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 non-dimensional intensity parameter. The non-dimensional 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 incorporates flights encompassing the time period 1977 through to 2001, but the analysis was limited to include only those data collected at the 700 mbar or higher level. Statistical models relating RMW to latitude and central pressure derived from the data set are compared to those derived for US landfalling storms during the period 1900 to 2005. 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 hrs to 24 hrs before landfall the hurricanes weaken as characterized by both an increase in central pressure and the radius to maximum winds, and a decrease in the Holland *B* parameter. This weakening characteristic of landfalling storms is not evident for hurricanes making landfall elsewhere along the United States coastline.

1. Introduction

In many hurricane risk models the inclusion of the Holland *B* parameter plays an important role in the risk prediction methodology, e.g., Vickery et al. (2000) and Powell et al. (2006). In this investigation 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, in an analysis of the radius to maximum winds and the Holland *B* parameter. The reconnaissance data incorporates flights encompassing the time period 1977 through to 2001, but the analysis was limited to include only those data collected at the 700 mbar or higher level. The flight level data is the same data set used by Willoughby and Rahn (2004), with a major difference between there analysis of *B* and ours is here we use the pressure field to estimate *B* whereas Willoughby and Rahn (2004), used the wind field to estimate *B*.

The Holland *B* parameter was found to be inversely correlated with both the size of a hurricane and the latitude of a hurricane. A weak positive correlation of *B* with central pressure deficit and sea surface temperature was also observed. A statistical relationship between the Holland B parameter and a non-dimensional parameter incorporating central pressure, radius to maximum winds, sea surface temperature and latitude was developed.

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 hrs to 24 hrs before landfall the hurricanes weaken as characterized by both an increase in central pressure and the radius to maximum winds, and a decrease in the Holland *B* parameter. This weakening characteristic of landfalling storms was not as evident for hurricanes making landfall elsewhere along the United States coastline.

2. Flight Level Data Analysis Methodology

Upper level aircraft data available at NOAA site were used to estimate Holland's pressure profile parameter (*B*). The upper level aircraft dataset used here contains a total of 4546 radial profiles from 62 Atlantic storms. This data is the same as that used by Willoughby, et al (2006), in their analysis of *B*, with the main difference in the analysis methodology being that pressures are used here and Willoughby and Rahn (2004) performed their analysis using wind speeds. For every storm, data has 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 was collected from the center of the storm to a certain radius (usually 150 km). Available data is then organized according to their 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, dew point temperature, wind speed and air temperature are available. Each profile from every flight and every storm is treated as an independent observation. Holland, (1980) describes the radial distribution of surface pressure in a hurricane in the form:

$$p(r) = p_0 + \Delta p \cdot \exp - \left[\frac{A}{r^B} \right] \qquad (1)$$

where *p*(*r*) is the surface pressure at a distance r from the storm center, p_0 is the central pressure, Δp is the central pressure difference, *A* is the location parameter and *B* is the Holland's pressure profile parameter. Holland (1980) showed that $RMW = A^{\frac{1}{B}}$ where *RMW* is the radius to maximum winds, and thus Equation (1) can be expressed as:

$$p(r) = p_0 + \Delta p \cdot \exp - \left[\frac{RMW}{r} \right]^B \qquad (2)$$

The surface pressure and radial distance are transformed to the form of Equation (2). The missing quantities in Equation (2) are *RMW* and *B*. First estimate of *RMW* is made from the recorded wind speed profile i.e. *RMW* is the radius to the measured maximum wind speed. From here on, the radius corresponding to the maximum wind speed in a profile is referred to as *RMW*. To estimate the optimum values of *B* and *RMW*, *RMW* and *B* are varied over the range [0.5*RMW*, 1.5*RMW*] and [0.5, 2.5] respectively. The algorithm calculates an optimum B value by minimizing the mean of the square differences between the measured and the modeled surface pressure in a range of 0.5*RMW* to 1.5*RMW* for different *B* and *RMW* values. Mathematically, the mean square error between the measured and the modeled surface pressure can be written as:

$$\varepsilon^2 = \frac{\sum_{i=0.5RMW}^{1.5RMW}\left(P_{obs_i} - P_{theo_i}\right)^2}{n} \tag{3}$$

where P_{obsi} is the measured pressure, P_{theoi} is the theoretical pressure calculated using equation (2) and n is the number of data points in the range [0.5*RMW*, 1.5*RMW*]. The values of *B* and *RMW* chosen correspond to those yielding the minimum mean square error, ε^2. The corresponding r^2 value for the fit is given by:

$$r^2 = 1 - \frac{\varepsilon^2}{\sigma^2} \tag{4}$$

where σ is the standard deviation of the measured pressure data in the range of [0.5*RMW*, 1.5*RMW*].

3. Quality control criteria:

A quality control criterion was used to filter out profiles. Each of the filtered profiles has at least one of the following characteristics associated with it, (a) Flight level pressure is less than 700 mbar i.e. height greater than 3000 m, (b) Central pressure difference is less than 25 mbar, (c) Radius to maximum winds is greater than two-third of the sampling domain, (d) the distance of aircrafts closest approach to the center is greater than half of the radius to maximum winds, (e) Data is available for less than one third of the sampling range i.e. less than 50 km, (f) visual inspection which involved eliminating profiles with a considerable amount of data missing in the range of interest $[0.5RMW, 1.5RMW]$. The rationale for using criteria (a) is that higher the measurement height, less representative measurements are of the surface observations. Criteria (b) results in the data associated with Category 1 or higher hurricanes only. The rationale for using criteria (c), (d), (e) and (f) is to ensure that there is a sufficient number of measurements on both sides of the radius to maximum winds to have a clear representation of the shape of the profile (Willoughby and Rahn (2004)).

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 filtering criteria. It is clear that criteria (a) and (b) are the most common reasons for profile elimination. 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 a central pressure difference of less than 25 mbar (e.g. Chantal in 1995) or a flight level pressure of less than 700 mbar (e.g. Hugo in 1989). Figure 1 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 Figure 1 is compromised by at least one of the above mentioned quality control criteria.

Figure 2 presents examples of pressure profiles that were retained for analysis. Each row in Figure 2 corresponds to a complete airplane traverse in one direction. The shaded regions in

Figure 2 represent the error minimizing range of 0.5*RMW* to 1.5*RMW*. The fit parameters i.e. the *B* value, the central pressure difference and the *RMW* are also provided in the title of every profile. For a given traverse through a hurricane, differences in the *B* values for two different profiles is due to the change in the radius to the maximum winds and the central pressure difference. The geographical distribution of the filtered profiles, based on the storm center, is shown in Figure 3. The filtered profiles have a wide geographical distribution and provides with a wide domain of hurricane climatic characteristics. The filtered dataset has an average *RMW* of 46 km (standard deviation of 22 km), an average central pressure difference of 51 mbar (18 mbar) and an average location of 25.84°N (5.74°N) and 74.78°W (12.82°W). 71% of the fits yield r^2 values greater than 0.95 and 80% of the fits have a mean square error less than 2.5 mbar. The maximum mean square error was 24.6 mbar 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. Figure 4 presents' ten examples of both the single flight (point estimates) and the smoothed estimates of *B* and *RMW* plotted vs. time, for landfalling hurricanes. 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 hrs and retained for use in the statistical analyses. The mean values of *B* and *RMW* for the smoothed data set are 1.21 and 47 km respectively. The corresponding standard deviations are 0.29 and 21 km respectively. Note that in only one of the 11 landfall's indicated in Figure 4, does the Holland *B* parameter appear to increase as a hurricane approaches land (Hurricane Floyd near the NC coast). Table 3 summarizes, qualitatively, the tendency in the changes of *B* over the final few hours before landfall.

4. Supplemental H*WIND Data

The flight level data encompasses storms through to 2001, and thus to supplement the data set 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 re-analyzed using the most recent SFMR calibrations. The intense storms that have been reanalyzed include Hurricanes Katrina (2005) and Hurricane Ivan (2004). Hurricane Rita was added to the data set even though it had not been re-analyzed, because at its most intense, the storm had a minimum central pressure of less than 900 mbar. Using the wind field model described in Vickery et al. (2007), and the values of central pressure, *RMW,* storm translation speed, and the maximum sustained wind speed, a *B* value chosen so that the maximum surface level wind speed (one minute sustained value) obtained from the model match the H*Wind estimate of the maximum wind speed. Thus the estimated *B* values are obtained through an indirect measure, matching the maximum wind speed rather than the shape of the entire wind field.

Figure 5 presents plots of *RMW*, and the derived *B* as a function of time for the three aforementioned hurricanes, in addition to data derived for hurricanes Dennis (2005), and Lili (1999). These two additional storms are given to examine the change in the characteristics of the storms as they approach land.

These five hurricanes represent all the Gulf of Mexico landfalling hurricanes in the H*Wind database that include information on both wind speeds and central pressure in each of the H*Wind snapshots. Additional storms are given in the H*Wind database that do not have central pressures provided on the H*Wind snapshots. All of the five hurricanes indicate an increase in central pressure (not shown) and a decrease in the magnitude of the Holland *B* parameter as they approach the Gulf Coast. An increase in the radius to maximum winds as the hurricanes approach landfall is also evident in four of the six cases examined.

A similar analysis of hurricane characteristics for hurricanes making landfall in regions other than along the Gulf of Mexico coast did not indicate that there is a strong tendency for the storms to weaken and enlarge before landfall.

5. Statistical Model for Radius to Maximum Winds

5.1. *All Hurricanes.*

The *RMW* for all points (flight level data plus H*Wind data) in the data set having a central pressure of less than 980 mbar were modeled as a function of central pressure difference and latitude in the form:

$$\ln(RMW) = 3.015 - 6.291\times10^{-5}\Delta p^2 + 0.0337\Psi \quad ; \quad r^2=0.297,\ \sigma_{\ln RMW} = 0.441 \qquad (4)$$

An analysis of the errors (difference between the regression model estimates and the data) indicates that the model error reduced with increasing Δp, as indicated in Figure 6.

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

$$\sigma_{\ln RMW} = 0.448 \qquad \Delta p \leq 87 \text{ mbar} \qquad (5a)$$

$$\sigma_{\ln RMW} = 1.137 - 0.00792\Delta p \qquad 87 \text{ mbar} \leq \Delta p \leq 120 \text{ mbar} \qquad (5b)$$

$$\sigma_{\ln RMW} = 0.186 \qquad \Delta p > 120 \text{ mbar} \qquad (5c)$$

Figure 7 presents the modeled and observed values of *RMW* plotted vs. Δp. The modeled data are given as the median estimates and the range defined by $\pm 2\sigma_{\ln RMW}$. The modeled range reflects the reduction in $\sigma_{\ln RMW}$ as a function of Δp.

5.2 *Gulf of Mexico Hurricanes.*

In order to determine if the characteristics of the *RMW* associated with the Gulf of Mexico storms differed from that obtained using the all storm data, the $RMW - \Delta p$ and RMW-ψ relationships were re-examined. For this analysis the Gulf of Mexico storms included all hurricanes west of 81^{o}W and north of 18^{o}N. The *RMW* for all storms (flight level data plus H*Wind data) in the Gulf of Mexico data set with central pressures less than 980 mbar were modeled as a function of central pressure difference in the form:

$$\ln(RMW) = 3.859 - 7.700\times10^{-5}\,\Delta p^2 \qquad r^2=0.290,\ \sigma_{\ln RMW} = 0.390 \qquad (6)$$

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 Figure 8.

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

$$\sigma_{\ln RMW} = 0.396 \qquad \Delta p \le 100 \text{ mbar} \qquad (7a)$$

$$\sigma_{\ln RMW} = 1.424 - 0.01029\Delta p \qquad 100 \text{ mbar} \le \Delta p \le 120 \text{ mbar} \qquad (7b)$$

$$\sigma_{\ln RMW} = 0.19 \qquad \Delta p > 120 \text{ mbar} \qquad (7c)$$

Figure 9 presents the modeled and observed values of *RMW* plotted vs. Δp for the Gulf of Mexico hurricanes. The modeled data are given as the median estimates and the range defined by $\pm 2\sigma_{\ln RMW}$. The modeled range reflects the reduction in $\sigma_{\ln RMW}$ as a function of Δp.

Figure 10 presents the median values of the *RMW* computed using Equation 4 (all hurricane *RMW* model) computed for latitudes of 25^{o}N (Southern Gulf of Mexico) and 30^{o}N (Northern Gulf of Mexico), where it is seen that for the Northern Gulf of Mexico storms, the all hurricanes *RMW* model over estimates the size of the Gulf of Mexico hurricanes, indicating that Gulf of Mexico hurricanes, are smaller than Atlantic hurricanes.

5.3. *RMW* FOR LANDFALLING STORMS

Figure 11 presents the values of the *RMW* for storms making landfall along the Gulf and Atlantic coasts of the United States. In the case of Gulf Coast storms, 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. 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 between *RMW*, Δp and latitude.

(i) Gulf of Mexico landfalling hurricanes:

$$\ln(RMW) = 3.558 \qquad \sigma_{\ln RMW} = 0.457 \tag{8a}$$

(ii) Atlantic Coast landfalling hurricanes:

$$\ln(RMW) = 2.556 - 5.963\times10^{-5}\Delta p^2 + 0.0458\psi\,; \quad r^2{=}0.336,\ \sigma_{\ln RMW} = 0.456 \tag{8b}$$

(iii) Gulf and Atlantic Coast landfalling hurricanes:

$$\ln(RMW) = 2.377 - 4.825\times10^{-5}\Delta p^2 + 0.0483\psi\,; \quad r^2{=}0.203,\ \sigma_{\ln RMW} = 0.457 \tag{8c}$$

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 errors (in log space) and the resulting standard deviations and r^2 values using the landfall *RMW* data and the flight level/H*Wind derived *RMW* models.

The mean error, $\mu_{\ln RMW}$, is defined as modeled *RMW* minus the observed *RMW*, thus a mean positive error indicates the model overestimates the size of the landfalling hurricanes. The comparisons yield the following findings:

(i) Gulf of Mexico landfalling hurricanes with GoM *RMW* model:

$\mu_{\ln RMW} = 0.032$; r^2=-0.008 $\sigma_{\ln RMW} = 0.459$

(ii) Atlantic Coast landfalling hurricanes with the all hurricane *RMW* model:

$\mu_{\ln RMW} = 0.058$; r^2=0.356 $\sigma_{\ln RMW} = 0.450$

(iii) Gulf and Atlantic Coast landfalling hurricanes with the all hurricane *RMW* model for the Atlantic Coast and GoM *RMW* model for the Gulf Coast:

$\mu_{\ln RMW} = 0.043$; r^2=0.219 $\sigma_{\ln RMW} = 0.453$

A comparison of the model errors noted above to 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 there are an insufficient number of intense landfalling hurricanes in the historical data to discern such a relationship.

6. Statistical Model for Holland's Parameter (*B*)

The *B* values computed as discussed above were found to be correlated to the radius to maximum winds, central pressure difference, latitude and sea surface temperature. Only points associated with central pressures less than 980 mbar are included in the analysis. The analysis was performed with the "smoothed" time series of *B*, with samples taken approximately every three hours along the track of each hurricane. Figure 12 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 Figure 12 that *B* decreases with increasing *RMW* and increasing latitude. A weak positive correlation of *B* with Δp is seen as is a weak positive correlation with sea surface temperature.

In order to incorporate the effects of *RMW*, Δp, latitude (ψ) and T_s into a single model, new non-dimensional variable, *A*, was developed defined as:

$$A = \frac{RMW \cdot f_c}{\sqrt{2R_d T_s \cdot \ln\left(1 + \frac{\Delta p}{p_c \cdot e}\right)}} \tag{9}$$

The numerator of *A* is the product of the *RMW* (in meters) and the Coriolis force, defined as 2Ωsinφ and represents the contribution to angular velocity associated with the coriolis force. The denominator of *A* is an estimate of the maximum potential intensity of a hurricane. From Emanuel (1988), the maximum wind speed in a tropical cyclone is:

$$V_{\max} = \sqrt{2R_d T_s \ln\left[\frac{p_{\max}}{p_c}\right]} \tag{10}$$

where V_{max} is the maximum wind speed, R_d is the gas constant for dry air, p_{max} is the pressure at r=RMW, T_s is the sea surface temperature in degrees K and p_c is the pressure at the storm center.

Using Holland's (1980) Equation it can be shown that

$$\frac{p_{max}}{p_c} = 1 + \frac{\Delta p}{p_c e} \qquad (11)$$

Hence, both the numerator and denominator of A have the units of velocity, and thus A, is non-dimensional. Modeling B as a function of the square root of A yields a linear model (Figure 13) with B negatively correlated with $\sqrt{A}$ and has an r^2 of 0.34, with a the standard deviation of the error equal to 0.225. The relationship between B and $\sqrt{A}$ is expressed as:

$$B = 1.732 - 2.237\sqrt{A} \; ; \qquad r^2=0.336,\ \sigma_B = 0.225 \qquad (12)$$

In order to determine if the relationship between B and A is valid for intense storms, the point values of B and the model values of B were plotted as a function of RMW for strong hurricanes (i.e. storms with a central pressure of < 930 mbar) as shown in Figure 14. The data presented in Figure 14 indicates 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 Atlantic), the data indicate that the likelihood of a storm with a central pressure less than ~930 mbar, a 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, strong hurricanes is 1.01, and the standard deviation is 0.082. In cases where these strong storms are simulated, B is constrained to lie within the range of the mean ±3σ.

As in the case of the analysis of Gulf of Mexico (GoM) 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* where 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 15 presents the individual *B* values for the GoM and Atlantic hurricanes along with the model 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.

Note that two simpler, but less elegant models, relating *B* with *RMW* and latitude were examined modeling *B* as a function of $f_c RMW$ and *B* as a function of $\sqrt{C}$, where *C* is defined as:

$$C = \frac{RMW \cdot f_c}{\sqrt{2R_d T_s \cdot \ln\left(1 + \frac{\Delta p}{P_c \cdot e}\right)}} \qquad (13)$$

where in Equation (13) T_s is expressed in degrees C rather than degrees K.

The regression model relating *B* to $\sqrt{C}$ is given in the form:

$$B = 1.7242 - 1.2098\sqrt{C} \;; \qquad r^2 = 0.345,\ \sigma_B = 0.226 \qquad (14)$$

The regression model relating *B* to $f_c RMW$ is given in the form:

$$B = 1.793 - 0.326\sqrt{f_c RMW} \;; \qquad r^2 = 0.357,\ \sigma_B = 0.221 \qquad (15)$$

The two simpler models (Equations 14 and 15) yield marginally improved r^2 values than does the model relating B to the non-dimensional relative intensity parameter, but have the small disadvantage in that the independent variable is not non-dimensional. The limitations of these models when applied to large intense storms are the same as those evident in the case of the non-dimensional model. The improvement of the r^2 value seen when changing the independent variable in the non-dimensional parameter given in Equation (9) to the dimensional parameter given in Equation (13) is due solely to the conversion of the sea surface temperature from degrees C (Equation 13) to degrees K (Equation 9). For practical purpose, any of the three linear regression models given in Equations (12), (14) or (15) can be used to model the Holland B parameter, with Equation (15) requiring the least computational effort. A mean value of B of 0.04 must be added to the regression equations (12), (14), and (15), since the smoothing process reduced the mean B value by 0.04. Again, note that the units of the RMW used in Equations (12), (14) or (15), is meters.

A statistical model relating B to RMW (in km) and ψ in the same form as that developed by Powell et al. (2006) also using the data processed by Willoughby and Rahn (2005) but with B derived using upper level wind speeds rather then pressures is

$$B = 1.881 - 0.00557RMW - 0.01295\,\psi; \qquad r^2=0.356,\ \sigma_B = 0.221 \qquad (16)$$

Equation 16 is similar to the model given in Powell et al. (2006) which is

$$B = 1.881 - 0.00557RMW - 0.01097\,\psi,; \qquad r^2=0.2,\ \sigma_B = 0.286 \qquad (17)$$

The intercept in Equation (16) includes the 0.04 adjustment, and the *RMW* is in km in both Equations (16) and (17).

7. Comparison of Flight Level B Values with Landfall Analysis B Values

Figure 16 presents a comparison of the Holland *B* parameters derived from the flight level data to those used in the wind field model described in Vickery et al. (2007) used for estimating the wind speeds associated with land falling storms. Although only 11 cases where both flight level data and post storm 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 is about 7% less than those derived from the flight level data. This difference could be due to either changes in the characteristics of the pressure field between the 700 mbar level and the surface or the smoothing process inherent in modeling the wind and pressure fields using a single value of *B*, or a bias in the windfield model, but further data is required to determine if this trend is a general trend or is associated with the limited sample.

8. SUMMARY

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 new non-dimensional parameter, *A*, defined by Equation 9, however; a two parameter model (with dimensions) relating *B* to the *RMW* and the coriolis parameter is an equally good predictor of *B*.

The limited data for large (as defined by *RMW*) hurricanes, having low central pressures (p_c<930 mbar) indicates that *B* has an upper limit of ~1.2 to 1.3. The relationship between *B* and *A* was found to be the same in the Atlantic Basin and in the Gulf of Mexico.

A qualitative examination of the characteristics of intense Hurricanes making landfall along the Gulf of Mexico coast (excluding Southwest Florida) suggests that these hurricanes weaken in the last 6 – 24 hours, with this weakening characterized by an increase in the central pressure, and increase in the radius to maximum winds and a decrease in the Holland *B* parameter. The reason for this weakening is beyond the scope of this investigation.

The few cases where flight level data were available up to the time a hurricane makes landfall indicates that in most cases, *B*, tends to decrease as the hurricane approaches land. Recognizing that the data set is limited, this observation suggests that using the statistical model for *B* derived using open ocean (or open Gulf) data may result in an overestimate of *B* for landfalling storms. This potential overestimate of the magnitude of the Holland *B* parameter along the Gulf Coast associated with the use of a statistical model developed using open water hurricane data may be further exaggerated because of the decrease in the Holland *B* parameter just before landfall observed in the limited number of landfalling cases examined.

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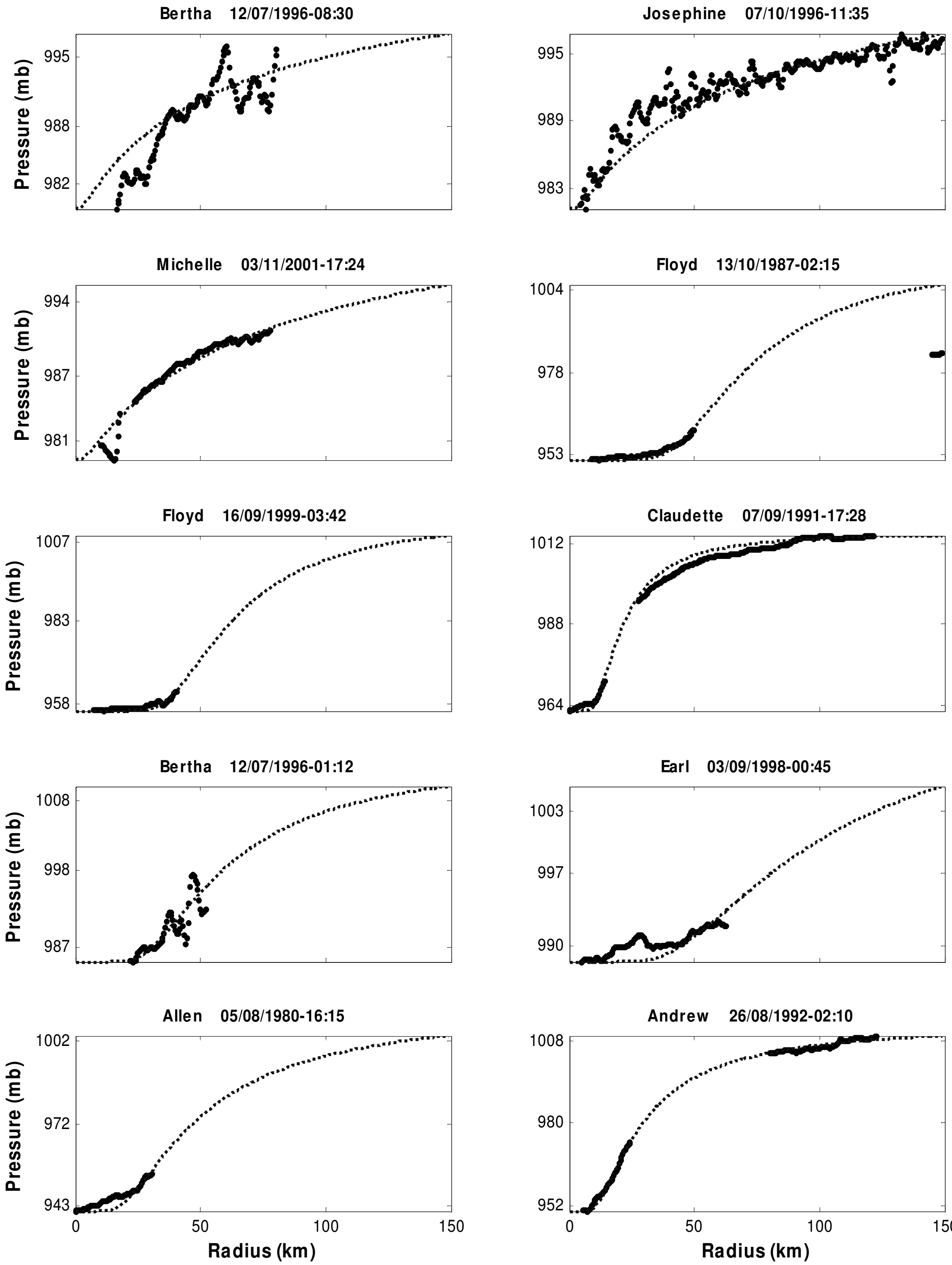

Figure 1. Examples of the eliminated profiles.

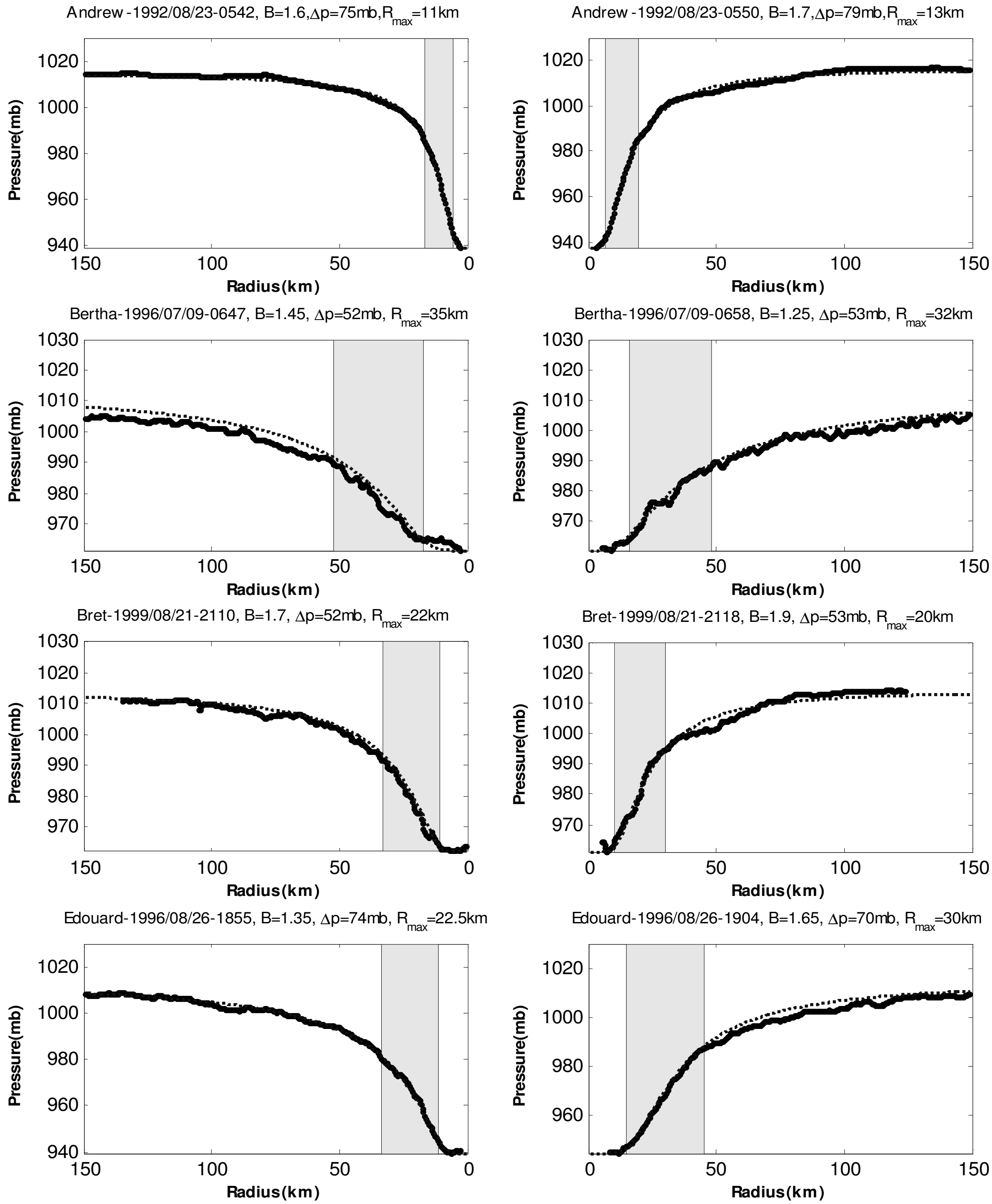

Figure 2. Examples of surface pressure profiles for a traverse across a given hurricane.

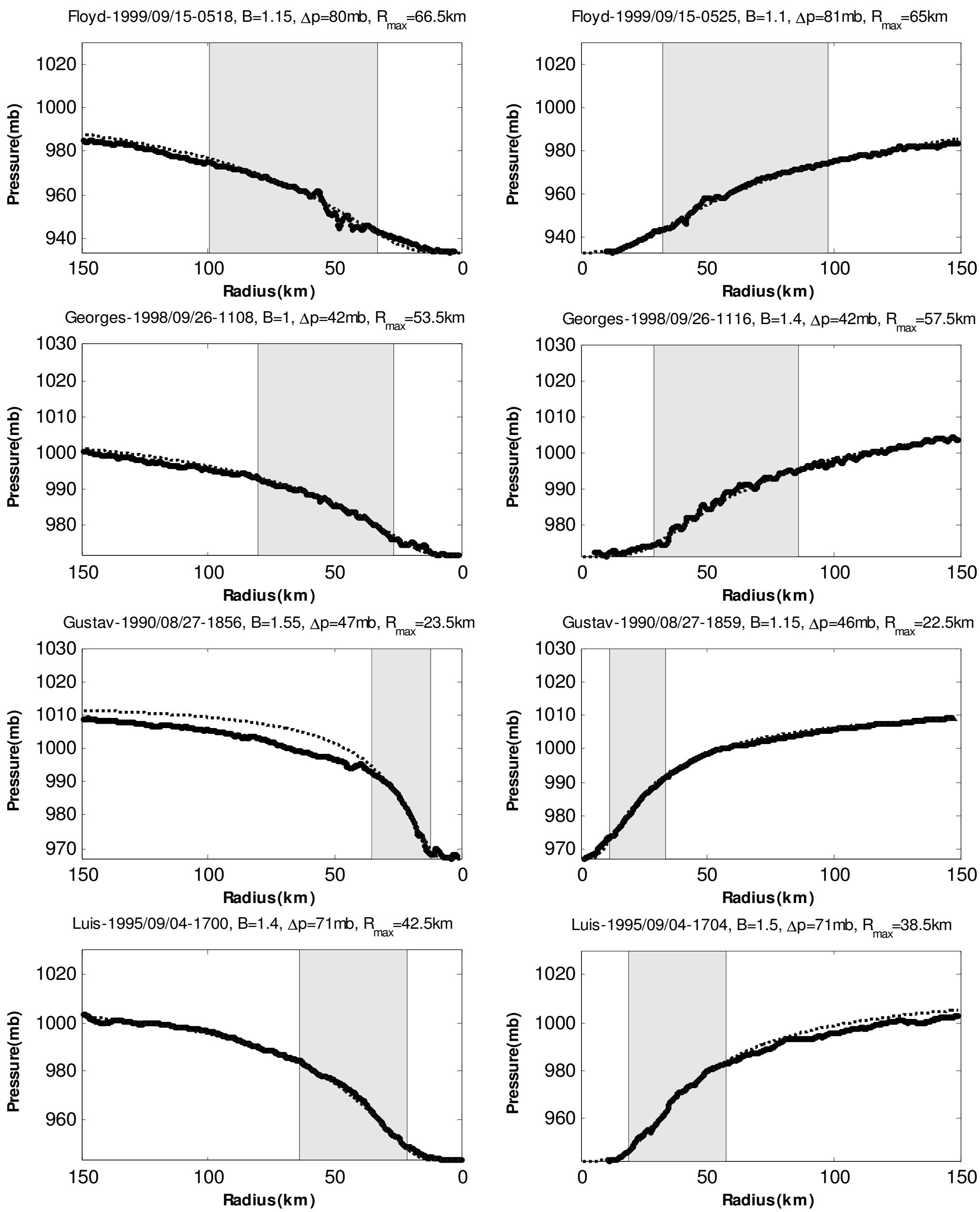

Figure 2. (Continued) Examples of surface pressure profiles for a traverse across a given hurricane.

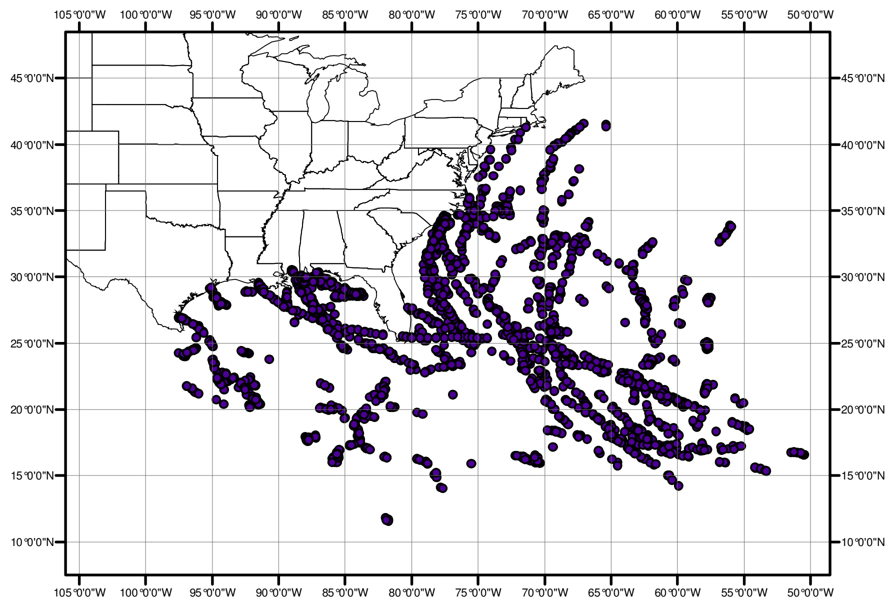

Figure 3. Geographical distribution of all the filtered profiles.

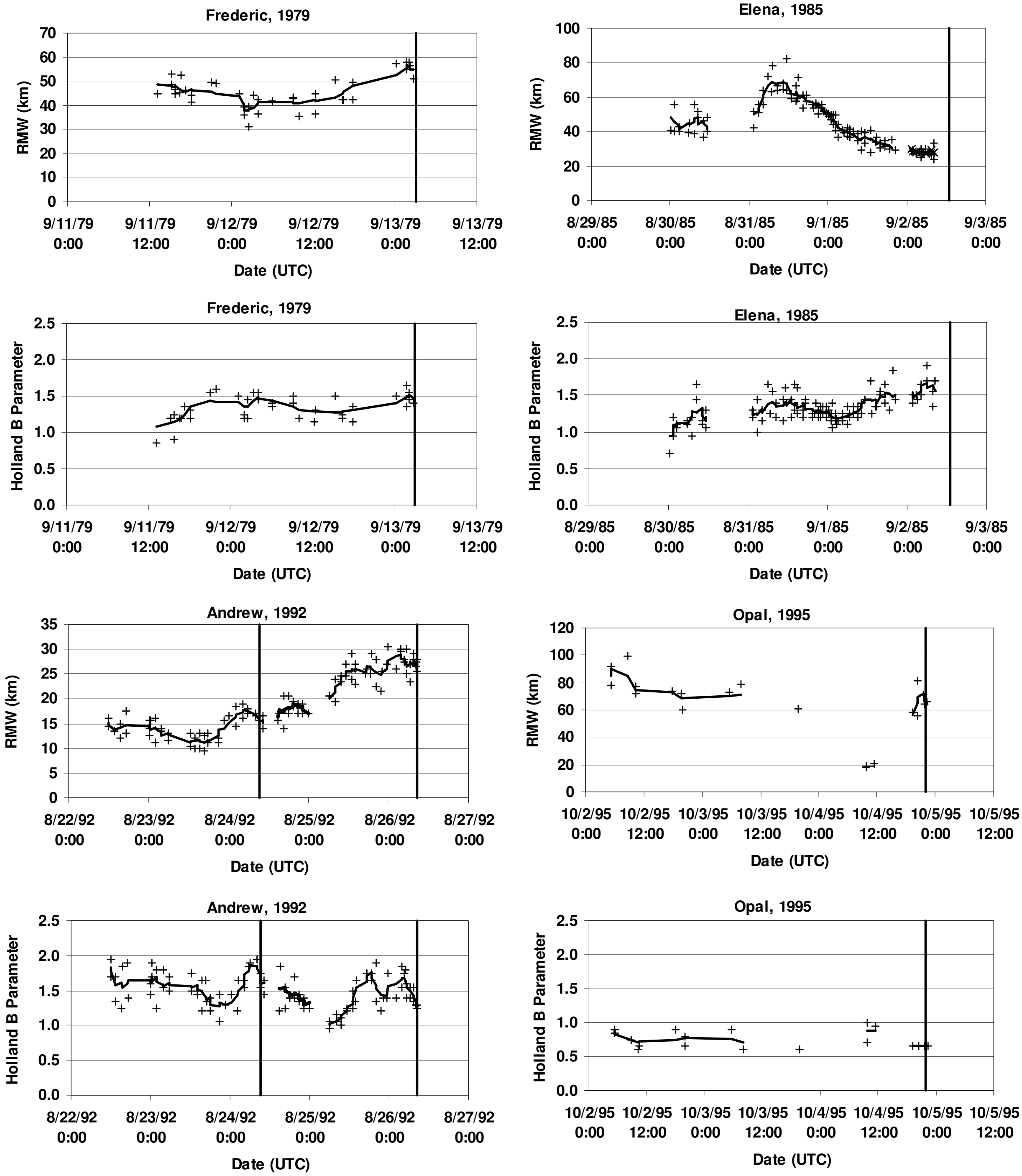

Figure 4. Examples of Smoothed (line) and Point Estimates (symbols) of *RMW* and *B* derived from 700 mbar level pressure data. Vertical line(s) represent time of landfall.

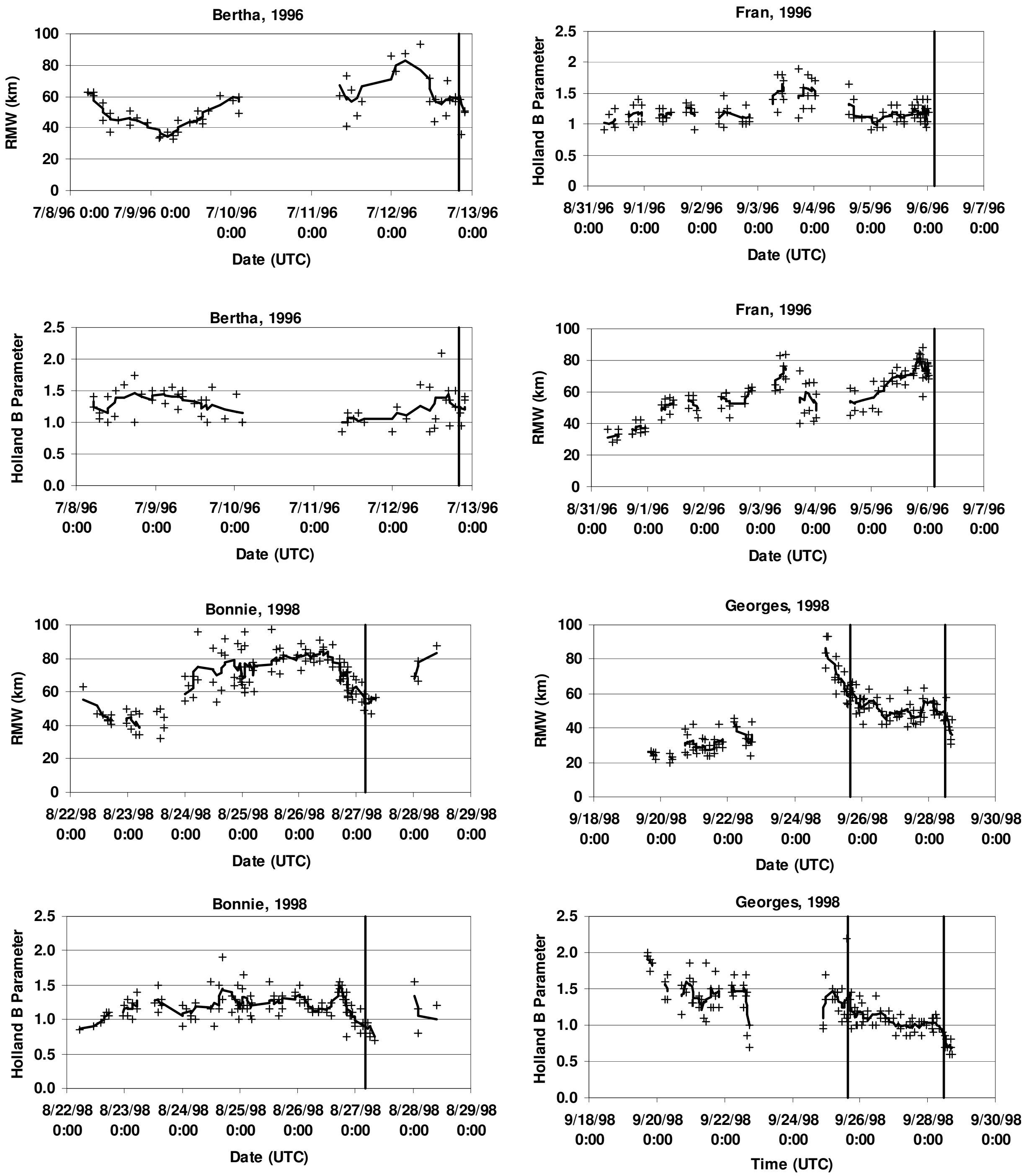

Figure 4. (Continued) Examples of Smoothed (line) and Point Estimates (symbols) of *RMW* and *B* derived from 700 mbar level pressure data. Vertical line(s) represent time of landfall.

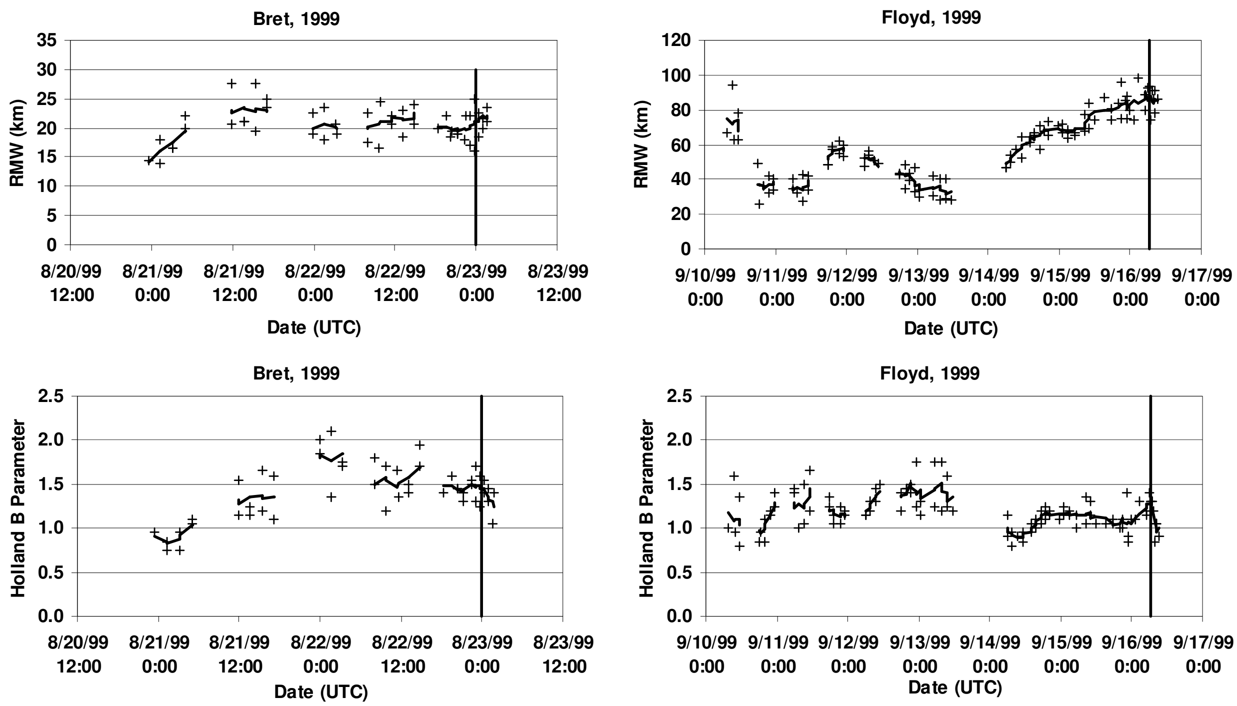

Figure 4. (concluded) Examples of Smoothed (line) and Point Estimates (symbols) of *RMW* and *B* derived from 700 mbar level pressure data. Vertical line(s) represent time of landfall.

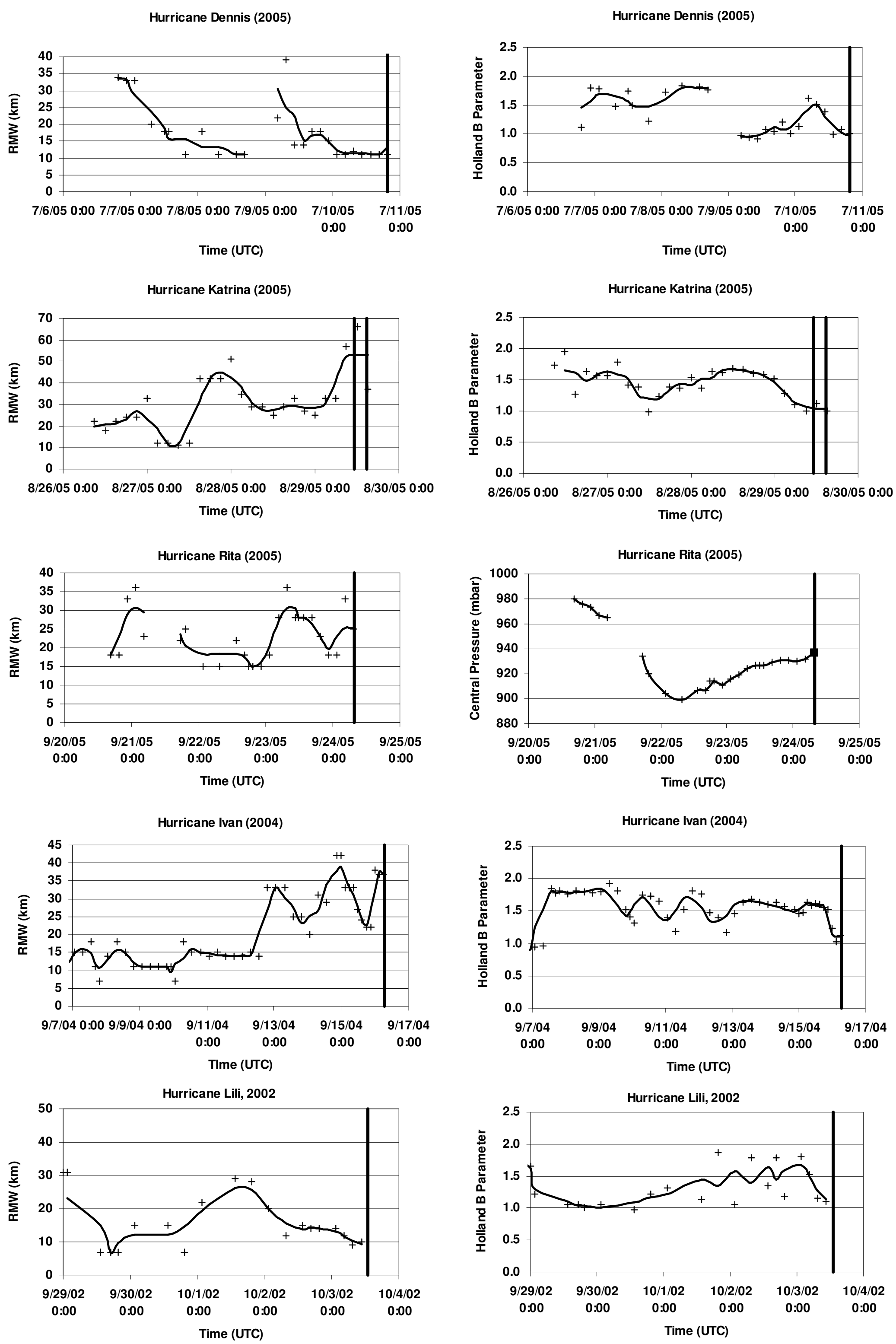

Figure 5. Smoothed (line) and Point Estimates (symbols) of *RMW* and *B* derived from H*Wind data. Vertical line(s) represent time of landfall. Solid square point at time of landfall represents NHC landfall pressure value.

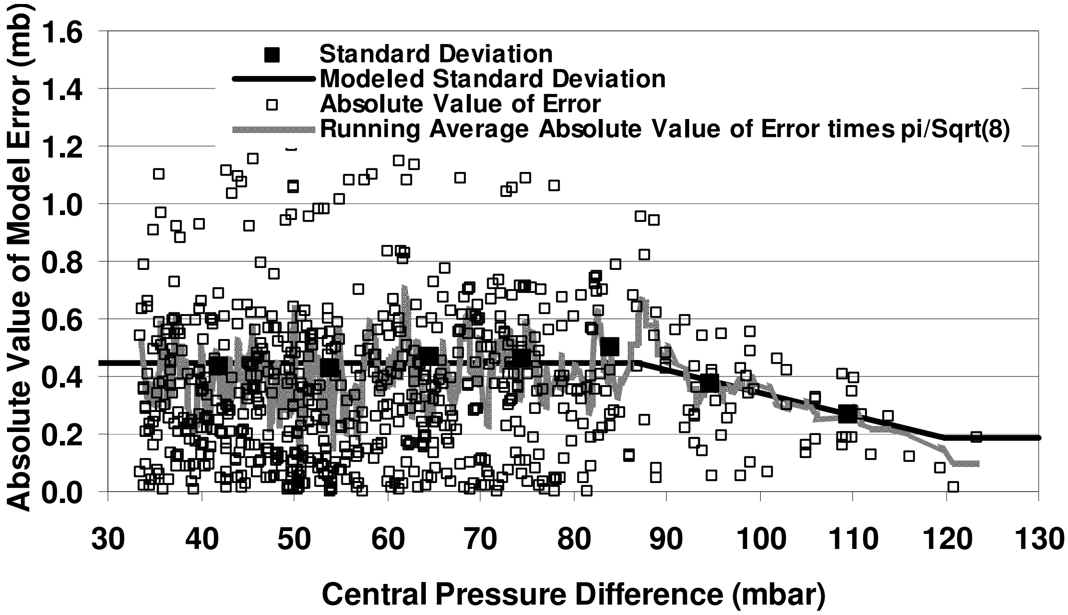

Figure 6. Absolute value of *RMW* model error vs. Δp

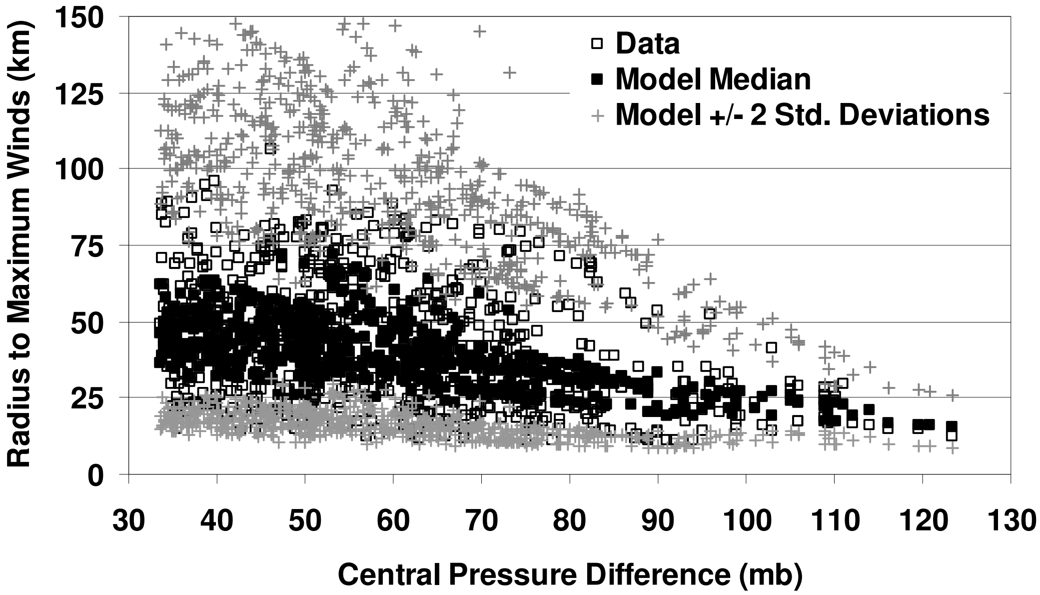

Figure 7. Modeled and observed *RMW* vs. Δp for all hurricanes

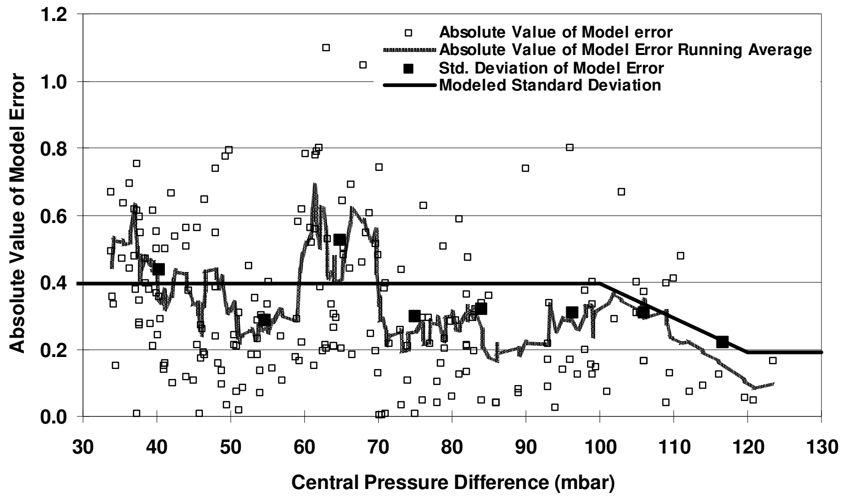

Figure 8. Absolute value of *RMW* model error vs. Δp for Gulf of Mexico hurricanes

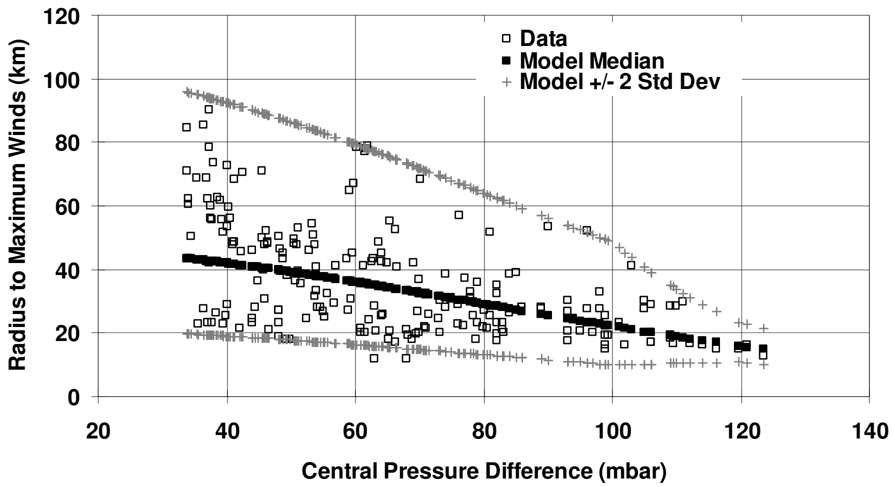

Figure 9. Modeled and observed *RMW* vs. Δp for Gulf of Mexico hurricanes.

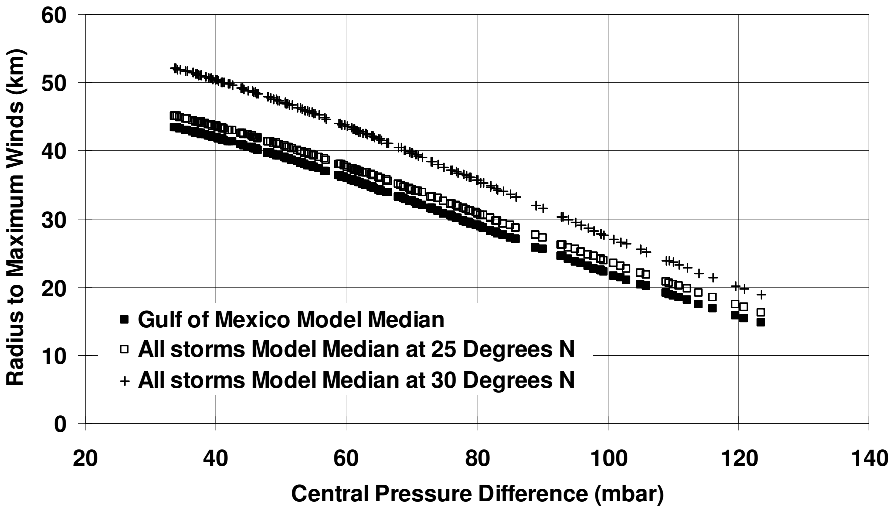

Figure 10. Comparison of all hurricanes model predicted median *RMW* to Gulf of Mexico model median *RMW*.

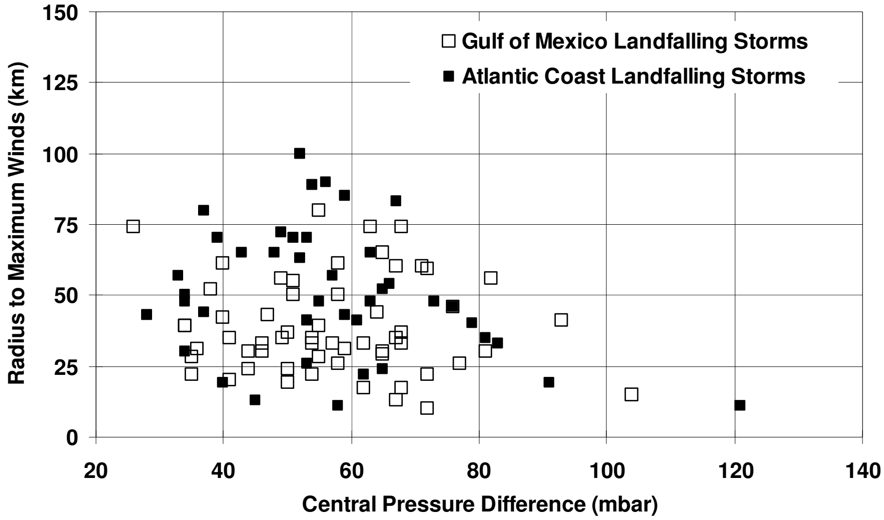

Figure 11. *RMW* for landfalling storms along the Gulf and Atlantic Coasts of the US

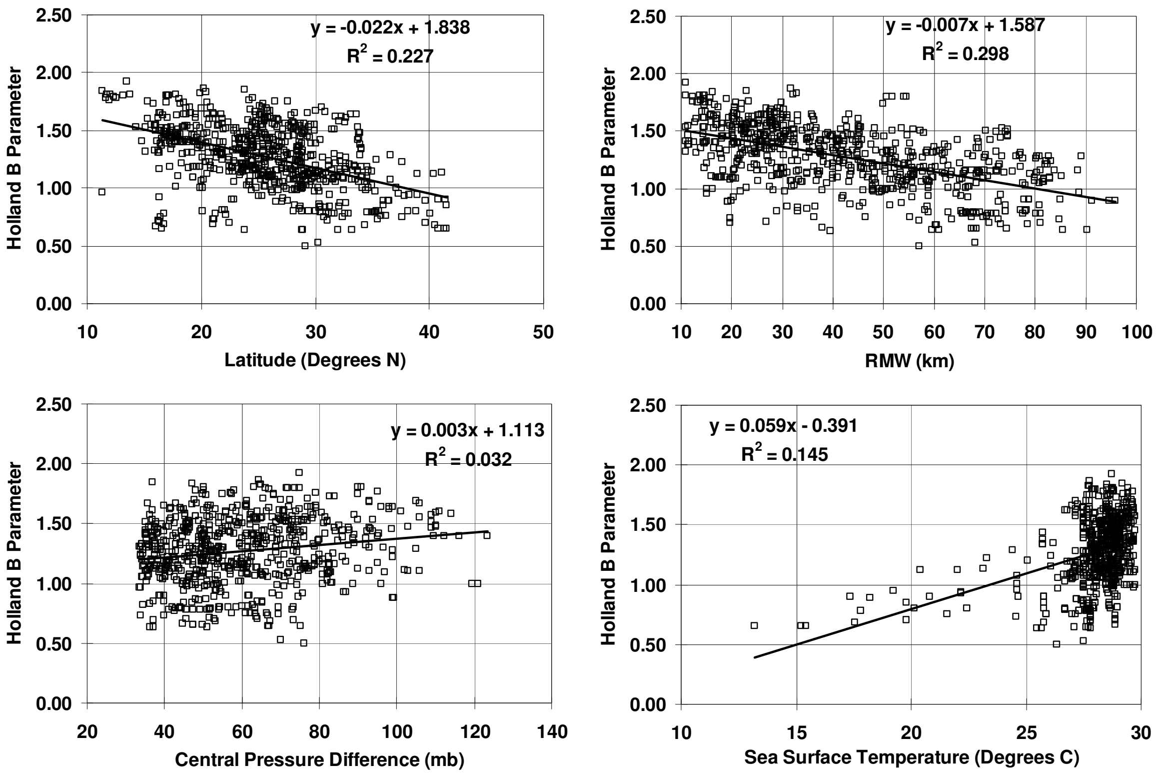

Figure 12. Relationships between the Holland *B* parameter, latitude, *RMW*, Δp, and T_s

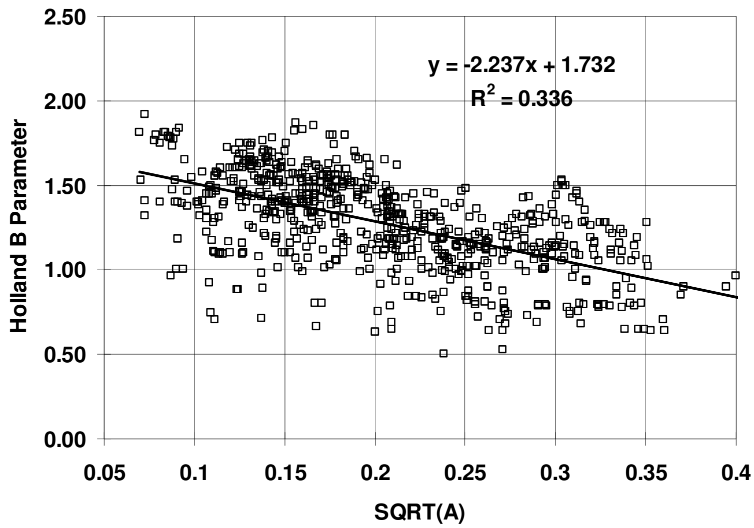

Figure 13. Relationship between the Holland *B* parameter dimensionless parameter, *A*.

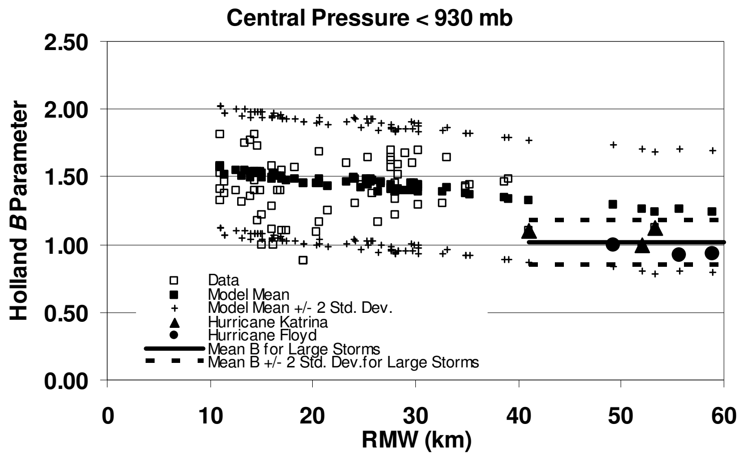

Figure 14 Holland *B* parameter vs. *RMW* for storms with central pressure < 930 mbar

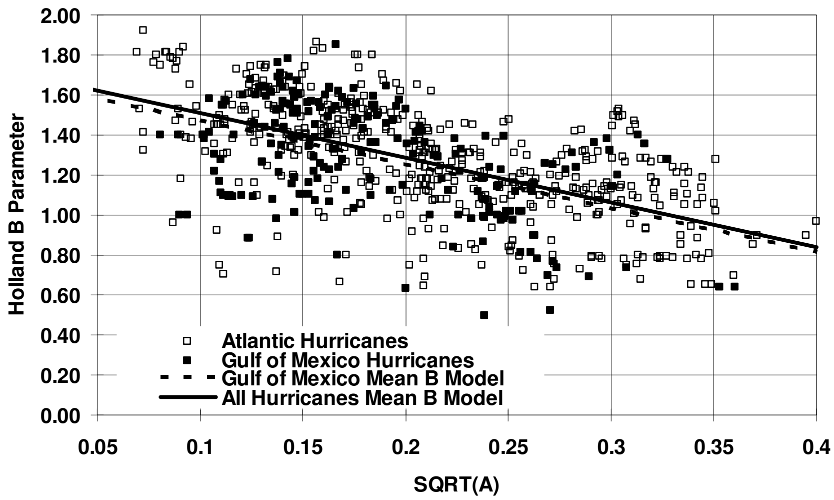

Figure 15. Relationship between the Holland *B* parameter and the dimensionless parameter, *A*, comparing the all hurricane data with the GoM hurricane data.

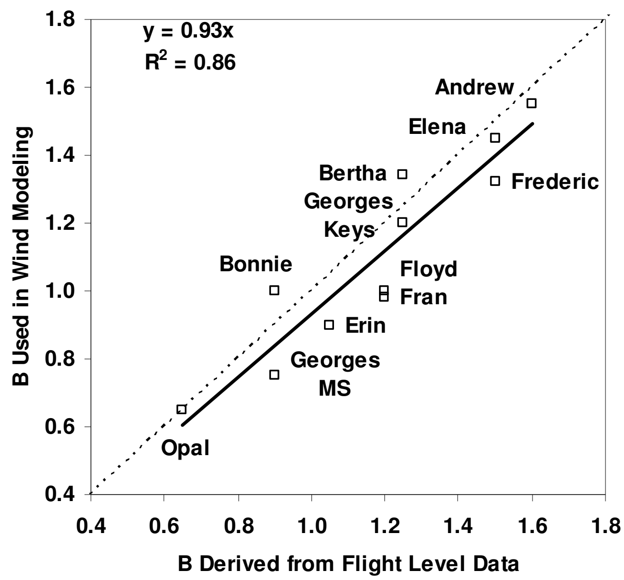

Figure 16. Comparison of Holland *B* parameters derived from flight level data to those derived using a post landfall windfield analysis.

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

Filter criteria	Number of profiles eliminated
(a)	459
(b)	1180
(c)	121
(d)+(e)+(f)	531
Total number of filtered profiles	2291

Table 2. Percentage of flight level pressure profiles retained.

Storm	Year	Total	Retained	%Retained	Comments
no-name	1938	5	5	100.00	Data extracted manually from Myers & 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	$\Delta p<25$mb for all the cases, except one.
Alicia	1983	50	39	78.00	
Arthur	1984	22	0	0.00	$\Delta p <25$mb for all the cases.
Diana	1984	128	67	52.34	
Danny	1985	26	0	0.00	$\Delta p <25$mb for all the cases.
Elena	1985	122	99	81.15	
Gloria	1985	42	24	57.14	
Isabel	1985	48	0	0.00	$\Delta p <25$mb for all the cases.
Juan	1985	36	6	16.67	
Charley	1986	28	0	0.00	$\Delta p <25$mb for all the cases.
Emily	1987	56	1	1.79	40 out of 56 profiles have flight level pressure <700mb.
Floyd	1987	22	0	0.00	$\Delta p <25$mb 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 <700mb 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	$\Delta p <25$mb for all the cases.
Gordon	1994	83	8	9.64	57 out of 83 profiles have $\Delta p <25$mb.
Allison	1995	39	3	7.69	35 out of 39 profiles have $\Delta p <25$mb.
Chantal	1995	72	0	0.00	$\Delta p <25$mb for all the cases.
Erin	1995	97	66	68.04	
Felix	1995	130	59	45.38	
Gabrielle	1995	16	0	0.00	$\Delta p <25$mb for all the cases.
Iris	1995	132	41	31.06	
Luis	1995	130	77	59.23	
Marilyn	1995	116	96	82.76	

Table 2 (concluded) Percentage of flight level pressure profiles retained.

Storm	**Year**	**Total**	**Retained**	**%Retained**	**Comments**
Opal	1995	76	21	27.63	
Roxanne	1995	141	52	36.88	
Bertha	1996	78	56	71.79	
Cesar	1996	34	0	0.00	Δp <25mb 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	Δp <25mb for all the cases.
Lili	1996	68	28	41.18	
Marco	1996	67	1	1.49	Δp <25mb 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	Δp <25mb for all the cases.
Michael	2000	21	11	52.38	
Humberto	2001	46	13	28.26	
Michelle	2001	89	61	68.54	

Table 3. Tendency of Holland B Parameter for Landfalling Storms.

Hurricane and Landfall Location	*B* Tendency at landfall
Frederic (Alabama)	~ constant
Elena (Mississippi)	~ constant
Andrew South Florida	~constant to ~negative
Andrew Louisiana	negative
Opal (North West Florida)	constant
Bertha (North Carolina)	negative
Fran (North Carolina)	~constant
Bonnie (North Carolina)	negative
Georges (Mississippi)	negative
Bret (Texas)	~constant
Floyd (North Carolina)	positive