A Revised Hurricane Pressure–Wind Model

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ABSTRACT

A new technique for relating central pressure and maximum winds in tropical cyclones is presented, together with a method of objectively determining a derivative of the Holland b parameter, b_s, which relates directly to surface winds and varies with the pressure drop into the cyclone center, intensification rate, latitude, and translation speed. By allowing this b_s parameter to vary, a realistic scatter in maximum winds for a given central pressure is obtained. This provides an improvement over traditional approaches that provide a unique wind for each central pressure. It is further recommended that application of the Dvorak satellite-interpretation technique be changed to enable a direct derivation of central pressure. The pressure–wind model derived here can then provide the maximum wind estimates. The recent North Atlantic data archive is shown to be largely derived from the use of the Dvorak technique, even when hurricane reconnaissance data are available and Dvorak overestimates maximum winds in this region for the more intense hurricanes. Application to the full North Atlantic hurricane archive confirms the findings by Landsea (1993) of a substantial overestimation of maximum winds between 1950 and 1980; the Landsea corrections do not completely remove this bias.

1. Introduction

A wide variety of relationships has been proposed for relating the minimum central pressure and maximum surface winds in tropical cyclones (see Harper 2002 for a complete summary).[1] The relationships provide a critical analysis tool for the assessment of maximum winds from a diverse set of observations and estimates, particularly in regions that have relied largely on the Dvorak satellite interpretation (Dvorak 1975, 1984) for assessing maximum intensity since the mid-1970s.

Almost all pressure–wind models (P–W models) are of the form (Harper 2002)

$$v_m = a\Delta p^x, \quad (1)$$

where v_m is the maximum wind, $\Delta p = p_n - p_c$ is the pressure drop from a defined external pressure p_n to the minimum central pressure p_c, and a and x are empirical constants, which will be described later.

Early empirical pressure–wind approaches utilized Eq. (1) with $x = 0.5$ and an empirical determination of parameter a. Fujita (1971) was the first to also empirically adjust the exponent, and since that time most techniques have adjusted both a and x. The most widely used of these techniques was derived by Atkinson and Holliday (1977, hereafter AH77):

$$v_m = 3.4(1010 - p_c)^{0.644}, \quad (2)$$

where v_m is the 1-min-mean wind at a 10-m elevation in m s^{-1}, surface pressure is in hPa, and the 1010 is an assumed constant environmental pressure valid for the western North Pacific, but generally utilized elsewhere as well.

Though it was never adequately documented at the time, the Dvorak pressure–wind model for both the North Atlantic and Western Pacific can easily be shown to be closely related to the AH77 model. The trick that was employed by Dvorak was to calculate the pressure drop in Eq. (2) using an environmental pressure, p_n =

[1] Throughout this paper, "surface" wind implies a standard 1-m elevation over clear, flat terrain. The North Atlantic data use 1-min averaging. Application to other regions with different averaging periods will require the use of a standard correction factor, with 0.88 being recommended for 1-min to 10-min conversions.

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1010 hPa, as per AH77, but then to apply this directly to the western North Pacific with $p_n = 1010$ and to the North Atlantic with $p_n = 1016$. A very close fit to the Dvorak tabular pressure–wind model can be obtained by

$$v_m = 3.92(1015 - p_c)^{0.644}, \quad (3)$$

for the North Atlantic, and by Eq. (2) for the western North Pacific. Equation (3) is used to derive the Dvorak data used in this paper [note that the 1015 value in Eq. (3) is correct].

Landsea et al. (2004) noted that Eq. (2) was derived from the raw data without first binning to remove a bias toward the more frequently sampled lower intensities, and this led Knaff and Zehr (2007) to derive a new version after binning the original AH77 data:

$$v_m = 2.3(1010 - p_c)^{0.76}. \quad (4)$$

A comprehensive reconsideration of pressure–wind models has been recently completed by Knaff and Zehr. They adopted the more general approach of fitting regression models and used pressure as the dependent variable to derive the following relationship:

$$p_c = 23.286 - 0.483v_{\mathrm{srm}} - \left(\frac{v_{\mathrm{srm}}}{24.254}\right)^2 - 12.587S - 0.483\phi + p_n, \quad (5)$$

where v_{srm} is the maximum winds with storm motion removed, S is related to storm size, φ is latitude, and p_n is the environmental pressure that is determined on a storm-by-storm basis.

All the standard approaches start from the implicit assumption that the empirical constants in Eqs. (1)–(4) are actually constant and do not in themselves contain any parameter variability. With the exception of the Knaff and Zehr (2007) approach, they thus provide a unique value of the wind for a particular pressure deficit, whereas there is a considerable scatter in the archived pressure–wind data (Fig. 1). Because of the assumption of there being no variability in parameter a in Eq. (1), a variety of derivatives has been developed by stratifying into subsets of latitudinal bands and sizes, for example (see Harper 2002 for a complete listing). As shown in Fig. 1, these do tend to cover the observed scatter, but at the cost of being unable to fully represent the real scatter. Harper (2002) noted that the differences in mean parametric models across different ocean basins are small compared to the storm-to-storm difference and that a more robust and adjustable form of pressure–wind relationship was desired.

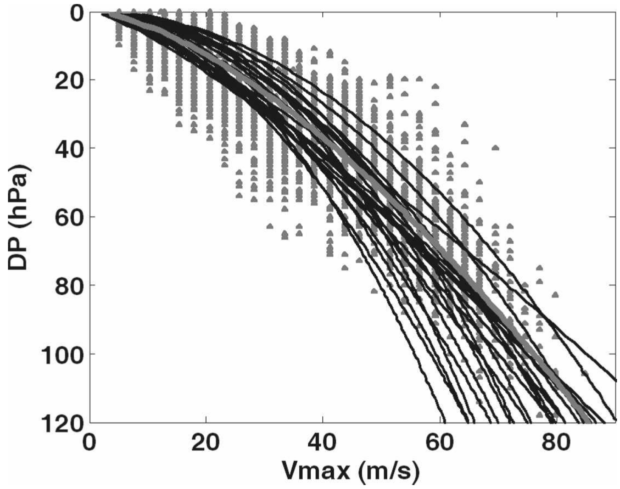

FIG. 1. Plot of all P–W models listed by Harper (2002), adjusted to 1-min-mean winds, and superimposed on the North Atlantic HURDAT data (Δ) for all westward-moving storms from 1995–2005. DP = $P_n - P_c$, $v_{\max}$ is the maximum sustained wind, and the heavy gray curve is for Dvorak (1975, 1984).

The relationship in Eq. (1) was originally derived from an assumption that the radial pressure profile can be approximated by rectangular hyperbole. Holland (1980, hereafter H80) extended the original form to include a parameter b, which enabled variation in the degree of pressure gradient near the maximum winds and thus captured the peakedness in the related wind profile (higher b gives a more peaked wind profile):

$$p = p_c + \Delta p e^{-\left(\frac{r}{r_m}\right)^b}, \quad (6)$$

with r_m being the radius of maximum winds. Using Eq. (6) in the cyclostrophic wind equation and setting $r = r_m$ leads to the following form of Eq. (1):

$$v_m = \left(\frac{b}{\rho e}\Delta p\right)^{0.5}, \quad (7)$$

where ρ is the surface air density in kg m^{-3}, Δp is in pascals, and e is the base of natural logarithms. It is notable that this analytic approach requires no information on storm size or the maximum wind radius; we shall return to this later.

Note that both parameter b and air density in Eq. (7) are variables and cannot reasonably be assumed to be constant; for example, the range in v_m is up to 5 m s^{-1} for reasonable variations in air density of 1.0–1.15 kg m^{-3} and around 20 m s^{-1} for variations in the b parameter of 1–2. This compares to a negligible 1 m s^{-1} for the cyclostrophic assumption and up to 5 m s^{-1} for variations in environmental pressure of up to 10 hPa.

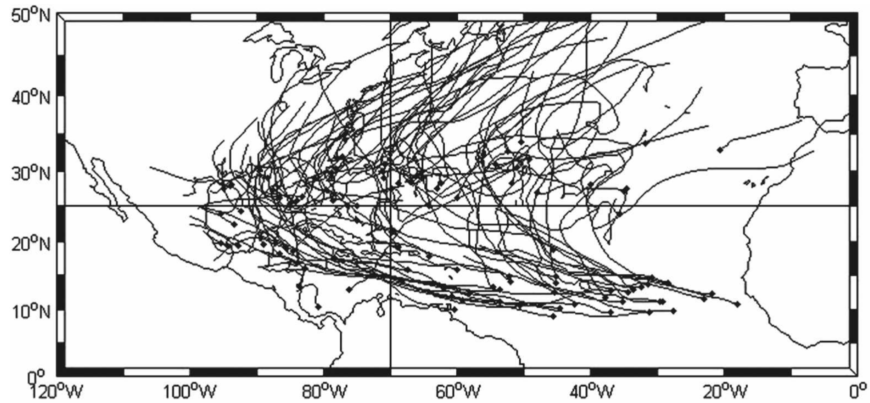

FIG. 2. North Atlantic region showing the demarcation at 70°W discussed in the text and all tropical cyclone formations (large dots) and tracks for the 2000–05 seasons.

Our purpose here, therefore, is twofold:

- to establish a more flexible pressure–wind model incorporating variations in parameter b and air density, together with considerations of other storm parameters; and
- to develop a parametric equation for the b parameter that can be used in general applications of the H80 model.

The goal is to only use information that is available in the standard tropical cyclone archives, though additional information can be introduced if available. The next section presents the data used, outlines the model development, and applies it to North Atlantic data; section 3 comments on the significance for the Dvorak satellite technique and on implications for the North Atlantic data archive; and the conclusions are presented in section 4.

2. Data and model derivation

a. Data

The North Atlantic HURDAT data (www.nhc.noaa.gov/pastall.shtml) are used throughout this study. Later studies will discuss the application to other ocean basins. No changes were made to the data, though these are of variable quality and usefulness for this project, the details of which are discussed at relevant stages in the paper.

Selecting the appropriate periods for dependent and independent data is not straightforward, as the quality of the data changes markedly over time; we shall see that the Dvorak pressure–wind model dominates the data over the eastern and northern oceanic regions, especially for eastward-moving cyclones. There is the additional potential complication of the change from one climatic regime to another in 1994–95 (Holland and Webster 2007). After some consideration, nonlandfalling, westward-moving tropical cyclones of >17 m s^{-1} maximum winds, <1005 hPa central pressure, and <20 m s^{-1} translation speed from 2000–05 and the region west of 70°W were chosen as the dependent dataset (the geographical regions discussed in this paper are shown in Fig. 2). This choice ensures a quality set without potential inconsistencies due to extratropical interactions or decay at land and with a predominance of observations using modern instrumentation from aircraft and satellites, which have been fully analyzed by experts at the National Hurricane Center (NHC). A deliberate choice was made not to use aircraft reconnaissance data exclusively, because the mix of applied techniques, including remote sensing and reconnaissance data, is considered to provide a more robust dataset. Unfortunately, the data also will be contaminated by the application of other empirical techniques and by an unknown amount of human judgment. The HURDAT does not contain any indication of the type of observations used in the derivation of the maximum winds, so no attempt is made to further break down the data by major observing type; further comments will be made on this overall topic later. Eastward-moving cyclones in the same region also were not selected, and we shall show that these data are largely derived from use of the Dvorak pressure–wind relation and derivatives.

The remaining data in the HURDAT set make up our independent data. Unfortunately, there is very limited availability of archived central pressures for North Atlantic tropical cyclones prior to 1980. As shown in Fig. 3, the number of central pressure observations drops sharply as we go back in time, to essentially none prior to 1950. Also, central pressures were typically only recorded for hurricanes prior to 1965. This se-

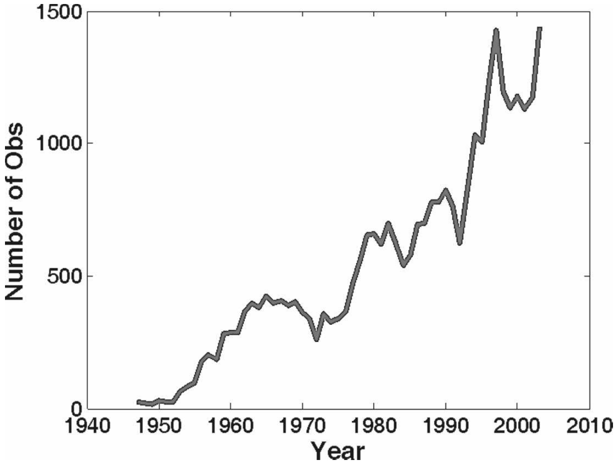

FIG. 3. Annual number of 6-hourly observations with recorded central pressure for all tropical cyclones in the North Atlantic. The series has been smoothed with a 5-yr running mean.

verely limits the application of pressure–wind relationships for historical storms, with the one advantage being that the early pressure data were normally observed independently of the winds (e.g., Jarvinen et al. 1984).

b. Derivation of the pressure–wind model

The Δp is used as the primary variable to derive an associated range of maximum wind speeds; this is based on the explicit assumption that the pressure drop is a conservative parameter and that much of the variability in Fig. 1 arises from variations in the maximum wind speed for a given pressure. An empirical relationship for the b parameter in terms of Δp is first derived and then empirical corrections are included to account for latitude, storm development, and storm speed to arrive at a final b parameter. Utilizing this together with a variable surface density in Eq. (7) leads to the pressure–wind model. A further extension of allowing the exponent in Eq. (7) to vary could also be tried (as done by, e.g., AH77). However, because this exponent is derived from the cyclostrophic wind equation, it is used as is.

The $\Delta p = p_n - p_c$ is derived using the observed central pressures, p_c, and a fixed environmental pressure, $p_n = 1015$, which is representative of the mean conditions for the region during the hurricane season and consistent with previous studies (e.g., Knaff and Zehr 2007 for a summary). While it would be preferable to use the variable p_n, this is not readily available in most cyclone archives, so this is fixed at a basin-wide mean to enable a more readily applicable technique. If actual values of p_n were to become available, they should be used in preference. Previous studies have indicated that cyclone size may also affect the pressure–wind relationship (e.g., Love and Murphy 1985). Willoughby and Rahn (2004) have suggested that this largely comes through the variations in peakedness, which would be best modeled through the b parameter. Again, this information is not readily available in most archives, so size is not included. The consequences of disregarding these features are addressed later.

A relationship for parameter b in terms of Δp can be derived by first rearranging Eq. (7) and using the equation of state to replace the air density:

$$b_s = \frac{v_m^2 p_{\text{rmw}} e}{\Delta p R T_{\text{vs}}}, \tag{8}$$

where p_{rmw} is the estimated surface pressure in the maximum wind region, R is the universal gas constant, and T_{vs} is the virtual temperature at a 10-m height in the maximum wind regime. The subscript on b_s is used to denote that the derived relationship for b will be made with surface data, not gradient winds as per the original H80 approach. A good approximation of $p_{\text{rmw}} = p_c + \Delta p/3.7$ can readily be derived from Eq. (6), and the latitudinal variation in virtual surface air temperature is approximated by

$$\begin{aligned} T_{\text{vs}} &= (T_s + 273.15)(1 + 0.81 q_m), \quad \text{where,} \\ T_s &= 28 - 3(\phi - 10)/20, \\ q_m &= 0.9 \frac{3.802}{p_{\text{rmw}}} e^{17.67 T_s/(243.5 + T_s)}, \end{aligned} \tag{9}$$

where T_s is the surface air temperature (°C) and q_m is the vapor pressure at an assumed relative humidity of 90%. The latitudinal variation of surface temperature was arrived at by examining SST analyses for the hurricane season. While this is of necessity a gross approximation, the resulting density errors of assuming this form compared to using actual surface temperatures are negligible. If actual SST data are available, $T_s = \text{SST} - 1$ is recommended as an alternative.

The v_m and Δp for the dependent dataset are next binned into 5 m s^{-1} bins, then a quadratic fit is used (Fig. 4) to arrive at

$$v_m = -0.0027 \Delta p^2 + 0.9 \Delta p + 11. \tag{10}$$

Next, we substitute Eq. (10) into Eq. (8) to arrive at a relationship for b_s in terms of a cubic in Δp and with T_{vs} provided by Eq. (9). After some experimentation, it was found that the full cubic relationship of b_s with Δp added no skill compared to the use of a quadratic, which was chosen. Additional skill was found by including intensity change, latitude, and translational speed.

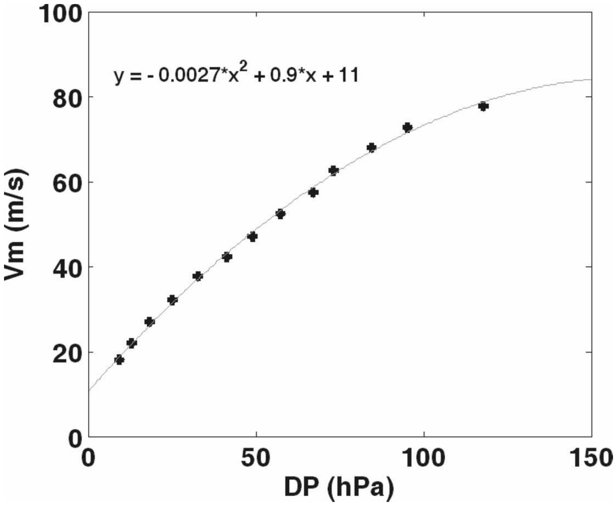

FIG. 4. Results of binning the dependent data maximum wind and pressure drop into 5 m s^{-1} bins (dots) and then fitting a quadratic (line) by least squares to arrive at Eq. (10).

These are consistent with other studies (e.g., Knaff and Zehr 2007). The final parametric P–W model is then

$$b_s = -4.4 \times 10^{-5}\Delta p^2 + 0.01\Delta p + 0.03\frac{\partial p_c}{\partial t} - 0.014\phi + 0.15 v_t^x + 1.0,$$

$$x = 0.6\left(1 - \frac{\Delta p}{215}\right), \quad \text{and}$$

$$v_m = \left(\frac{b_s}{\rho e}\Delta p\right)^{0.5}, \tag{11}$$

where air density, ρ, is derived from the equation of state and Eq. (9), e is the base of natural logarithms, Δp is the pressure drop to the cyclone center in hPa, $(\partial p_c/\partial t)$ is the intensity change in hPa h^{-1}, φ is the absolute value of latitude in degrees, and v_t is the cyclone translation speed in m s^{-1}.

Equation (11) (referred to as the P–W model) shows that for a given central pressure, the maximum winds can vary according to prior intensity change, latitude, translation speed, and the varying air density with surface pressure. The varying density has been justified on theoretical grounds. There is no a priori reason to expect that the relationships with intensity change and latitude is linear; this was made on the basis of examination of scatterplots of these parameters against a derivation of the b_s parameter directly from HURDAT data (see section 2c and Fig. 9 for further details). The nonlinear relationship with translational speed was arrived at by first finding that this contribution also varied with central pressure drop; the final form of the exponent in Eq. (11) is arbitrary but captures the essence of the actual variation. As noted earlier, it would be preferable to also include information on cyclone size and the environmental pressure. These were excluded here to enable ready application to standard hurricane archives that do not contain this information. It is recommended that actual environmental pressure be used when known.

Equation (11) explains 32% of the variance in a b parameter derived directly from the observations using Eq. (8). Of the predictors in Eq. (11), the pressure drop explains the most variance at 13% with translational speed, adding a further 13%, latitude a further 4%, and development rate 2%. The small contribution from the development rate has been noted by Knaff and Zehr (2007), but this is retained for completeness. The predictors are poorly correlated; the highest is between pressure drop and translational speed with $R^2 = 0.09$ and the rest are less than 2%.

The b_s parameter in Eq. (11) can also be used in a more general sense for those employing variants of the H80 wind model. As noted earlier, b_s is for *surface winds*. To convert to the H80 b parameter, use

$$b = b_s\left(\frac{v_{\mathrm{mg}}}{v_m}\right)^2 \sim 1.6 b_s,$$

where v_{mg}/v_m is the inverse of the gradient-to-surface wind reduction factor at the maximum wind radius. This empirical derivation also means that b_s includes azimuthal wind asymmetries (e.g., from cyclone translation) and is not simply representative of a symmetric system.

An example of the fit of this parametric form to observed b_s values derived from applying Eq. (8) to the HURDAT cyclone data from 2000–05 is shown in Fig. 5. The scatter in derived b_s values provides a good representation of the observed values. The outlying observations are in the minority: only 24% of observed b parameters lies outside the range of the calculated values; 61% of calculated b values lies within ±0.2 of the observed values; and 79% lies within ±0.3. The outliers are considered to be the result of errors together with transients and other effects that affect the maximum winds beyond the capacity of the parametric approach.

c. Application to dependent data

The P–W model provides a good fit to the dependent data of the westward-moving oceanic storm from 2000–05 (Figs. 6, 7). The analysis practice at NHC is to estimate maximum winds first and round these up to the nearest 5 kt, which limits the difference analysis to a resolution of around 2.5 m s^{-1}. The P–W model com-

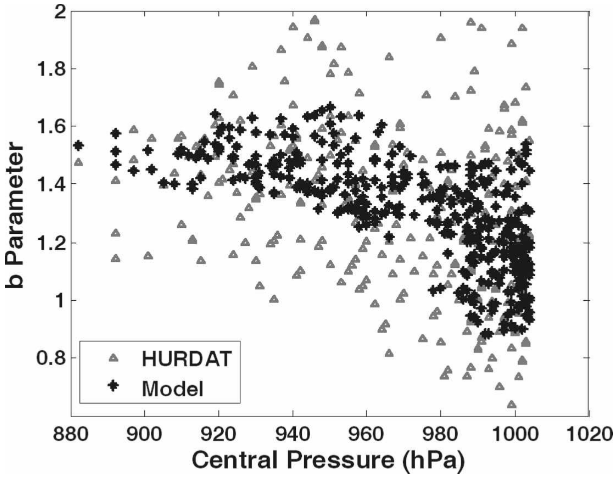

FIG. 5. Scatter diagram against central pressure of the model b_s parameter [Eq. (11)] and b_s derived directly from the dependent HURDAT data using Eq. (8). Note that this b_s is applicable to the maximum 10-m wind; see text for further discussion.

pares favorably to Dvorak in overall fit to the dependent data and is significantly better at the 99% level using the one-sided Student's *t* test. As shown in Table 1, 52% of P–W model and 44% of Dvorak winds lie within the 2.5-m s^{-1} resolution of HURDAT (note that the Dvorak model and derivatives have been used in the analysis of the original data; see later discussion). The P–W model also compares favorably with Knaff and Zehr (2007).

Of interest is the improvement in maximum wind estimates arising from the sequential addition of each predictor in order of variance explained (second row of Table 1; note that each calculation is adjusted to zero mean bias). The pressure drop and translational speed produce the greatest improvement, with small additional improvements from latitude and development rate.

Notice in Fig. 7 that allowing the b_s parameter to vary introduces considerable scatter in the maximum winds for a given central pressure. This derived scatter encompasses more than 80% of the scatter in the HURDAT observations and mimics to some extent the HURDAT data, but only if the scatter is in the correct sense. This was tested by comparing the model statistics with Dvorak; the use of Eq. (7) with fixed values of $b_s = 1.26$ (median observed value) and $\rho = 1.15$ kg m^{-3}; and a random perturbation of the winds derived from the Dvorak relationship in Eq. (3) with a similar structure to that for the P–W model in Fig. 6a. As shown in Table 1, both Dvorak and Eq. (7) were very similar and resulted in an increase of around 50% in mean absolute differences (MAD) and root-mean-square difference (RMSD), and a decrease of 20% in the ±2.5- and

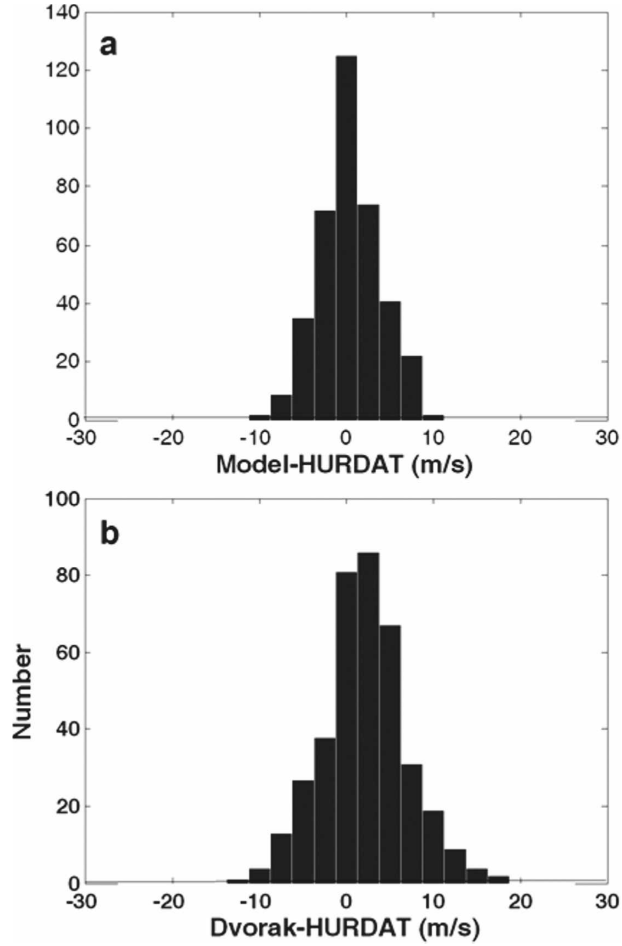

FIG. 6. Distributions in 2.5-m s^{-1} bins of the differences from the dependent data for (a) the P–W model Eq. (11) and (b) the Dvorak model [Eq. (3)]. Note that the Dvorak relationship was used as one of the factors in the analysis that created the dependent data.

±5-m s^{-1} bins compared to the multivalued approach in the P–W model. Random perturbation of Dvorak to produce a similar scatter to Eq. (11) also provided similar results to Dvorak alone. We conclude that the additional scatter in the P–W model is capturing real effects.

Removing the scatter by binning (Fig. 8) indicates there is no particular bias with intensity. This result is different to that found by Willoughby and Rahn (2004), who noted a considerable bias with intensity. However, they used a partial linear relationship for the variable b parameter of the form $b = 0.866 + 0.0177v_m - 0.0084\varphi$. This neglects the obvious nonlinear relationship between *b* and intensity [e.g., Eq. (7) and Fig. 5]. When such nonlinearity is include a quite close relationship arises, one that contains no bias with increasing intensity (Fig. 8). Application of the Willoughby and Rahn

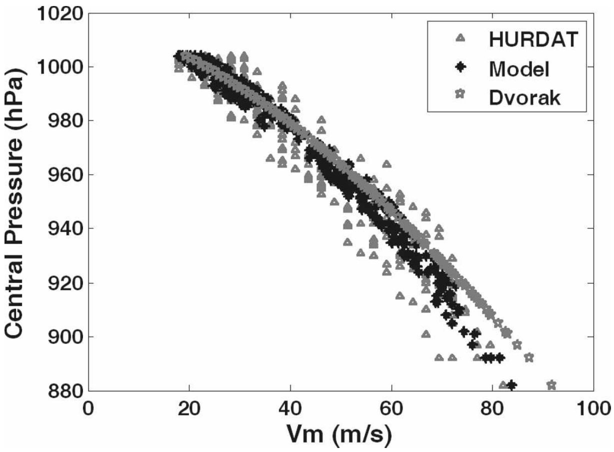

FIG. 7. Central pressure vs maximum for HURDAT observations and derived from Eq. (11) (P–W model) and Dvorak for the dependent dataset.

relationship to the dependent dataset used in this study resulted in a substantial overestimate of the maximum winds in major hurricanes, in agreement with their findings.

d. Parameter and sensitivity analysis

Model parameters of importance include the choice of surface air temperature in the eyewall; environmental pressure, p_n; intensity change; latitude; and cyclone translation speed. The sensitivity to the choice of eyewall surface air temperature is negligible, provided a reasonable estimate is available. The important variation to capture is the variation of density with surface pressure for the more intense systems. Varying the environmental pressure changes the maximum winds in proportion to the square root of the resulting difference in Δp [Eq. (11)]. Thus the sensitivity is highest for weak storms and lowest for the more intense systems. As an example, changing the environmental pressure for North Atlantic cyclones by ± 5 hPa produces a maximum wind change of 2.5–3 m s^{-1} for a central pressure of 980 hPa, and ± 1.5 m s^{-1} for a central pressure of 900 hPa. Because environmental surface pressures typically increase with latitude, part of the variance in environmental pressure will have been picked up in the latitudinal dependence in the P–W model. However, if a good estimate of the environmental pressure is available, it is recommended that this be used in preference to the fixed values used here.

The overall sensitivity of the b_s parameter to latitude, translational speed, and intensity change is shown in Fig. 9 for both the P–W model and dependent-data observations. The P–W model captures a large part of the overall observed variation and the bulk of the linear trends.

Differences from the observations arise from a combination of real effects and analysis uncertainties. In the former are wind asymmetries and transients, such as eyewall replacements. In the latter are the subjective judgment between conflicting sources of information and the application of other empirical methods (with their own error distributions) in the analysis process. Analysis errors are considered later in the context of

TABLE 1. Summary error statistics for application of the P–W model to dependent and independent datasets in the North Atlantic: NAT is North Atlantic, MAD is Mean Absolute Difference from observations, and RMSD is root-mean-square difference from observations. The numbers in italics indicate the Dvorak relationship applied to the same data. Note that the Knaff and Zehr results are for a specific set of aircraft reconnaissance data, included here simply for comparison, and that the ± 2.5-m s^{-1} column represents the resolution of the HURDAT data. Pressure drop is denoted by Dp and speed by spd. Under Bias the mean is in regular type and the median is in bold.

		Observation No.	Bias (m s^{-1})	MAD (m s^{-1})	RMSD (m s^{-1})	% within ± 2.5 m s^{-1}	% within ± 5 m s^{-1}
Dependent data NAT westward >70°W 2000–05	Eq. (11)	386	0.0	2.7	3.5	52	84
			−0.1	*4.0*	*5.1*	*44*	*70*
	Dp only		0.0	4.5	5.5	32	61
	Dp + spd		0.0	3.4	3.6	50	83
	Dp + spd + lat		0.0	2.8	3.5	51	83
	Eq. (7)	386	−1.5	3.9	5.0	43	69
			−0.4				
	Random scatter on Dvorak	386	1.5	3.9	5.2	43	69
			1.2				
	Knaff and Zehr (2007)	N/A	N/A	3.1	4.0	N/A	N/A
Independent data for Eq. (11)	NAT westward, <70°W 2000–05	606	0.2	2.4	3.2	62	90
			0.0	*1.8*	*3.0*	*78*	*91*
	NAT eastward, 2000–05	688	−0.1	3.0	3.9	51	82
			−0.4	*2.8*	*4.0*	*62*	*82*

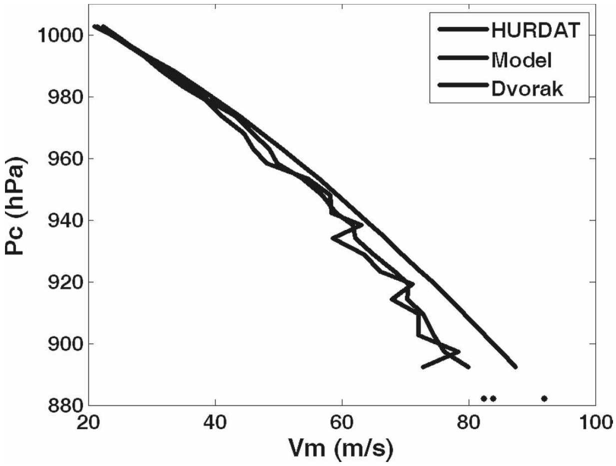

FIG. 8. Binned relationship of central pressure and maximum winds derived from Eq. (11) (model) and HURDAT (binned in 5-hPa ranges). Note the lack of any P–W model error trend with intensity and the tendency for Dvorak to overestimate the winds, especially at low central pressures. The gap to the data points near 880 hPa resulted from lack of data in this bin.

the historical data. The P–W model should be applied with caution where there are known substantial wind asymmetries (e.g., in an extratropical transition) or during eyewall replacement or other transient changes. It is not readily apparent how such asymmetries can be handled in any systematic manner, and this will remain an imprecise area dependent on a combination of available data and analyst interpretation.

e. Application to independent data

Applying the P–W model to all westward-moving storms from 2000–05 east of 70°W, provides a slightly improved fit to the HURDAT archive compared to the dependent data (Table 1). The P–W model results are similar to those for the dependent dataset. However, there are substantial "improvements" in the Dvorak model, which is now apparently more skillful than the P–W model. It is suggested that this skill is artificial and arises from the predominant use of the Dvorak model and related derivatives in the HURDAT data, as is clearly seen in Fig. 10. Thus, comparison of differences between the P–W model and the HURDAT data in this region becomes little more than a discussion on differences between pressure–wind relationships.

This finding applies to all eastward-moving storms across the whole basin from 2000–05, where the two models are of similar skill. As may be seen in Fig. 11, both models produce similar results for tropical storms and minor hurricanes, but the major hurricanes tend to follow Dvorak. There is also an increased scatter compared to the westward-moving storms in the HURDAT

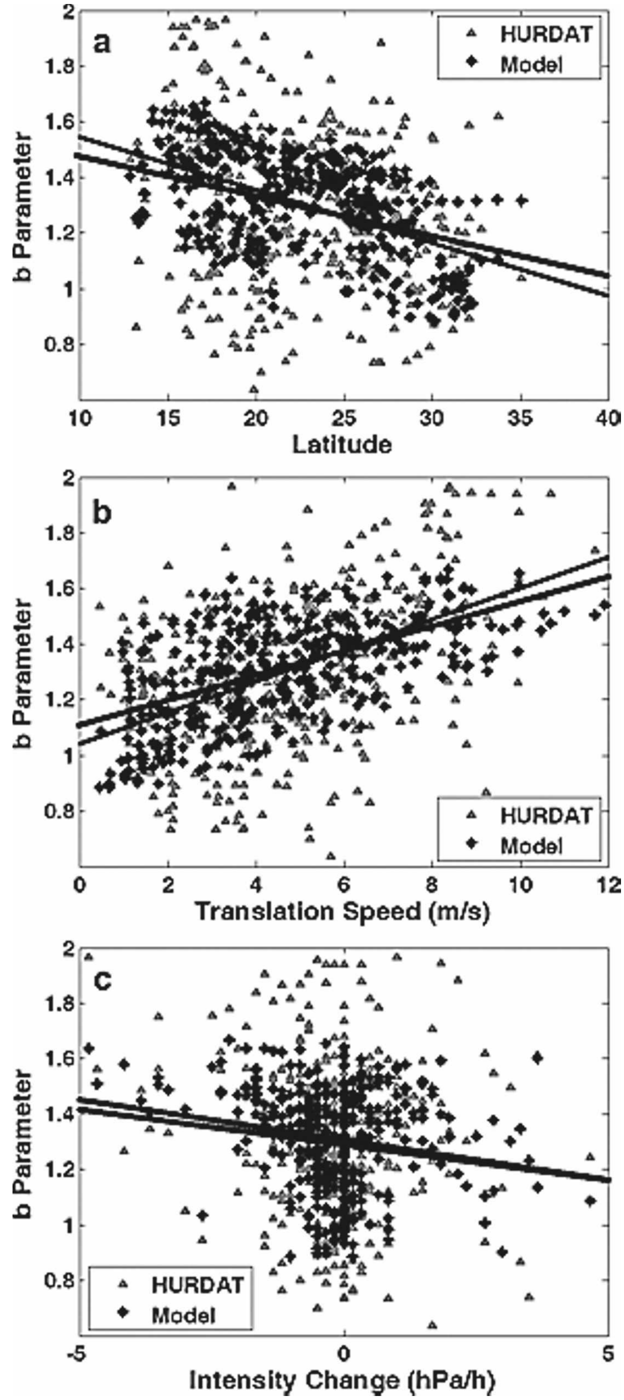

FIG. 9. Observed and modeled *b* parameter showing sensitivity to (a) latitude, (b) translation speed, and (c) intensity change for the dependent dataset. Lines of linear best fit are shown as dashed for observed and solid for derived.

data, some of which is captured by the P–W model. This scatter appears to arise from a combination of effects: increasing influence of translation speed and latitudinal variations, which can be captured by the P–W model;

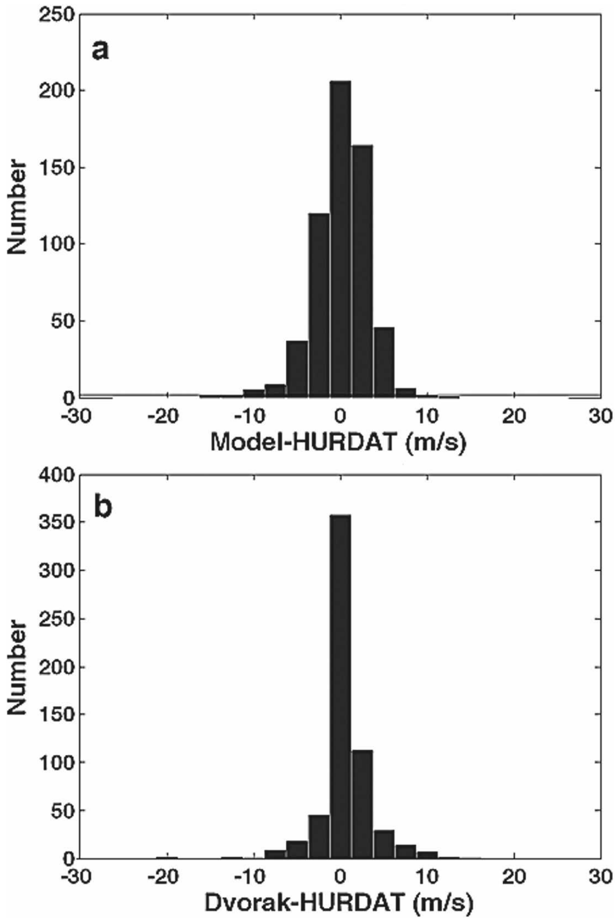

FIG. 10. Distributions in 2.5-m s^{-1} bins of the differences between application of (a) the P–W model and (b) Dvorak to independent data of westward-moving cyclones east of 0°–50°N, 70°W and 2000–05. The dominance of the Dvorak model in the derivation of the HURDAT data is apparent.

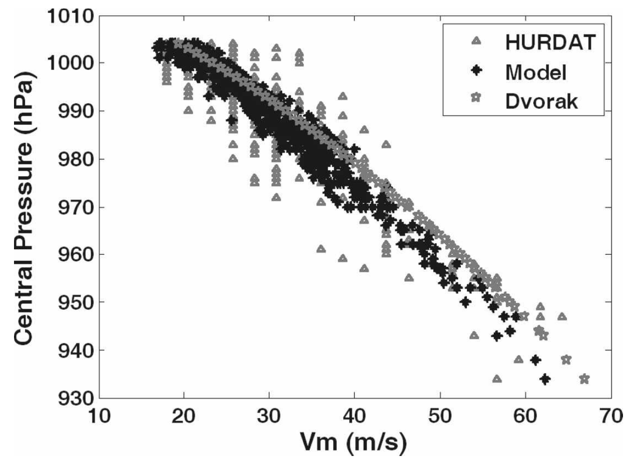

FIG. 11. Central pressure vs maximum wind in application of the P–W model to an independent dataset of all eastward-moving storms <1005 hPa and >17 m s^{-1} during 2000–05.

and extratropical transition, shearing and similar effects, which are not well handled. Unfortunately, because of the obvious dominance of the Dvorak model and related derivatives in the analysis process, especially for major hurricanes, there is no way of being able to adequately determine the applicability of the P–W model to eastward-moving storms.

3. Evidence for a best-track bias in the North Atlantic data

a. *The Dvorak approach*

The classical Dvorak approach (Dvorak 1975, 1984) is to apply a pattern-recognition technique to observed satellite features to arrive at an estimate of the central pressure and then use a pressure–wind model to obtain the maximum wind speeds. A full description of the technique and its history is provided by Harper (2002) and Velden et al. (2006). The technique has varied with time as observing technology has advanced and there is now also an automated version available (Velden et al. 1998). However, for the North Atlantic, the pressure–wind model used is essentially the same today as it was 30 yr ago.

The actual practice used in Dvorak applications varies around the world (see Harper 2002 for a comprehensive discussion). The operational approach is normally to use Dvorak by estimating the maximum winds first and then apply its pressure–wind model for the central pressure. This approach was also adopted by Knaff and Zehr (2007). Several centers historically did not even bother to archive central pressures, a shortsighted practice that has been largely discontinued in recent years. Yet estimating the central pressure first is what Dvorak originally intended (Kossin and Velden 2004). The choice of wind or pressure first is not important for the original relationships in which a 1 to 1 mapping between central pressure and winds was applied. However, the approach adopted here provides considerable scatter in maximum winds for a particular central pressure. Though a model could be derived that provided a wide scatter in central pressures for a specified maximum wind (as done by Knaff and Zehr 2007), the central pressure is considered to be the more conservative parameter. This is evidenced by the variability of parameter b in Eq. (11) and by other studies such as H80 and Willoughby and Rahn (2004). Varying the b parameter changes the peakedness of the wind field and thus the maximum winds without any change in the central pressure. Also, this approach is much more able to assess relatively stable wind asymmetry effects such

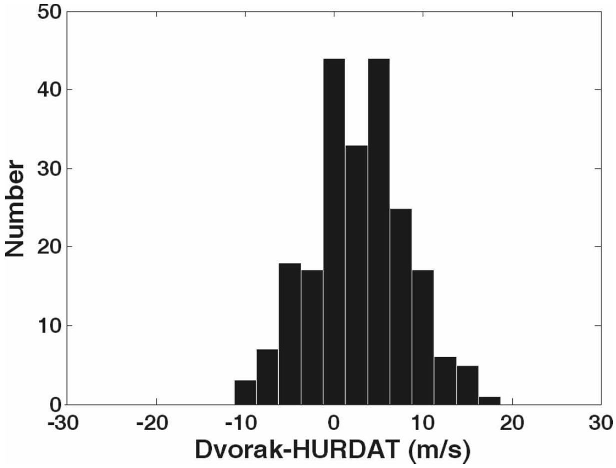

FIG. 12. Distributions in 2.5-m s^{-1} bins of the differences between application of Dvorak and HURDAT data for westward-moving hurricanes west of 0°–50°N, 70°W and 2000–05.

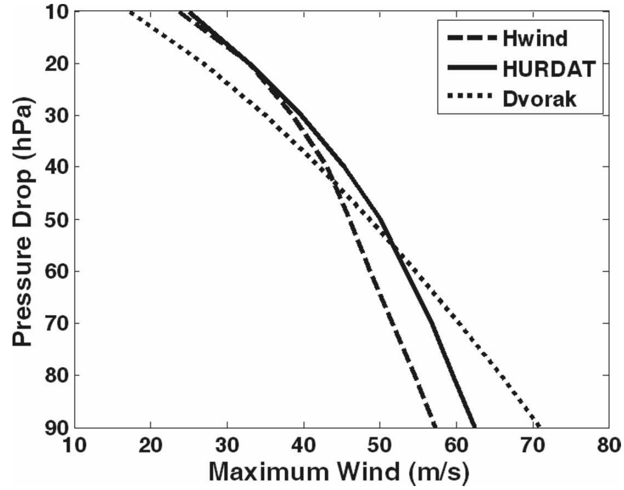

FIG. 13. Best-fit lines to the HURDAT and H*Wind estimates of the maximum wind vs actual central pressure drop for Hurricanes Floyd (1999), Keith (2000), Iris (2001), and Michelle (2001) compared to Dvorak [Eq. (3)]. Data taken from Harper (2002).

as those associated with translation speed. It is thus recommended that the Dvorak pattern recognition be changed to enable a direct assessment of the central pressure rather than maximum winds. This P–W model, or other derivatives, can then be used to estimate the maximum winds. Alternatively, the P–W model could be applied directly to the Dvorak T number to similar effect. This has the advantage of capturing real scatter in maximum wind observations for a particular central pressure observation.

b. Implications of North Atlantic Dvorak application

Several potential issues with the use of the Dvorak method were found during the course of this study. As shown in Fig. 10b, The Dvorak model is used almost exclusively in the derivation of the recent HURDAT archive over the region east of 70°W. It is also straightforward to show that this dominance also extends to eastward-moving cyclones across the entire Atlantic, especially for the more intense systems (e.g., Figure 11). This is not a surprising result as it has already been mooted by Harper (2002). However, there are two important implications:

- an overestimate of maximum winds for hurricanes, especially major hurricanes and those away from aircraft reconnaissance observations; and
- a lack of full consideration of storm motion in derivation of the maximum winds.

These are further considered below.

The skew to the right in Fig. 6b indicates that the Dvorak technique overestimates the maximum winds for a given central pressure. This overestimation is small for tropical storms but increases markedly with hurricane intensity (Fig. 7). For hurricanes, the differences between Dvorak and HURDAT appear to bifurcate into two distinct distributions (Fig. 12), one with no bias and a second with a high-wind bias of around 5 m s^{-1}. This is interpreted as being due to exclusive use of the Dvorak model in some cases and reliance more on direct aircraft observations in others.

Unfortunately, the emphasis on the Dvorak approach does not break down on a simple basis of whether there were aircraft reconnaissance data available. We illustrate this by the following analysis, first reported in Harper (2002), to determine if any systematic bias in adopted best-track information is evident from hurricanes where aircraft reconnaissance and other direct measurements are available. Figure 13 contains a comparison of combined data for Hurricanes Floyd (1999), Keith (2000), Iris (2001), and Michelle (2001) for periods when aircraft reconnaissance data were available. The original data came from Harper (2002), who derived them from the best-track, operational H*Wind analysis and an objective Dvorak analysis. The wind values are not storm relative and include movement or other asymmetries. The HURDAT data followed the H*Wind closely in the tropical storm stage, when Dvorak underestimated the intensity. But there was a clear tendency toward the higher Dvorak estimates during the hurricane stage, despite the presence of in situ aircraft data.

We next consider eastern region, westward-moving hurricanes, which are dominated by the Dvorak analy-

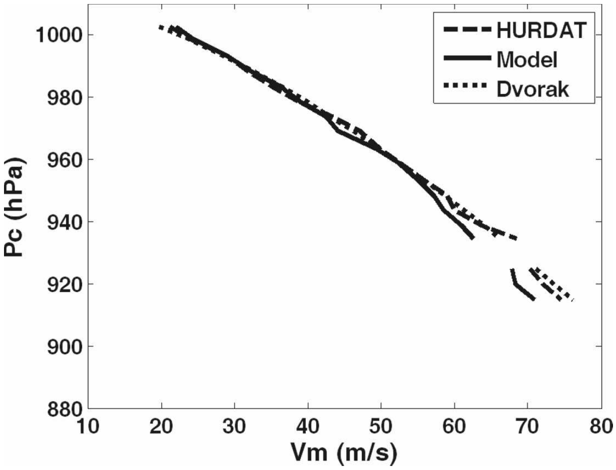

FIG. 14. Central pressure vs maximum wind in the P–W model for westward-moving storms east of 70°W and from 2000–05, together with the HURDAT data and Dvorak. The data have been binned by averaging into 5-hPa central pressure intervals, and the missing section contained insufficient data.

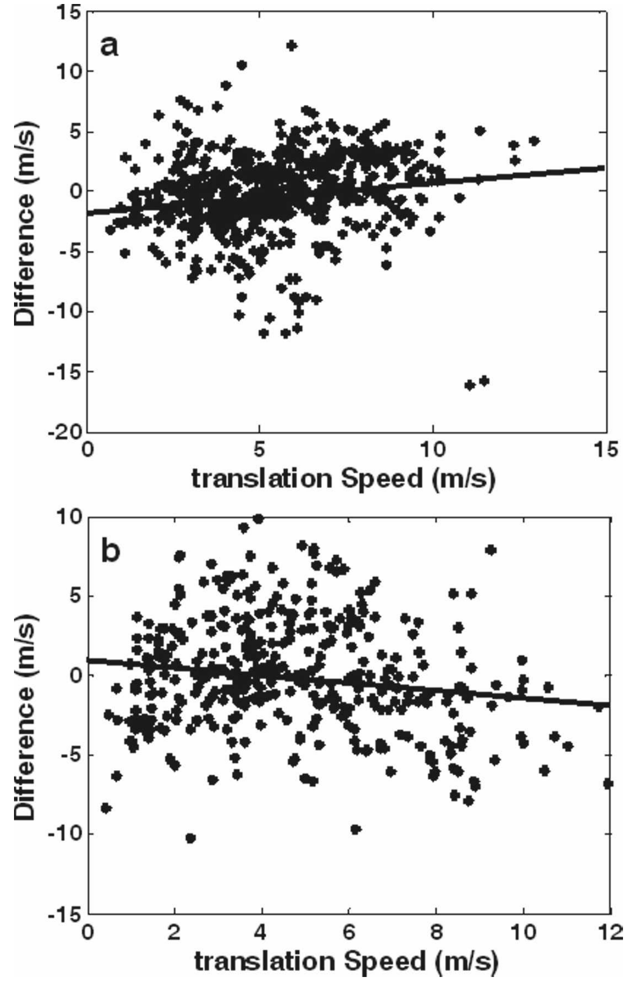

FIG. 15. Difference between the P–W model and HURDAT winds plotted against storm translation speed for westward-moving storms from 2000–05: (a) east of 70°W and (b) west of 70°W. Linear lines of best fit are also shown.

sis (Fig. 10b). Plotting the P–W model, HURDAT, and Dvorak after binning the data into 5-hPa central pressure intervals (Fig. 14) produces a similar pattern to that in Fig. 13; both models are similar for tropical storms and Dvorak is higher for hurricanes. In this case, the HURDAT data follow the Dvorak relationship closely over the whole range, indicating a potential bias toward wind observations that are too high.

Unfortunately, the P–W wind model will also have some level of the Dvorak model embedded within it. This is a consequence of our inability to fully differentiate between different analysis approaches and data sources that go into the final HURDAT archive. However, this is considered to have a minimal impact in the context for which it is being used.

We next consider the impact of storm motion. As shown in Fig. 15a, application of the P–W model to the cyclone data east of 70°W, which is dominated by the Dvorak technique and related derivatives, brings out a dependence on storm translation speed. The P–W model was derived from the data from similar storms but west of 70°W, which are dominated by aircraft reconnaissance. These data implicitly include the effects of storm translation speed, which has been incorporated into the P–W model [Eq. (11); Fig. 15b]. The differences in the linear trends between Figs. 15a,b indicate a potential underestimate of translation effects by 30% in the use of Dvorak. A check of other cyclone groupings, such as all eastward-moving storms, revealed similar problems.

The two cyclone sets are roughly similar: all cyclones were moving westward and were of similar intensity distributions; both sets contain similar numbers of hurricanes and major hurricanes, but the eastern set has more tropical storms. A general check of other possible consistent differences, such as latitude, intensity, and longitude, showed no other relationships. The only obvious difference lies in the method of analysis: primarily Dvorak for the eastern set and primarily aircraft for the western set.

Thus, application of the Dvorak analysis leads to an overestimation of maximum winds for hurricanes, especially for category 3 and above, and a somewhat counteracting underestimation of the effects of storm translation speed. This analysis concurs with Harper (2002) that even when aircraft reconnaissance data are available, there is a tendency toward application of the higher Dvorak estimates.

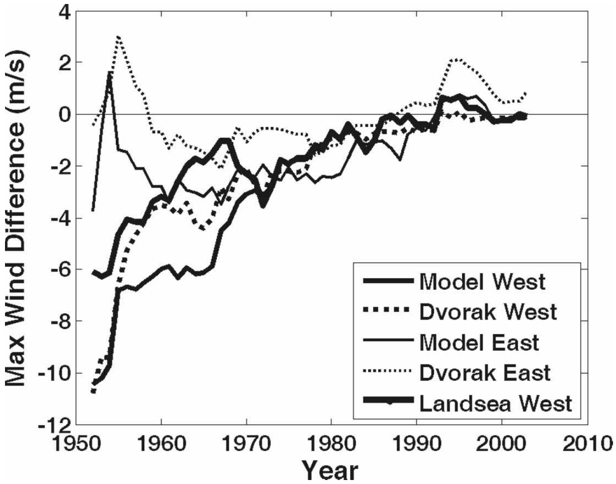

FIG. 16. Time series of annual median differences between P–W model- and Dvorak-derived maximum winds, and HURDAT for central pressures <1005 hPa and the entire Atlantic. Also shown are the Landsea (1993) corrections. "West" and "East" refer to westward- and eastward-moving cyclones, and the data have been smoothed with a running 5-yr filter. Note that the period before 1955 has very few observations.

c. North Atlantic tropical cyclones, 1950–2000

Recall the lack of consistent archived pressure data in earlier years (Fig. 3). Despite this limitation, there are some interesting features in the HURDAT database. For westward-moving storms, the derived maximum winds from both the P–W model and Dvorak are consistently less than the HURDAT winds until around 1980 (Fig. 16). After 1980 both models are consistent with HURDAT. For eastward-moving storms, the derived winds are much closer to HURDAT, being slightly higher after 1980 and in the mid-1950s and substantially lower in between.

This early underestimation for westward-moving cyclones can be partly attributed to application of an incorrect wind assessment algorithm for aircraft data, as identified by Landsea (1993). Landsea proposed a set of corrections for the period 1945 to 1969, which produces the changes shown by the heavy line in Fig. 16. It appears that the Landsea corrections were in the correct sense, but they did not go quite far enough and were applied to too short a time period.

d. Implications for the HURDAT database

The differences between the P–W model and HURDAT data described in previous sections have some implications for the overall database. Most obvious is the overestimation of intensities from 1950–80 (Fig. 16). But the general overestimation and translation-speed dependence using the Dvorak model also will have an impact across the entire database, one that will vary depending on proximity to in situ data and translation speed.

We illustrate the potential impact by applying the P–W model to "correct" the Atlantic data, commencing with the dependent data and then for all cyclones with recorded central pressures after 1955. This correction is deliberately naïve in its application. The actual HURDAT data are a complex amalgam of in situ observations, remote sensing, pattern recognition, and human analyst interpretation. However, we also have shown that tropical cyclone intensity in the eastern region of the North Atlantic is predominantly determined by the Dvorak method; the associated pressure–wind relationship for this method has not changed in 30 yr (Harper 2002) and appears to overestimate intense hurricanes (Fig. 8). Thus, comparative application of a more modern P–W model is of interest.

Before applying the P–W model, we note that the frequency of tropical cyclones decreases sharply with intensity from a maximum in the early tropical storm stage to very few at category 5. It is therefore instructive to consider the manner in which a random scatter induces change in such a distribution, as uniformly distributed scatter will tend to spread the distribution toward higher intensities leading to a bias. The impact of this effect was tested by using a random wind perturbation drawn from a normal distribution with a standard deviation of 2 m s^{-1} (similar to the HURDAT resolution and model scatter, e.g., Fig. 7 or 11). Applying this perturbation to the annual intensity distributions from the dependent data 10 times (to obtain a statistically meaningful set) changed the annual counts by an average of 0.1 (range 0–2) category 4–5 hurricanes, 0.04 (range 0–1) major hurricanes, and 0.1 (range 0–3) hurricanes. Perturbing the eastward-moving cyclones east of 70°W from 1995–2005 produced average annual changes (ranges) of 0.1 (0–3) category 4–5 hurricanes, 0.03 (0–1) major hurricanes, and 0.2 (0 to 3) hurricanes. Annual changes from application of the P–W model below these thresholds are meaningless as they could have been produced by random scatter. Because the standard deviation used was similar to the speed resolution used in HURDAT, these figures also provide a general assessment of errors in the dataset.

Application of the P–W model to the dependent dataset produced average annual changes of −0.1 category 4–5 hurricane, 0 major hurricanes, and 0 hurricanes. There were 3 category 4–5 hurricane changes: Isodore (2002, 57 m s^{-1}, 934 hPa) increased to 62 m s^{-1}; Brett (1999, 64 m s^{-1}, 944 hPa) decreased to 57 m s^{-1}; and Keith (2000, 61 m s^{-1}, 941 hPa) decreased to 57 m s^{-1} (the changeover between category 3 and category 4 hurricanes is approximately 58 m s^{-1}). Thus the

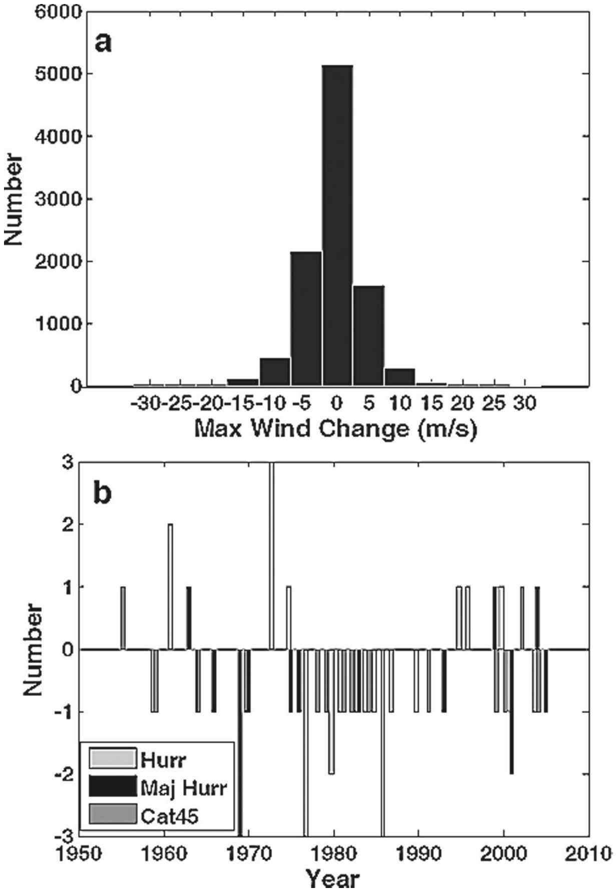

FIG. 17. Application of the P–W model to all tropical cyclones that had archived central pressures from 1955–2005: a) distribution of maximum wind changes; b) annual changes in hurricane, major hurricane, and category 4–5 hurricane numbers.

P–W model changes are minor and within the range expected from a randomly applied perturbation and the resolution of the HURDAT database. By way of comparison, applying the Dvorak model to the dependent data resulted in average annual changes of 0.2 category 4–5 hurricanes, 0 major hurricanes, and −0.2 hurricanes (noting again that Dvorak was used in derivation of the dependent dataset).

Applying the P–W model to all tropical cyclones from 1955–2005 (Fig. 17) produced a different outcome to that found by Landsea (1993). The P–W model removed the overestimate bias in Fig. 16 but also increased the winds for a substantial number of cyclones (Fig. 17a). The resulting impact (Fig. 17b) was for a marked reduction in major hurricanes prior to 1990; category 4–5 hurricanes dropped by 7 (10 down and 3 up) and major hurricanes by 8 (11 down, 3 up). Hurricanes remained about the same (18 down and 15 up). For comparison, applying the Dvorak model to the same dataset resulted in a net increase in more intense hurricanes, with +5 category 4–5 (7 up, 2 down), +6 major hurricanes (11 up, 5 down), and −3 hurricanes (13 up, 16 down).

The marked reduction in major hurricanes from application of the P–W model is consistent with Landsea's (1993) assessment of an incorrect relationship being applied in the early reconnaissance years. The overall hurricane changes are consistent with the expectation from a random perturbation and provide an overall indication of the uncertainty in using the hurricane categorization. The increased number of category 4–5 and major hurricanes when applying Dvorak is consistent with its general tendency for overestimation of intense hurricane winds (Fig. 7). A more comprehensive analysis is called for but is beyond the scope of this study.

4. Conclusions

A new approach to relating central pressures to maximum winds in tropical cyclones has been presented. Changing from the b parameter in the H80 model, which is representative of the gradient-level winds to a surface equivalent b_s, and allowing it to vary with central pressure, latitude, intensification rate, and storm translation speed [Eq. (11)], enables development of an empirical pressure–wind model that reproduces some of the scatter observed in real cyclones (e.g., Fig. 7). The resulting maximum-wind estimates are an improvement on models such as Dvorak (1975) or AH77, which produce a unique wind value for each central pressure (Table 1). By dividing the derived b_s by the square of the gradient-to-surface wind reduction factor, we can arrive at the original b parameter, enabling Eq. (11) to also be applied to more general use in the H80 model or derivatives thereof.

A comprehensive analysis of potential errors and sensitivity to chosen parameters has been provided. The b_s relationship in Eq. (11) successfully captures much of the observed scatter and trends in its component parameters, with major errors considered to arise from local transients and major asymmetries that cannot be covered by a general pressure–wind relationship.

It is recommended that the Dvorak pattern-recognition technique for estimating intensity from satellite data be recalibrated to provide a primary estimation of the central pressure only. Application of the pressure–wind model presented here then enables an objective analysis of some of the observed scatter in maximum winds. Major findings are

- intensity estimates for tropical cyclones in the eastern Atlantic and all Atlantic eastward-moving systems are dominated by the Dvorak satellite estimation and related pressure–wind model;

- the suggestion by Harper (2002) that there is a strong tendency to use Dvorak even when there are aircraft reconnaissance data available is confirmed;
- the Dvorak pressure–wind relationship overestimates maximum winds for hurricanes, especially so for major hurricanes, and its North Atlantic application underestimates the impact of translation on hurricane intensity.

The previous finding by Landsea (1993) that early pressure–wind models applied to aircraft reconnaissance observations of central pressure resulted in wind estimates that were too high have been confirmed. However, the corrections applied by Landsea were not sufficient to correct the problem and were applied to too short a time period.

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