.881 - 0.005\,57\mathrm{RMW} - 0.010\,97\psi; \quad r^2 = 0.2; \quad \sigma_B = 0.286. \tag{8}$$

The importance of B in hurricane wind speed risk modeling is demonstrated in Fig. 2 where, using the hurricane simulation model described by Vickery and Twisdale (1995) coupled with the wind field model described in Vickery et al. (2008), we estimate the magnitude of the peak (3 s) gust wind speed (10 m above ground in open terrain) at two locations using two different models describing B. The first model for B is that given in Vickery et al. (2000) and reproduced here as (5), and the second model is presented later in this paper as (22). The comparisons indicate that changing the statistical model for B from that described using (5) to that described using (22) results in a reduction in the estimated 100-yr return period wind speed of ~6% at Biloxi and ~9% at Cape Hatteras. These 6% and 9% reductions in wind speed correspond to 12% and 18% reductions of the wind loads needed to design building components, suggesting a possible significant economic penalty (or savings) associated with the modeling of B.

The RMW also plays an important role in hurricane risk prediction, particularly for storm surge and wave modeling. The RMW data provided in the NWS 38 publication constitute a primary reference for developing RMW models, as it provides information of the RMW for almost all hurricanes making landfall along the U.S. coastline between 1900 and 1985. Here we use the flight-level and H*Wind data to develop statistical models of the RMW (relating the RMW to other parameters that are usually modeled in a risk model) and compare these models with models developed using the more traditional approach that includes landfalling hurricane RMW data only. The models (both open ocean and landfall) are presented for all hurricanes, and separately for Gulf of Mexico (GoM) hurricanes and Atlantic Ocean hurricanes.

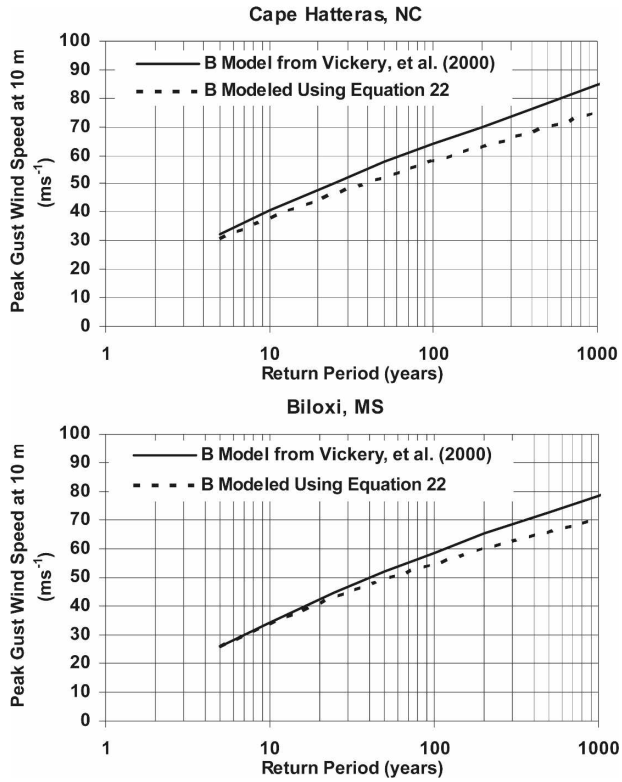

FIG. 2. Effect of changes in statistical models for B on predicted peak gust wind speed vs return period: (top) Cape Hatteras, NC and (bottom) Biloxi, MS.

Analysis approach and findings

To obtain information on both B and RMW we use pressure data collected during hurricane reconnaissance flights, coupled with additional information derived from the Hurricane Research Division's H*Wind (Powell et al. 1998) snapshots of hurricane wind fields. We examine the correlation of RMW with latitude and central pressure as well as region (Gulf of Mexico versus Atlantic Ocean). We compare statistical models developed using the reconnaissance and H*Wind data with those derived using landfall-only data and show that in the case of Gulf of Mexico storms the limited landfall dataset does not exhibit the negative RMW–Δp relationship included in most risk models and the reconnaissance and H*Wind data.

We find that B is inversely correlated with both the size and latitude of a hurricane. A weak positive correlation of B with central pressure deficit and sea surface temperature is also evident. A statistical relationship between B and a nondimensional parameter incorporating central pressure, radius to maximum winds, sea surface temperature, and latitude is introduced. A separate assessment of B obtained by modeling the surface level wind speeds of landfalling hurricanes is used in a comparison with the characteristics of B deduced using the reconnaissance and H*Wind data.

2. Datasets and estimation of *B* and *RMW*

The primary dataset used to develop a database of B and RMW was the upper-level reconnaissance data (available at ftp://ftp.aoml.noaa.gov/hrd/pub/data/flightlevel/). This dataset is described in more detail in Willoughby and Rahn (2004), and includes 606 "logical" sorties taken during the period 1977 through 2004. All data have been processed as described in Willoughby and Chelmow (1982). This dataset was supplemented with additional information on B and RMW derived from H*Wind snapshots of hurricane wind fields.

a. Estimation of B and RMW using reconnaissance data

The upper-level aircraft dataset used here contains a total of 4546 radial profiles from 62 Atlantic tropical cyclones. These data are the same as those used by Willoughby and Rahn (2004) in their analysis of B. For each storm in the database, data have been organized based on the different flights that passed through the storm. For each flight, the airplane traversed through the hurricane a number of times in different directions. For every pass the data were collected from the center of the storm to a certain radius (usually 150 km). The data are then organized according to radial distance from the center of the storm. For each bin (based on the radius from the center of the storm), flight-level pressure, flight altitude, dewpoint temperature, wind speed, and air temperature are available.

A quality control (QC) criterion was used to filter out profiles. Each of the filtered profiles has at least one of the following characteristics associated with it: (i) flight-level pressure is not equal to 700 hPa, (ii) Δp is less than 25 hPa, (iii) the RMW is greater than two-thirds of the sampling domain, (iv) the distance of the aircraft closest approach to the center is greater than half of the RMW, (v) data are available for less than one-third of the sampling range (i.e., less than 50 km), and (vi) visual inspection that involved eliminating profiles with a considerable amount of data missing in the range of interest [0.5RMW, 1.5RMW]. The rationale for using criterion i is that the pressure fields derived from flight-level surfaces of less than 700 hPa are likely to be less representative measurements of the surface observations. Criterion ii results in the data associated with more intense storms. The rationale for using criteria iii–vi is to ensure that there are a sufficient number of measurements on both sides of the RMW to have a clear representation of the shape of the profile (Willoughby and Rahn 2004). In the case of criterion ii, we note that category 1 hurricane winds can occur when Δp is less than 25 hPa; however, we attempt to limit the data to be biased toward the more intense storms, which govern wind risk studies. As will be noted later, we further truncate the data to include only storms with central pressures less that 980 hPa, or $\Delta p \sim 33$ hPa.

TABLE 1. Distribution of filtered pressure profiles based on filtering criteria.

Filter criteria	No. of profiles eliminated
i	459
ii	1180
iii	121
iv + v + vi	531
Total No. of filtered profiles	2291

The use of the quality control criteria eliminated a total of 2291 profiles from a set of 4556 profiles. Table 1 presents the count of the eliminated pressure profiles based on the QC criteria. It is clear that criteria i and ii are the most common reasons for profile elimination. The storm by storm percentage of the retained profiles is given in Table 2. For some storms, no profiles were retained as all the profiles either had Δp of less than 25 hPa (e.g., Chantal in 1995) or a flight-level pressure of less than 700 hPa (e.g., Hugo in 1989).

The geographical distribution of the profiles that passed the QC criteria is shown in Fig. 3.

Figure 4 presents a few examples of pressure profiles that were eliminated from the analysis. Both the measured pressure data and the corresponding fit to Holland's equation are shown. It is observed that each of the subplots in Fig. 4 is compromised by at least one of the above-mentioned quality control criteria.

TABLE 2. Percentage of flight-level pressure profiles retained.

Storm	Year	Total	Retained	Percent retained	Comments
No name	1938	5	5	100.00	Data extracted manually from Myers and Jordan (1956)
Anita	1977	20	20	100.00	
David	1979	24	17	70.83	
Frederic	1979	62	38	61.29	
Allen	1980	125	43	34.40	
Gert	1981	78	1	1.28	$\Delta p < 25$ hPa for all the cases, except one
Alicia	1983	50	39	78.00	
Arthur	1984	22	0	0.00	$\Delta p < 25$ hPa for all the cases
Diana	1984	128	67	52.34	
Danny	1985	26	0	0.00	$\Delta p < 25$ hPa for all the cases
Elena	1985	122	99	81.15	
Gloria	1985	42	24	57.14	
Isabel	1985	48	0	0.00	$\Delta p < 25$ hPa for all the cases
Juan	1985	36	6	16.67	
Charley	1986	28	0	0.00	$\Delta p < 25$ hPa for all the cases
Emily	1987	56	1	1.79	40 out of 56 profiles have flight-level pressure < 700 hPa
Floyd	1987	22	0	0.00	$\Delta p < 25$ hPa for all the cases
Florence	1988	20	11	55.00	
Gilbert	1988	50	39	78.00	
Joan	1988	6	5	83.33	
Dean	1989	12	1	8.33	
Gabrielle	1989	12	10	83.33	
Hugo	1989	40	0	0.00	Flight-level pressure < 700 hPa for all the cases
Jerry	1989	17	5	29.41	
Gustav	1990	84	82	97.62	
Bob	1991	92	34	36.96	
Claudette	1991	73	71	97.26	
Andrew	1992	141	95	67.38	
Debby	1994	10	0	0.00	$\Delta p < 25$ hPa for all the cases
Gordon	1994	83	8	9.64	57 out of 83 profiles have $\Delta p < 25$ hPa
Allison	1995	39	3	7.69	35 out of 39 profiles have $\Delta p < 25$ hPa
Chantal	1995	72	0	0.00	$\Delta p < 25$ hPa for all the cases
Erin	1995	97	66	68.04	
Felix	1995	130	59	45.38	
Gabrielle	1995	16	0	0.00	$\Delta p < 25$ hPa for all the cases
Iris	1995	132	41	31.06	
Luis	1995	130	77	59.23	
Marilyn	1995	116	96	82.76	
Opal	1995	76	21	27.63	
Roxanne	1995	141	52	36.88	
Bertha	1996	78	56	71.79	
Cesar	1996	34	0	0.00	$\Delta p < 25$ hPa for all the cases
Edouard	1996	178	135	75.84	
Fran	1996	143	102	71.33	
Hortense	1996	109	59	54.13	
Josephine	1996	23	1	4.35	
Kyle	1996	8	0	0.00	$\Delta p < 25$ hPa for all the cases
Lili	1996	68	28	41.18	
Marco	1996	67	1	1.49	$\Delta p < 25$ hPa for all the cases, except two
Erika	1997	56	36	64.29	
Bonnie	1998	193	113	58.55	
Danielle	1998	133	48	36.09	
Earl	1998	32	3	9.38	
Georges	1998	202	125	61.88	
Mitch	1998	86	57	66.28	
Bret	1999	102	49	48.04	
Dennis	1999	158	83	52.53	
Floyd	1999	163	103	63.19	
Keith	2000	50	40	80.00	
Leslie	2000	29	0	0.00	$\Delta p < 25$ hPa for all the cases
Michael	2000	21	11	52.38	
Humberto	2001	46	13	28.26	
Michelle	2001	89	61	68.54	

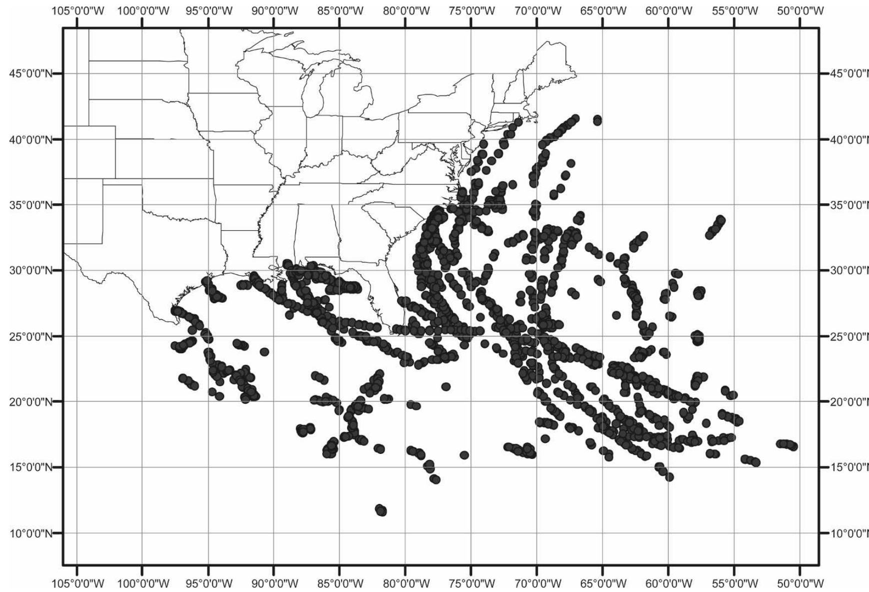

FIG. 3. Geographical distribution of the profiles passing the QC criteria.

To estimate the values of B and RMW that best represent the pressure field using (2), we first estimate RMW using the radius to the measured maximum wind speed. We then vary the values of RMW and B over the range [0.5RMW, 1.5RMW] and [0.5, 2.5], respectively, and retain the values that minimize the mean of the square difference between the measured and modeled surface pressure over the range [0.5RMW, 1.5RMW]. The mean square error is defined as

$$\varepsilon^2 = \frac{\sum_{i=0.5\mathrm{RMW}}^{1.5\mathrm{RMW}} (P_{\mathrm{obs}_i} - P_{\mathrm{theo}_i})^2}{n}, \qquad (9)$$

where P_{obs_i} is the measured pressure, P_{theo_i} is the theoretical pressure calculated using (2), and n is the number of data points in the range [0.5RMW, 1.5RMW]. The corresponding r^2 value for the fit is given by

$$r^2 = 1 - \frac{\varepsilon^2}{\sigma^2}, \qquad (10)$$

where σ is the standard deviation of the measured pressure data in the range of [0.5RMW, 1.5RMW]. Minimizing the error over the range [0.5RMW, 1.5RMW] ensures that the estimate of B is associated with the

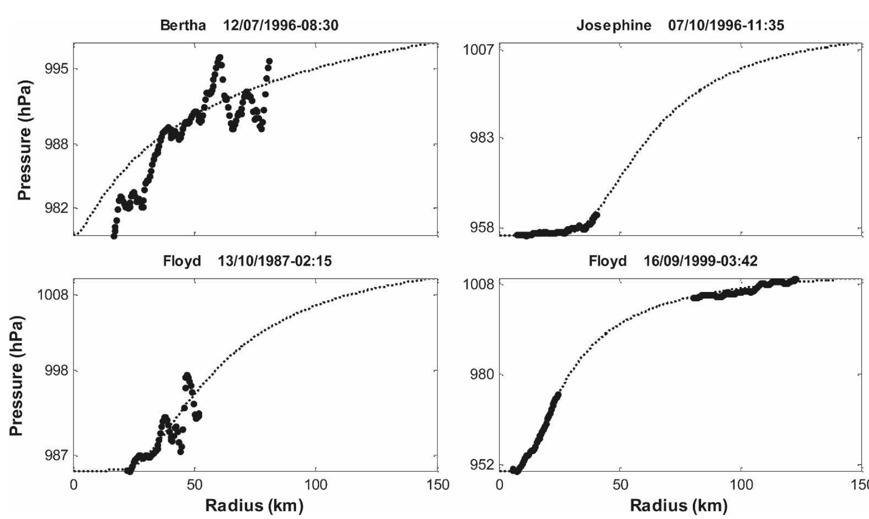

FIG. 4. Examples of the eliminated profiles: (top left) Bertha (1996), (top right) Josephine (1996), (bottom left) Floyd (1987), and (bottom right) Floyd (1999).

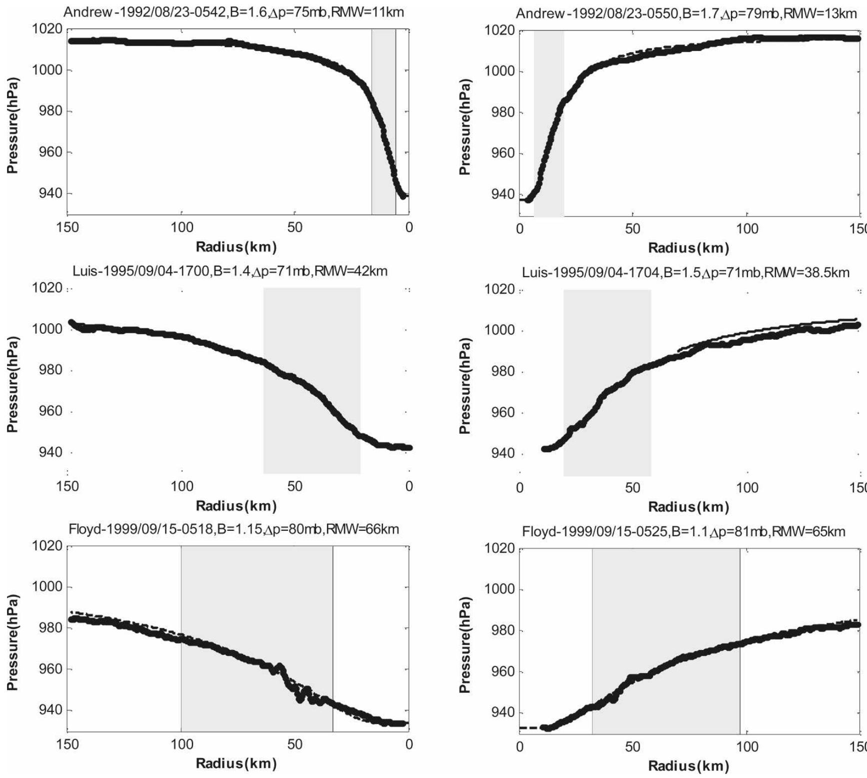

FIG. 5. Examples of surface pressure profiles for a traverse across a given hurricane: (top) Andrew at (left) 0542 and (right) 0550 UTC; (middle) Luis at (left) 1700 and (right) 1704 UTC; and (bottom) Floyd at (left) 0518 and (right) 0525 UTC.

area of a hurricane producing the maximum wind speeds, which is most important when using the results to derive design-wind speeds.

Figure 5 presents examples of model and measured surface pressure profiles, where each row corresponds to a complete airplane traverse in one direction. The shaded regions in Fig. 5 represent the error-minimizing range of [0.5RMW, 1.5RMW]. The fit parameters (i.e., the B, Δp, and RMW) are also provided in the title of each profile. For a given traverse through a hurricane, the differences in B and RMW arise from real asymmetries that exist in storms (i.e., both B and RMW vary with azimuth), errors in parameter estimation, and differences brought about by temporal changes of the hurricane as a whole. The average RMW is 46 km (standard deviation of 22 km), and the mean and standard deviation of Δp are 51 and 18 hPa, respectively. The mean and standard deviation of B are 1.25 and 0.32, respectively. The mean B value of 1.25 is slightly less than the value of 1.31 computed by Willoughby and Rahn (2004) in their analysis, and the standard deviation, 0.32, is slightly less than their value of 0.36. Seventy-one percent of the fits yield r^2 values greater than 0.95 and 80% of the fits have rms errors less than 2.5 hPa. The maximum rms error was 24.6 hPa, which occurred for one of Hurricane Opal's profiles where Holland's equation overestimated the pressures at all points.

The approach for analyzing the B and RMW data involved the estimation of RMW and B from each single pass of a flight through the storm, and then smoothing the variations in B and RMW as a function of time. The smoothing procedure used was a five-point moving average. The approach taken here to smooth the estimates of B obtained from a single pass through the storm differs from that used in Willoughby and Rahn (2004), where they used B estimated from an azimuthal average. Both approaches are flawed in that they eliminate the azimuthal variation in B that exists in real hurricanes; however, as will be shown later, the statistical models resulting from the two sets of data are remarkably similar to one another. Furthermore, when applied in real-world problems, the modeled input pressure or wind field is assumed to be axisymmetric, consistent with the analysis assumptions.

Figure 6 presents 10 examples of both the single flight (point estimates) and the smoothed estimates of B and RMW plotted versus time, for landfalling hurri-

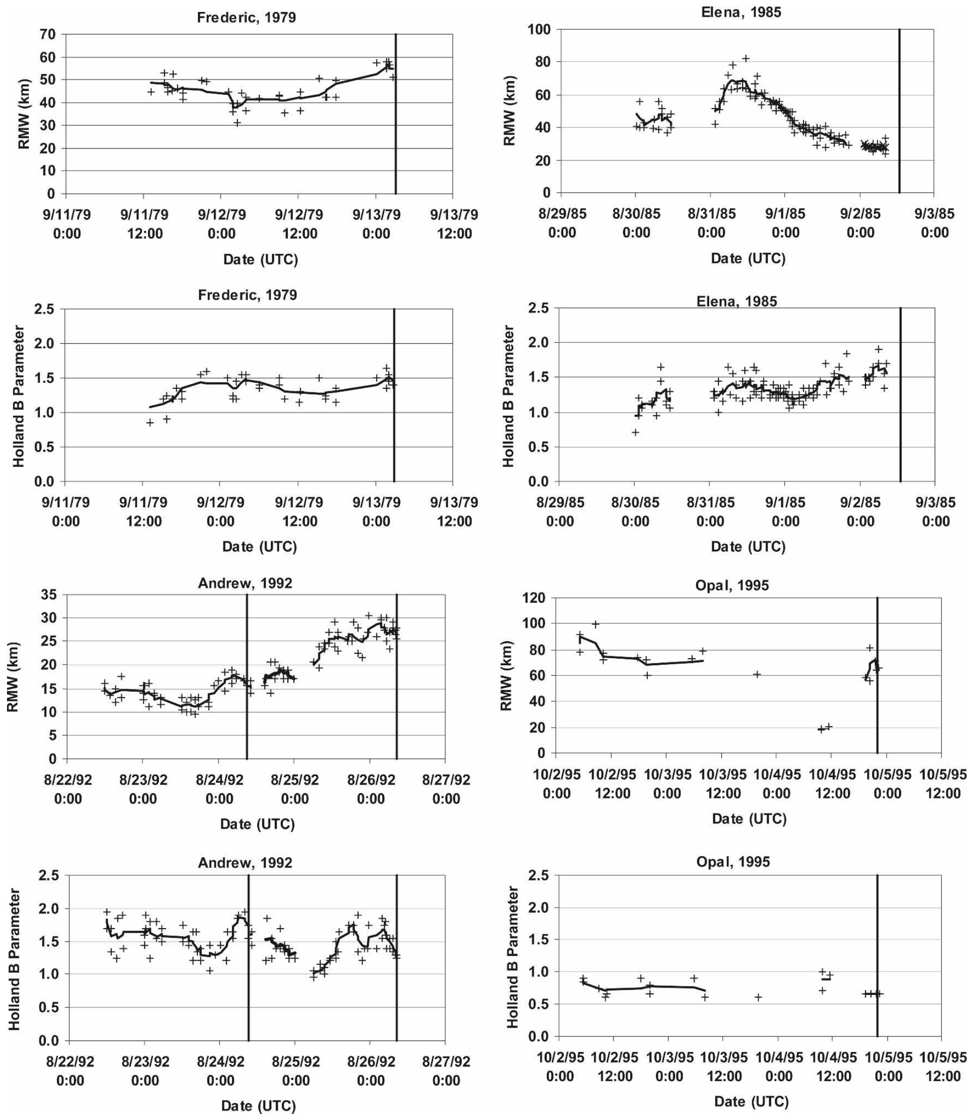

FIG. 6. Examples of smoothed (line) and point estimates (symbols) of RMW and B derived from 700-hPa-level pressure data. The vertical lines represent time of landfall.

canes. The landfall time is indicated with a vertical line in each plot. Using the smoothed data, values of B and RMW were extracted at intervals of approximately 3 h and retained for use in the statistical analyses. The mean values of B and RMW for the smoothed dataset are 1.21 and 47 km, respectively. The corresponding standard deviations are 0.29 and 21 km, respectively.

*b. Estimation of B and RMW using H*WIND data*

The flight-level data encompass storms through 2001, and thus to supplement the dataset with more recent storms, some additional storms analyzed using the H*Wind methodology were added. The only storms added were the intense storms from the 2004 and 2005 seasons that had been reanalyzed using the most recent stepped frequency microwave radiometer (SFMR) calibrations. The intense storms that have been reanalyzed include Hurricane Katrina (2005) and Hurricane Ivan (2004). Hurricane Rita was added to the dataset even though it had not been reanalyzed, because at its most intense, the storm had a minimum central pressure of less than 900 hPa.

Since the pressure field is not available with H*Wind data, a more simplistic approach is taken to estimate the value of B associated with a given H*Wind snapshot. Using the wind field model described in Vickery et al. (2008) and the values of central pressure, RMW, storm translation speed, and the maximum sustained

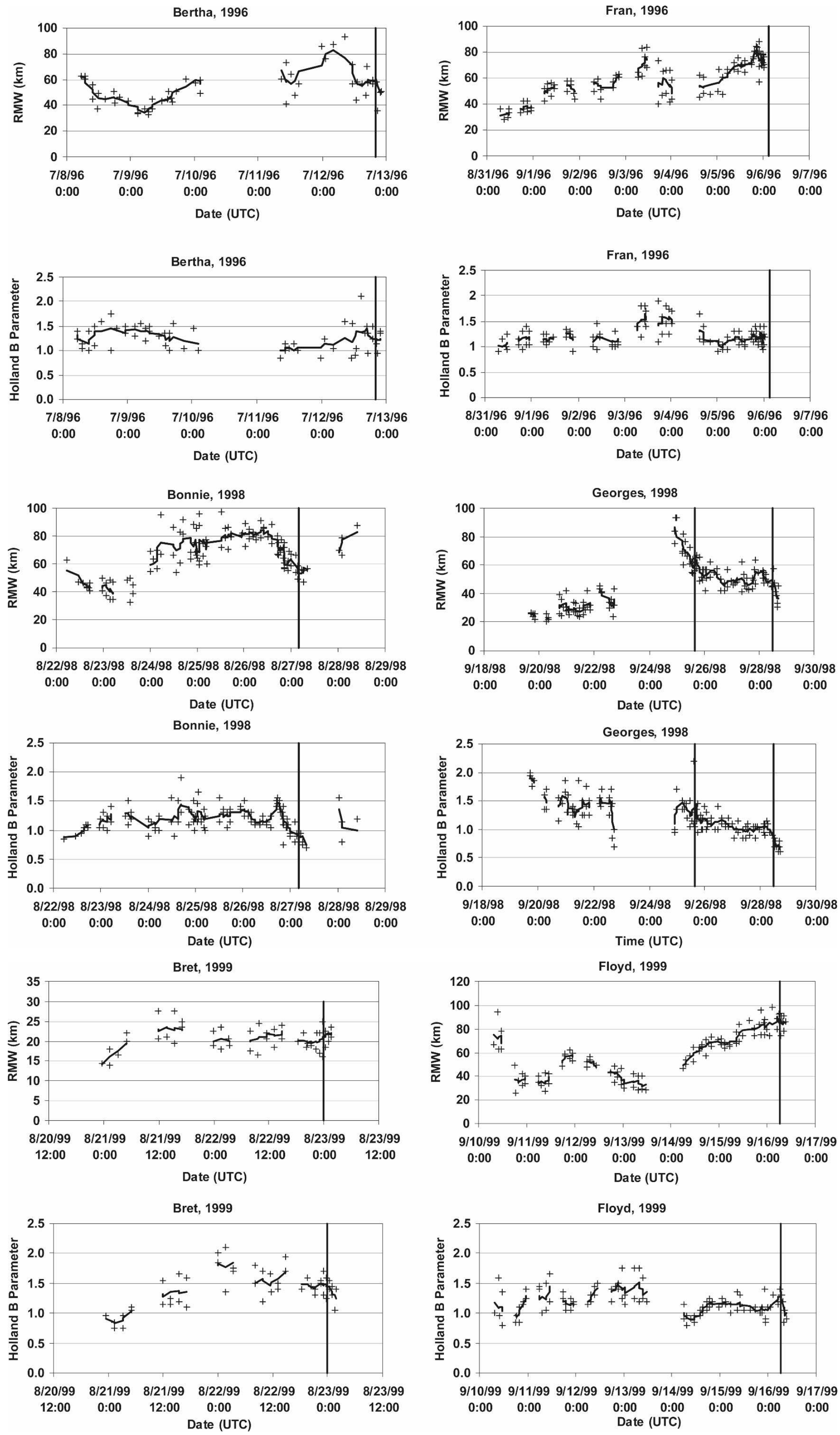

FIG. 6. (*Continued*)

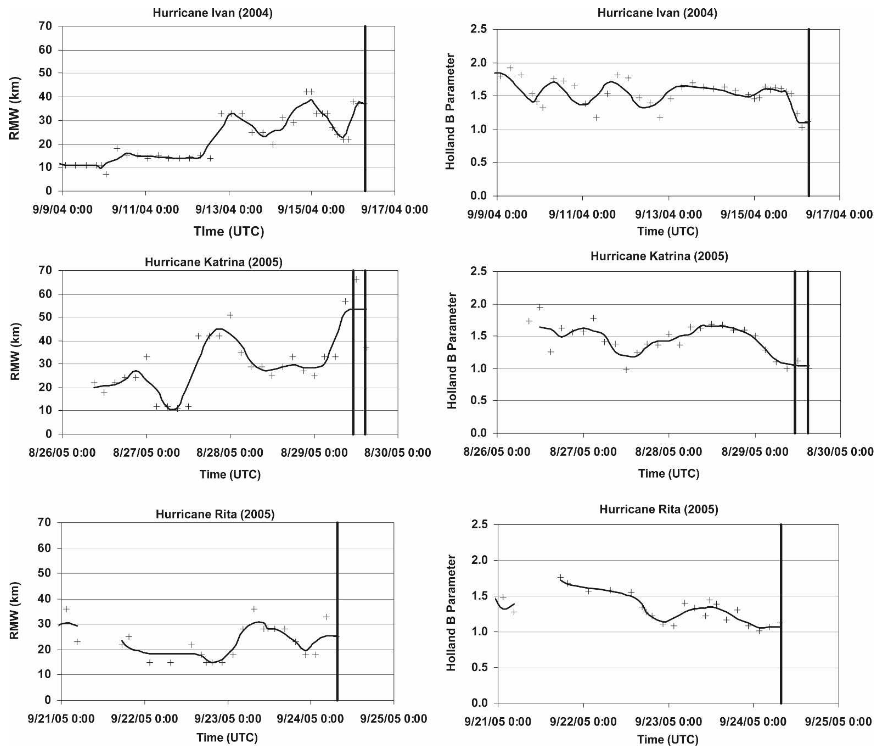

FIG. 7. Smoothed (line) and point estimates (symbols) of (let) RMW and (right) B derived from H*Wind data. Vertical line(s) represents time of landfall: (top) Ivan, (middle) Katrina, and (bottom) Rita.

wind speed, a B value is chosen so that the maximum surface level wind speed (1-min sustained value) obtained from the model matches the H*Wind estimate of the maximum wind speed. Thus the estimated values of B are obtained through an indirect measure, matching the maximum wind speed rather than the shape of the entire wind field. Matching the peak wind rather than the shape of the wind field ensures that the estimate of B is associated with the maximum sustained wind speed in the hurricane, which is most important when using the results to derive design wind speeds. Figure 7 presents plots of RMW and B as a function of time for the three aforementioned hurricanes.

3. Statistical models of radius to maximum winds

The RMW plays an important role in hurricane risk prediction, with the RMW data provided in the NWS 38 publication being a primary source for developing RMW models since they provide information of the RMW for almost all hurricanes making landfall along the U.S. coastline between 1900 and 1985. Here we use the flight-level and H*Wind data to develop statistical models for the RMW (relating RMW to other parameters that are usually modeled in a risk model) and compare these models with models developed using the more traditional approach that includes landfalling hurricane RMW data only. The models (both open water and landfall) are presented for all hurricanes, and separately for Gulf of Mexico hurricanes and Atlantic Ocean hurricanes. Unless noted otherwise, in the statistical analyses that follow, all model parameters are statistically significant at the 95% confidence level.

a. All-, Gulf of Mexico, and Atlantic Ocean hurricane RMW models

1) ALL HURRICANES

The RMW for all points (flight-level data plus H*Wind data) in the dataset having a central pressure of less than 980 hPa was modeled as a function of Δp and latitude, ψ, in the form

$$\ln(\text{RMW}) = 3.015 - 6.291 \times 10^{-5}\Delta p^2 + 0.0337\Psi;$$
$$r^2 = 0.297, \quad \sigma_{\ln\text{RMW}} = 0.441. \tag{11}$$

An analysis of the errors (difference between the regression model estimates and the data) indicates that

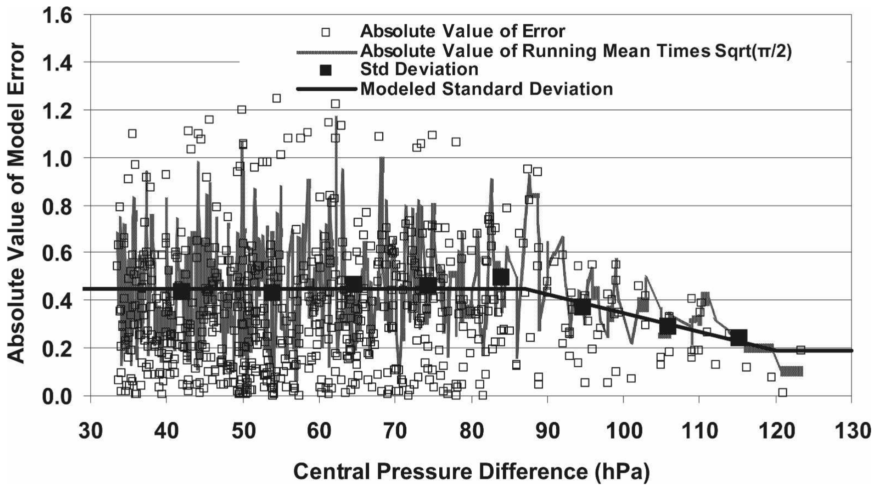

FIG. 8. Absolute value of RMW model error vs Δp for all hurricanes.

the model error reduces with increasing Δp, as indicated in Fig. 8.

The error, $\sigma_{\ln\mathrm{RMW}}$, is modeled in the form

$$\sigma_{\ln\mathrm{RMW}} = 0.448, \quad \Delta p \leq 87, \tag{12a}$$

$$\sigma_{\ln\mathrm{RMW}} = 1.137 - 0.007\,92\Delta p, 87\ \mathrm{hPa} \leq \Delta p \leq 120\ \mathrm{hPa}, \tag{12b}$$

and

$$\sigma_{\ln\mathrm{RMW}} = 0.186, \quad \Delta p > 120\ \mathrm{hPa}. \tag{12c}$$

Figure 9 presents the modeled and observed values of RMW plotted versus Δp. The modeled data are given as the median and the range is defined by $\pm 2\sigma_{\ln\mathrm{RMW}}$. The modeled range reflects the reduction in $\sigma_{\ln\mathrm{RMW}}$ as a function of Δp.

2) GULF OF MEXICO HURRICANES

To determine if the characteristics of the RMW associated with the Gulf of Mexico storms differed from those obtained using the all-storm data, the RMW–Δp and RMW–ψ relationships were reexamined. For this analysis the Gulf of Mexico storms included all hurricanes west of 81°W and north of 18°N. The RMW for all storms (flight-level data plus H*Wind data) in the Gulf of Mexico dataset with central pressures less than 980 hPa were modeled as a function of Δp in the form

$$\ln(\mathrm{RMW}) = 3.858 - 7.700 \times 10^{-5}\Delta p^2;$$

$$r^2 = 0.290, \quad \sigma_{\ln\mathrm{RMW}} = 0.390. \tag{13}$$

The RMW was found to be independent of latitude. As in the all-storm case, the model error reduces with increasing Δp, as indicated in Fig. 10.

The error, $\sigma_{\ln\mathrm{RMW}}$, for Gulf of Mexico hurricanes is modeled in the form

$$\sigma_{\ln\mathrm{RMW}} = 0.396, \Delta p \leq 100\ \mathrm{hPa}, \tag{14a}$$

$$\sigma_{\ln\mathrm{RMW}} = 1.424 - 0.010\,29\Delta p, 100\ \mathrm{hPa} \leq \Delta p \leq 120\ \mathrm{hPa}, \tag{14b}$$

and

$$\sigma_{\ln\mathrm{RMW}} = 0.19, \Delta p > 120\ \mathrm{hPa}. \tag{14c}$$

Figure 11 presents the modeled and observed values of RMW plotted versus Δp for the Gulf of Mexico hurricanes. The modeled data are given as the median estimates and the range defined by $\pm 2\sigma_{\ln\mathrm{RMW}}$. The modeled range reflects the reduction in $\sigma_{\ln\mathrm{RMW}}$ as a function of Δp.

Figure 12 presents the median values of the RMW computed using (11) (all-hurricane RMW model) computed for latitudes of 25°N (southern Gulf of Mexico) and 30°N (northern Gulf of Mexico), where it is seen that for the northern Gulf of Mexico storms, the all-hurricane RMW model overestimates the size of the Gulf of Mexico hurricanes.

3) ATLANTIC OCEAN HURRICANES

In the case of Atlantic Ocean hurricanes, defined as all hurricanes east of 80°W, the RMW for all storms (flight-level data plus H*Wind data) are best modeled as a function of Δp and ψ in the form

$$\ln(\mathrm{RMW}) = 3.421 - 4.600 \times 10^{-5}\Delta p^2 + 0.000\,62\psi^2;$$

$$r^2 = 0.236, \quad \sigma_{\ln\mathrm{RMW}} = 0.466. \tag{15}$$

The error, $\sigma_{\ln\mathrm{RMW}}$, for Atlantic Ocean hurricanes is independent of central pressure.

b. *Comparisons of open-water RMW models with landfalling RMW models and data*

The statistical models for RMW derived from the flight-level and H*Wind data are representative of re-

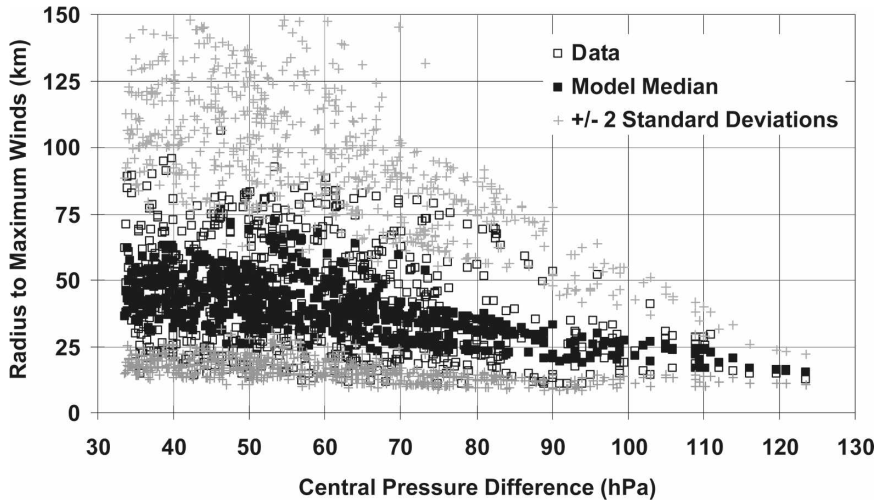

FIG. 9. Modeled and observed RMW vs Δp for all hurricanes.

lationships between the RMW, Δp, and so on for hurricanes located primarily in the open water. Here we compare these models with the RMW models derived using the more traditional approach of including only landfalling hurricane data. The landfall RMW data are given in Vickery (2005), which presents a summary of RMW, Δp, and landfall location data compiled primarily from a combination of RMW data given in NWS 38 (Ho et al. 1987) and RMW data obtained from H*Wind snapshots for hurricanes valid at or near the time of landfall.

Figure 13 presents the RMW for storms making landfall along the Gulf and Atlantic coasts of the United States plotted as a function of Δp. In the case of Gulf Coast landfalling hurricanes, no statistically significant correlation exists between the RMW and either latitude or Δp. In the case of hurricanes making landfall along the Atlantic coast, the RMW is positively correlated with latitude, and negatively correlated with Δp^2. (The negative correlation between RMW and Δp^2 is significant at the 94% confidence level.) As a group (i.e., both Atlantic and Gulf Coast landfalling hurricanes), the RMW is also positively correlated with latitude and negatively correlated with Δp^2.

Using only landfall values of RMW, the following statistical models best define the relationship among RMW, Δp, and latitude:

(i) Gulf of Mexico landfalling hurricanes:

$$\ln(\text{RMW}) = 3.558; \quad \sigma_{\ln\text{RMW}} = 0.457, \tag{16}$$

(ii) Atlantic coast landfalling hurricanes:

$$\ln(\text{RMW}) = 2.556 - 5.963 \times 10^{-5}\Delta p^2 + 0.0458\psi;$$

$$r^2 = 0.336, \quad \sigma_{\ln\text{RMW}} = 0.456, \quad \text{and} \tag{17}$$

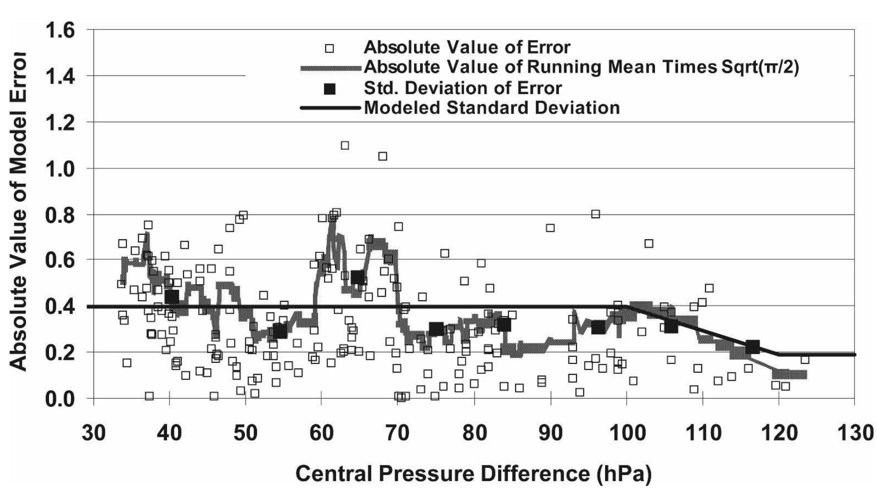

FIG. 10. Absolute value of RMW model error vs Δp for GoM hurricanes.

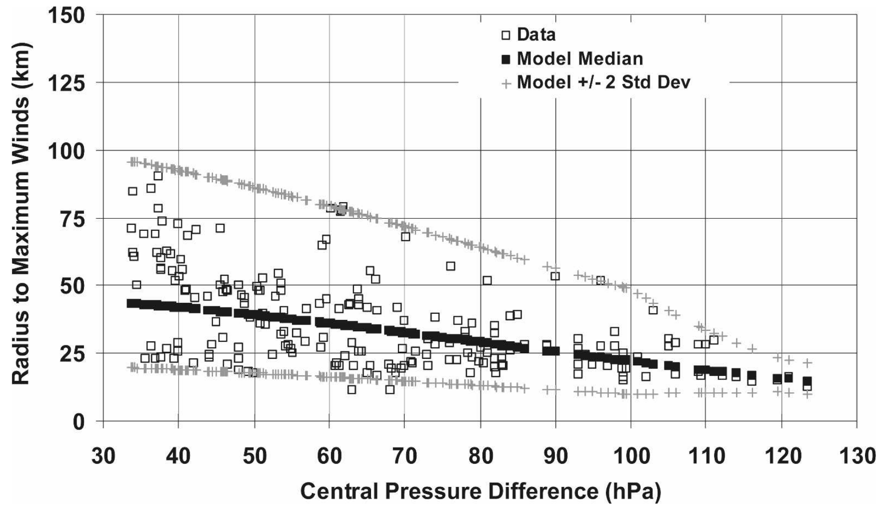

FIG. 11. Modeled and observed RMW vs Δp for GoM hurricanes.

(iii) Gulf and Atlantic coast landfalling hurricanes:

$$\ln(\mathrm{RMW}) = 2.377 - 4.825 \times 10^{-5}\Delta p^2 + 0.0483\psi;$$

$$r^2 = 0.203, \quad \sigma_{\ln\mathrm{RMW}} = 0.457. \tag{18}$$

The ability of the RMW models developed using the flight-level and H*Wind data (primarily open-ocean data) to model the landfalling hurricane RMW was tested by computing the mean and root-mean-square errors (in both logarithmic and linear space) and r^2 values resulting from using (11)–(15) (open-ocean models) with the landfall RMW data. The results are summarized in Table 3 (errors in log space) and Table 4 (errors in linear space). Tables 3 and 4 also present the errors associated with the statistical models for the landfall RMW developed with the landfall RMW data. The mean error, $\mu_{\ln\mathrm{RMW}}$, is defined as modeled RMW minus the observed RMW; thus a mean positive error indicates that the model overestimates observed RMW. A comparison of the model errors given in Tables 3 and 4 with those resulting from the statistical analyses of the landfalling storms alone indicates that the models derived from the flight-level and H*Wind data can be used to define the characteristics of landfalling hurricanes. In the case of landfalling Gulf of Mexico hurricanes, the use of the GoM RMW model, which contains the negative correlation between RMW and Δp^2, is not statistically significantly different from the uncorrelated RMW–Δp relationship derived from the landfalling hurricanes alone. This observation suggests that

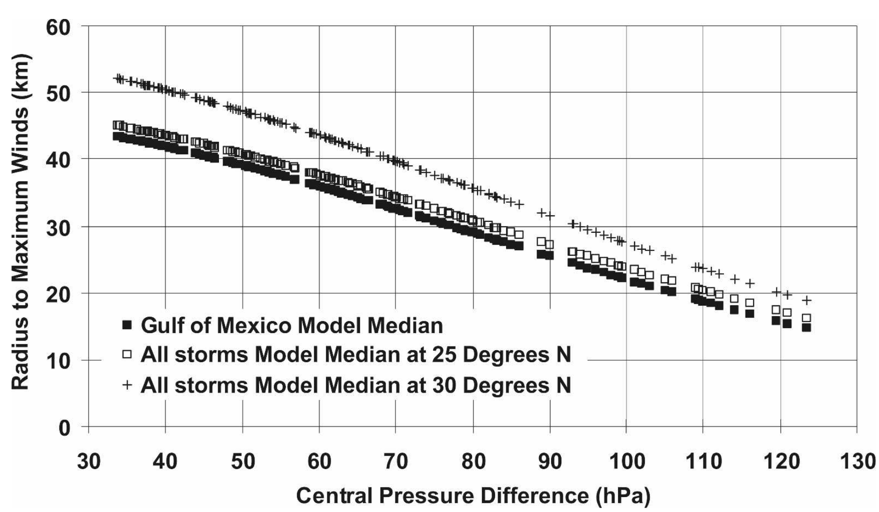

FIG. 12. Comparison of all hurricanes' model-predicted median RMW with GoM model median RMW vs Δp.

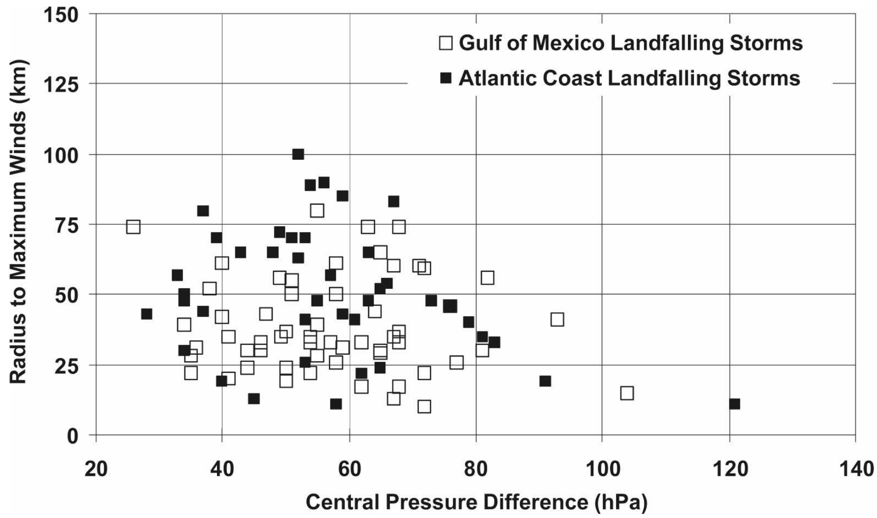

FIG. 13. RMW vs Δp for landfalling storms along the Gulf and Atlantic coasts of the United States.

there are an insufficient number of intense landfalling hurricanes in the historical landfall data to discern the RMW–Δp correlation, and a model developed using the GoM landfall data alone would not include this important negative RMW–Δp relationship. The recommended statistical models are shown in boldface type in Tables 3 and 4.

4. Analysis and behavior of *B*

In this section we use the time series of B, RMW, Δp, and so on derived from the H*Wind and reconnaissance data to develop a statistical model (or models) for B that can be used to estimate B given other parameters that are usually used in hurricane risk models. We also examine an apparent reduction in B as hurricanes approach the northern Gulf of Mexico coastline, and compare B values estimated from the H*Wind and reconnaissance data with those estimated using a wind field model and surface level wind speed measurements.

a. Statistical model for B

The B values computed as discussed in section 2 were found to be correlated to the radius to maximum winds, Δp, latitude, and sea surface temperature. Only points associated with central pressures less than 980 hPa are included in the analysis. The analysis was performed with the "smoothed" time series of B, with samples taken approximately every 3 h along the track of each hurricane. Figure 14 presents the variation of B as separate linear functions of the RMW, Δp, latitude (ψ), and the mean sea surface temperature T_s. It is clear from the data presented in Fig. 14 that B decreases with increasing RMW and increasing latitude. A weak positive correlation with both Δp and sea surface tempera-

TABLE 3. RMW model errors. Errors are computed in natural log space.

RMW data	Model	Error (natural log km) Mean	Std dev	Mean significantly different from 0?	r^2
Gulf-landfall	Mean (Gulf-landfall) [Eq. (16)]	0.00	0.46		0.00
Gulf-landfall	**Gulf-ocean [Eq. (13)]**	0.03	0.46		−0.01
Gulf-landfall	All–open water [Eq. (11)]	0.21	0.45	Yes	0.00
Gulf-landfall	All-landfall [Eq. (18)]	0.05	0.46		0.00
Atlantic-landfall	Mean	0.00	0.56		0.00
Atlantic-landfall	Atlantic-landfall [Eq. (17)]	0.00	0.44		0.37
Atlantic-landfall	All-landfall [Eq. (18)]	−0.06	0.44		0.37
Atlantic-landfall	Atlantic–open water [Eq. (15)]	0.11	0.45		0.35
Atlantic-landfall	**All–open water [Eq. (11)]**	0.06	0.45		0.35
All-landfall	Mean	0.00	0.51		0.00
All-landfall	All-landfall [Eq. (18)]	0.00	0.45		0.22
All-landfall	All–open water [Eq. (11)]	0.15	0.46	Yes	0.20

TABLE 4. RMW model errors. Errors are computed in linear space.

RMW data	Model	Error (km) Mean	Std dev	Mean significantly different from 0?	r^2
Gulf-landfall	Mean (Gulf-landfall) [Eq. (16)]	0.0	16.8		0.00
Gulf-landfall	**Gulf–open water [Eq. (13)]**	**−2.1**	**17.2**		**−0.04**
Gulf-landfall	All–open water [Eq. (11)]	5.0	17.4	Yes	−0.07
Gulf-landfall	All-landfall [Eq. (18)]	−1.7	17.2		−0.05
Atlantic-landfall	Mean	0.0	22.8		0.00
Atlantic-landfall	Atlantic-landfall [Eq. (17)]	−3.6	19.1		0.29
Atlantic-landfall	All-landfall [Eq. (18)]	−6.3	19.0	Yes	0.30
Atlantic–landfall	Atlantic–open water [Eq. (15)]	0.9	19.2		0.29
Atlantic-landfall	**All hurricane–ocean [Eq. (11)]**	**−1.3**	**19.0**		**0.30**
All-landfall	Mean	0.0	20.3		0.00
All-landfall	All-landfall [Eq. (18)]	−3.7	18.1	Yes	0.21
All-landfall	All–open water [Eq. (11)]	2.4	18.2		0.19

ture is also evident. We know that T_s is correlated with latitude, RMW is positively correlated with latitude, and RMW is negatively correlated with Δp; hence we also look at partial correlations. Figure 15 presents partial correlations of B adjusted for RMW, Δp, latitude (ψ), and the mean sea surface temperature T_s. The partial correlation for adjusted B with adjusted RMW, T_s, and latitude (ψ) cases is significant at a 95% confidence level. For Δp partial correlation is insignificant at a 95% confidence level.

To incorporate the effects of RMW, Δp, latitude (ψ), and T_s into a single model, a new nondimensional variable A was developed, defined as

$$A = \frac{\mathrm{RMW} f_c}{\sqrt{2R_d(T_s - 273)\ln\left(1 + \frac{\Delta p}{p_c e}\right)}}. \tag{19}$$

Equation (19) was derived with the intent to model B as a function of a nondimensional parameter. The parameter A was developed considering

(i) as RMW increases B decreases,
(ii) as latitude increases B decreases, and
(iii) maximum wind speed in a hurricane is proportional to $\sqrt{B}$ and has an upper theoretical limit (e.g., Emanuel 1988).

To include the maximum wind speed in the model we use the relationship (Emanuel 1988) that the maximum wind speed in a tropical cyclone is

$$V_{\max} = \sqrt{2R_d T_s \ln\left(\frac{p_{\max}}{p_c}\right)}, \tag{20}$$

where $V_{\max}$ is the maximum wind speed, R_d is the gas constant for dry air (N m kg^{-1} K^{-1}), $p_{\max}$ is the pressure at r = RMW, T_s is the sea surface temperature (K), and p_c is the pressure at the storm center.

This expression was simplified using Holland's (1980) pressure profile equation [(2)] from which it can be shown that at r = RMW,

$$\frac{p_{\max}}{p_c} = 1 + \frac{\Delta p}{p_c e}. \tag{21}$$

Equation (21) was substituted into (20) to obtain the denominator in (19). A value of 273° was subtracted from the SST in (20) because the regression model performed better using SST in degrees Celsius rather than Kelvin. The numerator of A is the product of the RMW (in meters) and the Coriolis force, defined as $2\Omega \sin\psi$, and represents the contribution to angular velocity associated with the Coriolis force. Hence, both the numerator and denominator of A have the units of velocity, and thus A is nondimensional.

Modeling B as a function of $\sqrt{A}$ yields a linear model (Fig. 16) with B negatively correlated with $\sqrt{A}$ and has an r^2 of 0.34, with a standard deviation of the error equal to 0.225. The relationship between B and $\sqrt{A}$ is expressed as

$$B = 1.7642 - 1.2098\sqrt{A}; \quad r^2 = 0.345, \quad \sigma_B = 0.226. \tag{22}$$

To determine if the relationship between B and A is valid for intense storms, the observed and model values of B were plotted as a function of RMW for strong hurricanes (i.e., storms with a central pressure of <930 hPa), as shown in Fig. 17. The data presented in Fig. 17 indicate that in the case of strong storms with large RMW (RMW > 40 km), the relationship between B and A described earlier breaks down, with the values of B being less than those predicted by the model. Although only two storms with large RMW and low central pressures exist in the data analyzed (Hurricane Katrina in the Gulf of Mexico and Hurricane Floyd in the

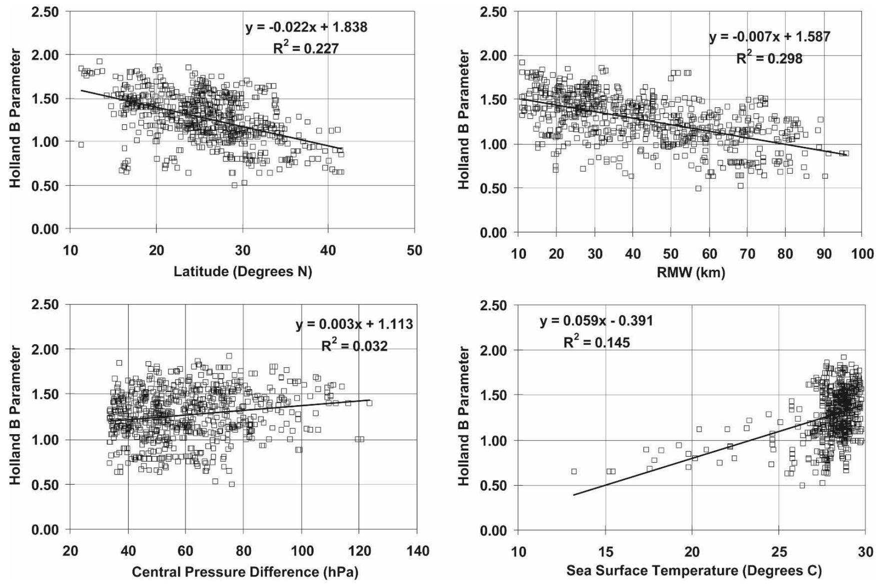

FIG. 14. Relationships between B and (top left) latitude, (top right) RMW, (bottom left) Δp, and (bottom right) T_s.

Atlantic), the data indicate that the likelihood of a storm with a central pressure less than ~930 hPa and an RMW greater than 40 km, combined with a B value greater than about 1.1, is remote. The mean value of B for these large, intense hurricanes is 1.01, and the standard deviation is 0.082. In cases in which these strong storms are simulated, B is constrained to lie within the range of the mean $\pm 3\sigma$.

As in the case of the analysis of Gulf of Mexico hurricanes with respect to the behavior of RMW with Δp and latitude, B values for all hurricanes within the Gulf of Mexico were extracted and analyzed alone. Unlike the results seen for the RMW in which the GoM hurricanes were found to be smaller than the other hurricanes, the variation of B with A for the GoM hurricanes is essentially identical to that seen in the all-hurricane case. Figure 18 presents the individual B values for the GoM and Atlantic hurricanes along with the model-

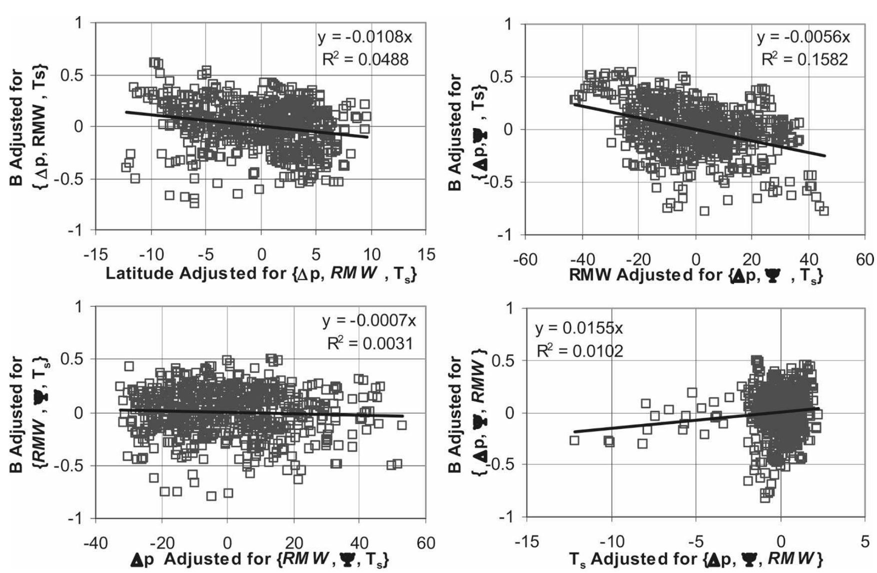

FIG. 15. Partial correlations for B adjusted for (top left) latitude, (top right) RMW, (bottom left) Δp, and (bottom right) T_s.

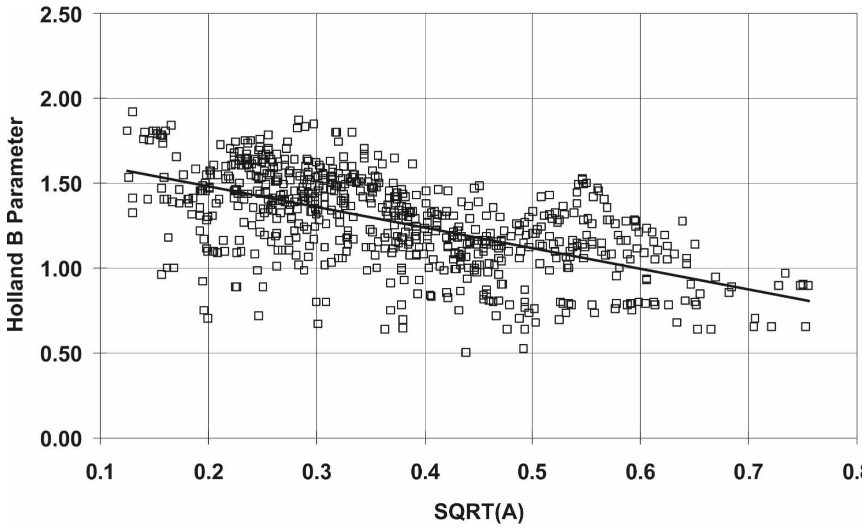

FIG. 16. Relationship between the Holland B parameter and the dimensionless parameter $A^{1/2}$.

predicted mean values of B, where it is clearly evident that there is, for practical purposes, no difference in the variation of B with A between the two regions.

An alternate model relating B to the product of f_c and RMW is given in the form

$$B = 1.833 - 0.326\sqrt{f_c\mathrm{RMW}};$$
$$r^2 = 0.357, \quad \sigma_B = 0.221. \tag{23}$$

A statistical model relating B to RMW (km) and ψ in the same form as that developed by Powell et al. (2005) is

$$B = 1.881 - 0.005\,57\mathrm{RMW} - 0.012\,95\psi;$$
$$r^2 = 0.356, \quad \sigma_B 0.221. \tag{24}$$

Equation (24) is similar to the model given in Powell et al. (2005) presented earlier in (8).

For practical purposes, any of the three linear regression models given in (22), (23), or (24) can be used to model B. Again, note that the units of RMW used in (22) and (23) are meters, but (24) uses RMW in kilometers.

b. Changes in B near land

During the 2004 and 2005 storm season, it was noted that the four storms that made landfall along the Gulf of Mexico coastline (Ivan in 2004, and Dennis, Katrina, and Rita in 2005) all weakened over a 12–24-h period before making landfall, with this weakening (increasing

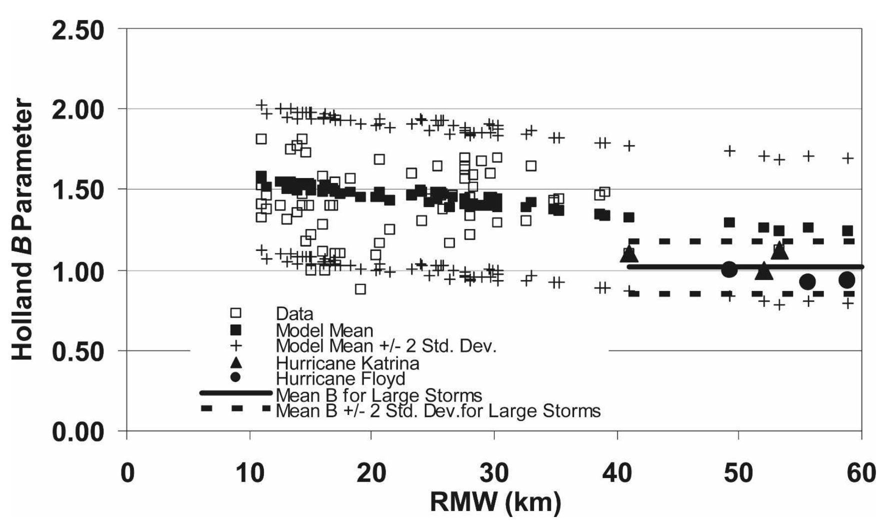

FIG. 17. Holland B parameter vs RMW for storms with central pressure <930 hPa.

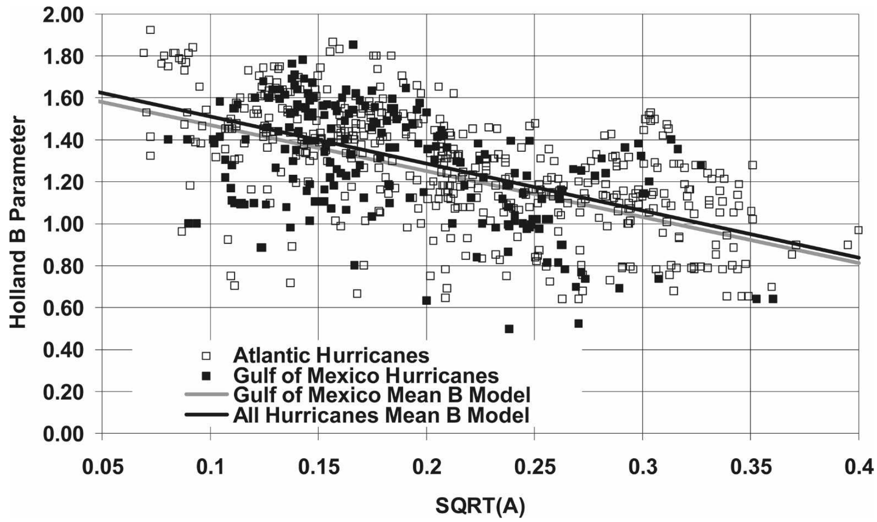

FIG. 18. Relationship between B and the dimensionless parameter $A^{1/2}$, comparing the all-hurricane data with the GoM hurricane data.

central pressure) accompanied by a decrease in B and an increase in the RMW. The magnitude of the decrease in B is larger than the decrease expected to be brought about by the increase in RMW alone as estimated through any of (22), (23), or (24). This observed decrease in B was included in the modeling of the coastal flood risk for both coastal Louisiana and Mississippi. In the Louisiana and Mississippi studies, B was reduced from a mean value of 1.27 (open water) to 1.0 at the time of landfall for all hurricanes with RMW less than 8 nm, where for these smaller storms B at landfall remained at 1.27. The reduction in B from 1.27 to 1.0 was implemented over the last 6–12 h before landfall (varying with storm translation speed). Using the reconnaissance and H*Wind derived times series of B we examine whether these data also support a consistent decrease in B as hurricanes approach land. Qualitatively the time series of B presented in Fig. 6 (reconnaissance data) and also in Fig. 7 (H*wind data) show a reduction in B as hurricanes approach the Gulf of Mexico coastline. Table 5 presents the change in B during the 12 h prior to landfall derived from both the H*Wind data and the reconnaissance data. Gulf of Mexico storms are treated separately from the Florida

TABLE 5. Change in B during the last 12 h before U.S. landfall.

Gulf of Mexico storms		Change in B during last 12 h prior to landfall		Atlantic coast and Florida Peninsula hurricanes		Change in B during last 12 h prior to landfall	
Year	Hurricane name	ReCon	H*Wind	Year	Hurricane name	ReCon	H*Wind
1979	Frederic	0.19		1984	Diana	0.08	
1985	Elena	0.04		1985	Gloria	0.02	
1992	Andrew	−0.24		1991	Bob	−0.14	
1995	Opal	−0.23		1992	Andrew	0.27	
1998	Georges	−0.24		1996	Fran	0.06	
1999	Bret	−0.23	−0.03	1998	Bonnie	−0.43	
2002	Lili		−0.37	1996	Bertha	0.04	
2004	Ivan		−0.46	1999	Floyd	0.23	0.24
2005	Dennis		−0.53	2004	Frances		−0.10
2005	Katrina		−0.26	2004	Jeanne		0.19
2005	Rita		−0.11	2003	Isabel		0.00
				2004	Charley		0.00
				2004	Wilma		0.04
Mean		−0.21		Mean		0.04	
Std dev		0.20		Std dev		0.18	
Std error in mean		0.06		Std error in mean		0.05	

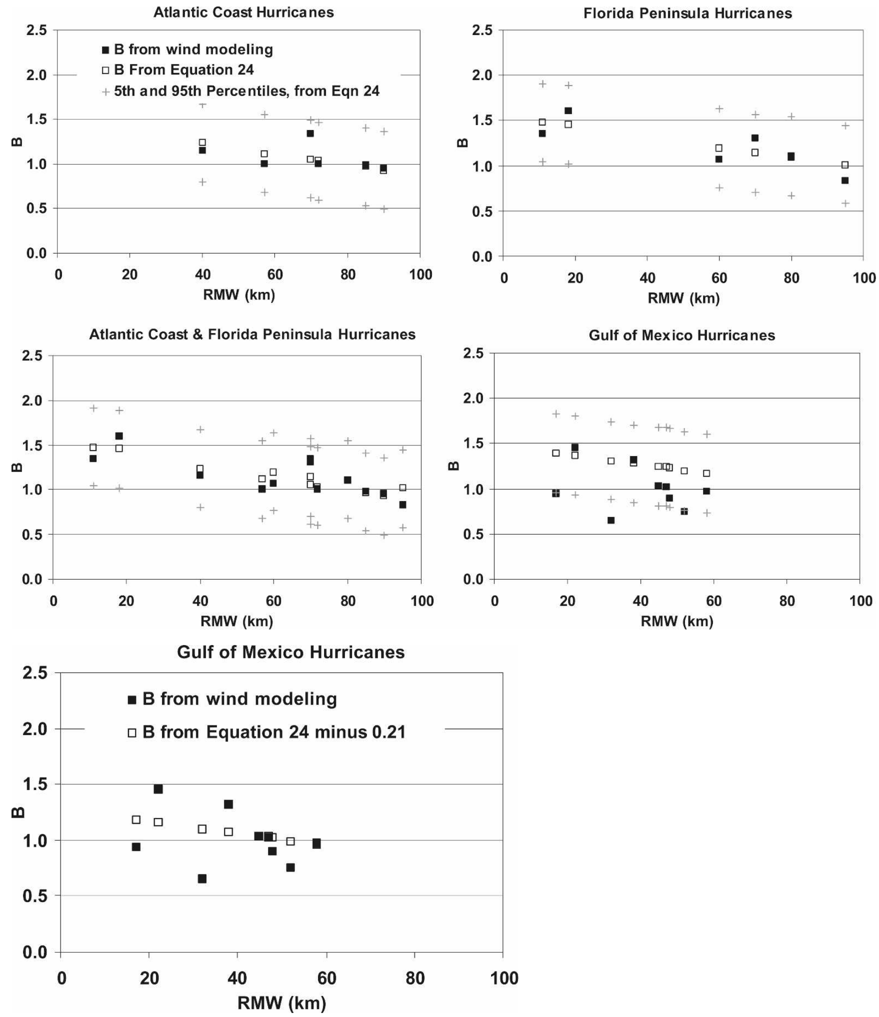

FIG. 19. Comparison of modeled [(24)] and independently observed values of *B* for landfalling hurricanes: (top left) Atlantic coast, (top right) Florida Peninsula, (middle left) Atlantic coast and Florida Peninsula, (middle right) GoM, and (bottom) GoM with *B* from wind modeling and from (24) minus 0.21.

Peninsula and Atlantic coast landfalling hurricanes. In the case of hurricanes making landfall along the Gulf of Mexico coastline, a mean reduction of 0.21 in *B* over the last 12 h is evident. The reduction of 0.21 is significantly different from zero at a 95% confidence level. In the case of Atlantic and Florida Peninsula landfalling hurricanes a mean increase in *B* of 0.04 over the past 12 h is evident, but this difference (from zero) is not statistically significant. Thus, the limited dataset supports a reduction in *B* as hurricanes approach the Gulf of Mexico. In the case of the 2004 and 2005 hurricanes, with *B* estimated from the maximum wind speeds estimated using H*Wind, there is some concern as to the possibility that a nonhomogeneous input wind speed dataset may yield variations (in this case reductions) of wind speed that are caused by the H*Wind analysis methodology rather than true variations of the wind speed within the hurricane. For example, if a series of reconnaissance aircraft were not equipped with the SFMR, then the estimates of the surface level winds rely heavily on the algorithm used in H*Wind to convert the aircraft winds to surface winds. Similarly, if a subsequent series of reconnaissance aircraft were equipped with the SFMR, then H*Wind will rely on the SFMR wind speed estimates to estimate the surface wind speeds rather than adjusting flight-level wind speeds to surface values. If there were a bias in either of the approaches for estimating wind speeds, then H*Wind would produce artificial changes in the maximum wind speed in a hurricane. As indicated in Table 5, the reduction in *B* over the last 12 h deduced from the H*Wind wind speed estimates appears only in the

Gulf of Mexico hurricanes and not the Florida hurricanes, suggesting that the variation of B as a hurricane approaches the Gulf of Mexico coastline is not an artifact of the H*Wind wind speed estimates.

Comparison of flight-level B values with landfall analysis B values

An independent analysis of the behavior of B using estimates of B derived from comparisons of modeled and surface wind fields using the hurricane boundary layer model described in Vickery et al. (2008) was performed and is discussed here. In Vickery et al., estimates of B are obtained by changing estimated values of B and RMW for a model hurricane near the time of landfall to match time series of measured and modeled surface level wind speeds, wind directions, and pressures. Recalling that the primary use of the statistical models for B is as an input to a hurricane wind field, demonstrating that the values of B used in a wind field model are consistent with those derived from the aircraft, is a critical and important step. Figure 19 presents a comparison of B values computed using (24) with those derived from the landfall analyses for the Atlantic coast, Florida Peninsula, Atlantic and Florida Peninsula combined, and Gulf Coast (excluding the Florida Peninsula). In the case of the Atlantic coast and the Florida Peninsula hurricanes, it is clear that the estimates of B derived from (24) are consistent with those estimated independently using the analyses of landfalling wind fields, with the B values derived from the landfall analyses falling well within the 95% confidence bounds. In the case of the Gulf of Mexico landfalling storms, (24) overestimates the mean value of B by 0.21, consistent with a reduction in B for the majority of the sample hurricanes approaching and making landfall along the Gulf of Mexico coast.

Figure 20 presents a comparison of B values derived from the flight-level data to those used in the wind field model described in Vickery et al. (2008) used for estimating the wind speeds associated with landfalling storms. Although there are only 11 cases for which both flight-level data and poststorm wind analyses are available, the comparison indicates that the B values used within the hurricane wind field model to match the surface observations of wind speeds and pressures are about 7% less than those derived from the flight-level data, but is not a statistically significant difference.

The limited comparisons of B derived from surface-level wind speed analyses with those derived from the reconnaissance data provide additional confidence to the statistical models developed using the reconnaissance data. The comparisons also demonstrate that there is consistency between the B values estimated

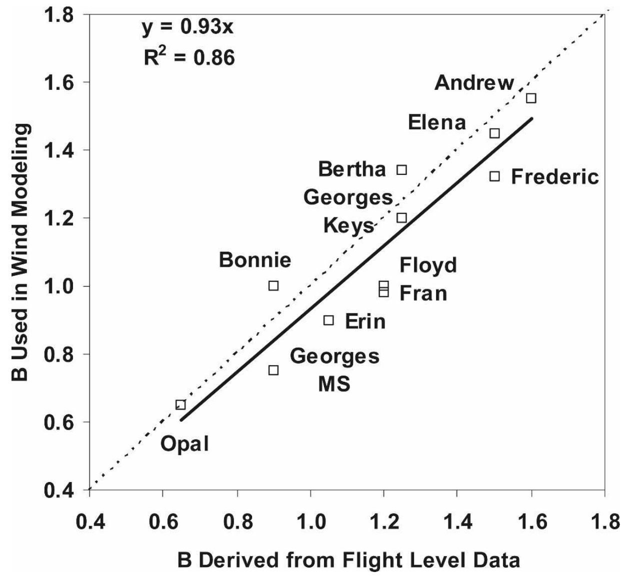

FIG. 20. Comparison of Holland B parameters derived from flight-level data with those derived using a postlandfall wind field analysis.

from the aircraft data and the wind field model that subsequently uses the B values in probabilistic modeling.

5. Summary

Statistical models relating RMW to latitude and central pressure derived from the reconnaissance and H*Wind dataset are compared to those derived for U.S. landfalling storms during the period 1900–2005. The analysis indicates that using RMW data comprising only landfalling Gulf of Mexico hurricanes suggests that there is no inverse relationship between RMW and the central pressure deficit. The RMW data also demonstrate that Gulf of Mexico hurricanes are, on average, smaller than Atlantic Ocean hurricanes.

The Holland pressure profile parameter B was found to decrease with increasing latitude and increase with decreasing RMW. A weak positive correlation between B and both Δp and sea surface temperature was also observed. The effect of all four of these parameters was accounted for by defining a nondimensional parameter A, defined by (19); however, a two-parameter model (with dimensions) relating B to the RMW and the Coriolis parameter is an equally good predictor of B. The relationship between B and A was found to be the same in the Atlantic Basin and in the Gulf of Mexico. The limited data for large (as defined by RMW) hurricanes, having low central pressures ($p_c < 930$ hPa), indicate that B has an upper limit of approximately 1.2–1.3.

The few cases for which flight-level data were available up to the time a hurricane made landfall along the Gulf of Mexico coastline indicate that in most cases B tends to decrease as the hurricane approaches land. Recognizing that the dataset is limited, this observation suggests that using the statistical model for B derived using open-water data may result in an overestimate of B for landfalling storms along the Gulf of Mexico.

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