An Examination of the Pressure–Wind Relationship for Intense Tropical Cyclones

CHANH Q. KIEU

Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

HUA CHEN AND DA-LIN ZHANG

Department of Atmospheric and Oceanic Science, University of Maryland, College Park, College Park, Maryland

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ABSTRACT

In this study, the dynamical constraints underlining the pressure–wind relationship (PWR) for intense tropical cyclones (TCs) are examined with the particular focus on the physical connections between the maximum surface wind (VMAX) and the minimum sea level pressure (PMIN). Use of the Rankine vortex demonstrates that the frictional forcing in the planetary boundary layer (PBL) could explain a sizeable portion of the linear contributions of VMAX to pressure drops. This contribution becomes increasingly important for intense TCs with small eye sizes, in which the radial inflows in the PBL could no longer be neglected. Furthermore, the inclusion of the tangential wind tendency can make an additional contribution to the pressure drops when coupled with the surface friction.

An examination of the double-eyewall configuration reveals that the formation of an outer eyewall or wellorganized spiral rainbands complicates the PWR. An analysis of a cloud-resolving simulation of Hurricane Wilma (2005) shows that the outer eyewall could result in the continuous deepening of PMIN even with a constant VMAX. The results presented here suggest that (i) the TC size should be coupled with VMAX rather than being treated as an independent predictor as in the current PWRs, (ii) the TC intensity change should be at least coupled linearly with the radius of VMAX, and (iii) the radial wind in the PBL is of equal importance to the linear contribution of VMAX and its impact should be included in the PWR.

1. Introduction

The relationship between the tropical cyclone (TC) maximum surface wind (VMAX) and minimum sea level pressure (PMIN) plays an important role in the assessment and documentation of TC activities (e.g., Koba et al. 1990; Harper 2002; Kossin and Velden 2004; Knaff and Zehr 2007, hereafter KZ07; Holland 2008, hereafter H08). Given one variable such as PMIN or VMAX, an appropriate pressure–wind relationship (PWR) could provide information about the other variable consistently. Such a PWR is very useful in the sparse-data areas where direct TC observations are difficult to perform, and the subjective estimation of the TC intensity based on the Dvorak (1975) technique has to be employed. With the vast distribution of TCs over different ocean basins but the

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limited number of observations, the combination of the Dvorak technique and the PWR is of key importance in providing a reasonable description of the TC intensity and distributions. It is also vital for constructing a consistent climatology of TC intensity (Landsea et al. 2004; Brown et al. 2006; Webster et al. 2005; Weber 2007; Kruk et al. 2008).

The current framework for the PWRs is based mostly on the gradient wind approximation (e.g., see Harper 2002), which is given by

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{v^2}{r} + fv,\tag{1}$$

where p is the pressure, f is the Coriolis parameter, ρ is the air density, and v is the tangential wind. Under this approximation, the functional form for PMIN and VMAX is often given in the form of (Atkinson and Holliday 1977; Harper 2002)

$$V = a\Delta p^x,\tag{2}$$

Corresponding author address: Dr. Da-Lin Zhang, Dept. of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742-2425. E-mail: dalin@atmos.umd.edu

where V denotes VMAX, Δp is the pressure drop with respect to the environmental pressure (i.e., $\Delta p = P_{env} -$ PMIN), and a and x are model parameters [the values of a = 2 and x = 0.5 correspond to the exact cyclostrophic relationship; see Harper (2002) for a review of various PWRs]. In addition, use of the least squares best fit allows one to obtain the regression coefficients for the effects of various factors on the PWRs, such as the TC size, the tangential wind tendency, latitude, and TC translation speed (see KZ07 and H08).

Recent availability of aircraft reconnaissance data provides reasonable estimates of both PMIN and VMAX independently. Such data offer a rigorous benchmark for testing and improving various PWRs and for retrievals of PMIN and VMAX over different regions. For example, KZ07 present a thorough examination of the existing PWRs and propose a revised PWR in which the above-mentioned factors are shown to have significant impacts. While such reconnaissance data provide essential information about TCs during their development, this type of data is available mostly in the Atlantic Ocean basin. Moreover, both PMIN and VMAX are rarely observed directly but have to be either extrapolated from the flight level to the surface or interpolated at the surface; thus, the values are subject to some inherent errors due to uncertain vertical structures of rotational flows in the inner-core regions (Willoughby et al. 1989; Zhang et al. 1999; Franklin et al. 2003; Courtney and Knaff 2009).

Despite the fact that the most recent PWRs developed by KZ07 and H08 appear to fit the TC data better than the earlier PWRs, there are several issues that remain to be addressed. For instance, to what extent can the existing PWRs be applied to the extreme cases of intense TCs with small eyes? How are the PWR predictors dynamically related? How could the formation of spiral rainbands and the subsequent double eyewalls affect the PWR? In this study, we wish to address the above issues by examining the dynamical constraints underlining the PWR, with particular attention paid to the physical connections between PMIN and VMAX. This may seem trivial at first as the gradient-wind balance used in the PWRs appears to contain all of the essential dynamics. However, one should be cautioned that such a balance relationship is not valid in the planetary boundary layer (PBL) where the radial inflows may be no longer negligible in intense TCs. In this regard, the theoretical model of Kieu and Zhang (2009, hereafter KZ09) on the rapid intensification of TCs will be shown to be helpful for studying the PWR from a nonlinear dynamics perspective.

In this study, a cloud-resolving simulation of Hurricane Wilma (2005) will be chosen to examine the dynamical constraints behind the PWR. This case possesses several unique opportunities to study the PWR, such as its recordbreaking intensification rate, the small eye size during its mature stage, its clear spiral rainbands, and an eyewall replacement process. Wilma evolved initially as a result of a monsoonlike lower-tropospheric circulation with a broad trough developed over much of the Caribbean Sea around 1800 UTC 15 October 2005 (see Pasch et al. 2009). Starting on early 18 October, Wilma strengthened into a hurricane as it turned west-northwestward and experienced a 12-h explosive deepening episode between 1800 UTC 18 and 0600 UTC 19 October after moving into an area of high oceanic heat content. It deepened 29 hPa in the first 6 h and 54 hPa in the next 6 h. During the rapid intensification episode, a U.S. Air Force reconnaissance flight indicated that the hurricane eye contracted to a diameter of about 3-5 km. The estimated minimum central pressure at the time of peak intensity is 882 hPa, which is the recorded lowest value for TCs in the Atlantic basin. The lack of observational data at these extreme limits puts any statistical PWR at some considerable risk, and it is therefore of importance to understand the validity of the PWRs at these extremes. Two main advantages of using the modeling data are the dynamical consistency between various variables, like the PWR, and the ease of obtaining any variable at high temporal and spatial resolutions that the current observational data could not afford.

The next section discusses the behaviors of the PWR in intense TCs and during the eyewall replacement process from both a theoretical perspective and for the model-simulated Wilma case. These features will be examined in relation to the most comprehensive PWRs to date that have been developed by KZ07 and H08 (see appendix A for a summary of the two PWRs). Section 3 provides a theoretical framework and some dynamical constraints behind the PWR as a time-dependent problem. Concluding remarks are given in the final section.

2. Effects of double eyewalls and TC size

In this section, we examine first whether or not the recent PWRs could capture the evolution of PMIN and VMAX for a double-eyewall configuration with dual radii of maximum wind (RMWs). Several observational and modeling studies have shown the development of double eyewalls and significant intensity changes during the life cycles of many TCs, with dual VMAXs during the eyewall replacement process (Willoughby et al. 1982; Blackwell 2000; McNoldy 2004; Zhu et al. 2004; Kossin and Sitkowski 2009). This double-eyewall pattern often lasts only for a few hours, and it is usually accompanied by a gradual contraction of the outer eyewall and dissipation of the inner eyewall with considerable fluctuations



FIG. 1. (a) Time series of the simulated PMIN (hPa, boldface dashed) and VMAX (m s⁻¹, boldface dashed) vs the best-track analysis (boldface solid) from the 48-h simulation of Hurricane Wilma (2005), initialized at 0000 UTC 18 Oct 2005. (b) Hovmöller diagram of the radar reflectivity (shaded at intervals of 5 dBZ) at 850 hPa. Dashed lines in (b) denote the RMW.

in intensity (i.e., in PMIN and VMAX; see Willoughby et al. 1982; Black and Willoughby 1992).

A quick inspection of the gradient wind balance indicates that the PWR so derived does not capture the impacts of double eyewalls if the TC size is not taken into account properly (see Cocks and Gray 2002; Harper 2002). Due to the lack of observations, most PWRs do not include the information on TC size in their regressional forms explicitly. Using the reconnaissance data, KZ07 show that the TC size could account for up to 10-hPa differences in the pressure drop between the large and small TCs on average (see Fig. 9 therein), given the same VMAX. To take into account the impacts of TC size, KZ07 introduce into their regressional PWR a parameter *S*, which is defined as the ratio of the tangential wind at r = 500 km to its climatological value at the same radius; the latter is estimated in accordance with a modified Rankine vortex model.

While KZ07's size parameter *S* can explain statistically up to 40% of the variance of the average radius of gale force winds (i.e., 34-kt winds), it is necessary to see if the size parameter could capture the behavior of the PWR during the eyewall replacement cycle. Figure 1 shows the time series of PMIN and VMAX from a cloud-resolving simulation of Hurricane Wilma (2005) with the Weather Research and Forecasting (WRF) model at the



FIG. 2. Time series of the central pressure drop (hPa) during the 36–48-h model simulation (solid), Holland's profile (dashed), and Knaff and Zehr's profile (dotted).

finest resolution of 1 km. (A more detailed description of the case simulation will appear in a forthcoming paper.) The WRF model reproduces reasonably well the rapid intensification of the storm, including the VMAX of about 80 m s⁻¹; the simulated PMIN is only about 4 hPa deeper than the observed at the end of the rapid deepening stage (i.e., 36 h into the integration; see Fig. 1a). Of importance is that while PMIN keeps deepening after 36 h of integration, the simulated VMAX is nearly constant or even decreases with time. The period of such anticorrelation between VMAX and PMIN coincides with the eyewall replacement and the spiral rainband stage before and after the appearance of a full outer eyewall (Fig. 1b).

An examination of H08's and KZ07's work, given in appendix A, reveals that both PWRs could not capture this anticorrelation between VMAX and PMIN. Indeed, both show high fluctuations in Δp with positive tendencies, rather than a steady increase of Δp , as simulated or observed, during this replacement period (Fig. 2). Although we should not expect a perfect fit between a statistical curve and the model output, as the statistical curve contains some margin variance, these PWRs exhibit either little trend (i.e., H08's curve) or decreases of Δp with VMAX (i.e., KZ07's curve). This indicates that some physical processes are not properly included in the PWRs. A further examination of the Wilma case reveals that the KZ07's simulated size parameter S is nearly constant during the eyewall replacement, even though its RMW more than doubles. As a result, the estimation of the mean tangential flow at r = 500 km could not reflect the actual variation of Wilma's inner core, after the formation of the outer eyewall. Such stiffness of the size parameter from the model output is different from the actual size variation presented in Knaff and Zehr (2008), which is actually consistent with KZ07's analysis that their size parameter can account only for about 40% of the variances of the average radius of the 34-kt wind. Apparently, the size parameter plays an important role for strong TCs with small eye sizes.

To see this point, consider first a single-eyewall pattern during the quasi-stationary evolution such that the temporal variations of both VMAX and PMIN can be neglected. Under the axisymmetric approximation, the radial momentum equation is

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + w \frac{\partial u}{\partial z} - \frac{v^2}{r} = -\frac{1}{\rho} \frac{\partial p}{\partial r} + fv + \frac{C_D}{H} |\mathbf{V}|u, \quad (3)$$

where $\mathbf{V} = (u^2 + v^2)^{1/2}$, C_D is the drag coefficient, and H is the depth of the well-mixed boundary layer. Because of the quasi-stationary assumption and because the PWR is applied at the surface where $w \approx 0$, Eq. (3) can be rewritten as

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = -u\frac{\partial u}{\partial r} + \frac{v^2}{r} + fv + \frac{C_D}{H}|\mathbf{V}|u, \quad \text{at} \quad z = 0.$$
(4)

In the following, we will assume a familiar Rankine two-region model in which the tangential flows increase linearly with radius in the inner-core region, and then decrease as an inverse function of radius in the outer region. Although the Rankine model has some drawbacks in the outer region where tangential flows appear to decrease more slowly than a simple inverse function of radius, such drawbacks will not lead to significant differences in the radially accumulated pressure deficit, provided that the size of the TCs is not too large. As long as the pressure drop associated with the outer eyewall is not small compared to that of the inner eyewall, the Rankine model should be sufficient to capture the main contribution of the outer eyewall.

Region I (inner core): $u = -\omega r$ and $v = \Omega r$ where ω and Ω are the two different constant coefficients integrating Eq. (4) from r = 0 to r = R (RMW) gives

$$\begin{split} \delta p_I &= \int_0^R \rho \Big(\Omega^2 - \omega^2 + f\Omega + \kappa \omega \sqrt{\Omega^2 + \omega^2} r \Big) r \, dr \\ &\approx \overline{\rho} \int_0^R \Big(\Omega^2 - \omega^2 + f\Omega + \kappa \omega \sqrt{\Omega^2 + \omega^2} r \Big) r \, dr \\ &= \overline{\rho} \bigg[\frac{(V^2 + fVR - U^2)}{2} + \frac{\kappa |U|R\sqrt{V^2 + U^2}}{3} \bigg], \end{split}$$
(5)

where $\kappa = C_D/H$, $\overline{\rho}$ is the mean density in the inner core, and U and V are the maximum radial wind and VMAX at r = R, respectively.

Region II (outer region): $u = -\gamma/r$ and $v = \Gamma/r$. (A more realistic profile for the tangential wind in the outer region should be approximated by $v = \Gamma/r^{\alpha}$ where $\alpha > 0$. Details and implication of α can be found in appendix B.) Integrating Eq. (4) outward from r = R to $r = R_{\infty}$ yields

$$\begin{split} \delta p_{II} &= \int_{R}^{R_{\infty}} \rho \Biggl(\frac{\Gamma^2}{r^3} + \frac{\gamma^2}{r^3} + \frac{f\Gamma}{r} + \frac{\kappa\gamma\sqrt{\Gamma^2 + \gamma^2}}{r^2} \Biggr) dr \\ &\approx \overline{\rho} \int_{R}^{R_{\infty}} \Biggl(\frac{\Gamma^2}{r^3} + \frac{\gamma^2}{r^3} + \frac{f\Gamma}{r} + \frac{\kappa\gamma\sqrt{\Gamma^2 + \gamma^2}}{r^2} \Biggr) dr \\ &= \overline{\rho} \Biggl[\frac{(V^2 + U^2)}{2} + fVR \ln\Biggl(\frac{R_{\infty}}{R} \Biggr) + \kappa |U|R\sqrt{V^2 + U^2} \Biggr] \end{split}$$
(6)

It should be noted that for the Rankine model in which the tangential wind decreases inversely with the radius, R_{∞} cannot be arbitrarily large as its radial profile is not compactly distributed. Only for a modified Rankine profile in which $V \sim 1/r^{\alpha}$, where $\alpha > 1$, can the radial profile of V extend to infinity. Therefore, R_{∞} has to take some finite value, that is, $R_{\infty} = 1000$ km in the present study. A summation of Eqs. (5) and (6) leads to

$$\Delta p = \overline{\rho} \left\{ V^2 + f V R \left[\frac{1}{2} + \ln \left(\frac{R_{\infty}}{R} \right) \right] + \frac{4\kappa |U| R \sqrt{V^2 + U^2}}{3} \right\},\tag{7}$$

where Δp is the sea level pressure difference between r = 0 and $r = R_{\infty}$. The mean density \overline{p} can be estimated by

$$\overline{\rho} \approx \frac{p_e + p_c}{2RT_e} = \frac{2p_e - \Delta p}{2RT_e} = \rho_e \bigg(1 - \frac{\Delta p}{p_e} \bigg),$$

where p_e and p_c are the ambient and central surface pressures, respectively. So Eq. (7) can be rewritten as

$$\Delta p \approx \rho_e \left\{ V^2 + fVR \left[\frac{1}{2} + \ln\left(\frac{R_{\infty}}{R}\right) \right] + \frac{4\kappa |U|R\sqrt{V^2 + U^2}}{3} \right\}$$
$$\times \left\{ 1 + \frac{1}{\rho_e} \left[V^2 + fVR \left[\frac{1}{2} + \ln\left(\frac{R_{\infty}}{R}\right) \right] + \frac{4\kappa |U|R\sqrt{V^2 + U^2}}{3} \right] \right\}.$$
(8)

Unlike the simple gradient balance relationship [Eq. (B1)] in which the RMW (i.e., R), corresponding to the size parameter S in KZ07, only appears in the Coriolis-related term depending linearly on VMAX (i.e., the second terms in the two paired brackets), it is now also coupled with the drag coefficient κ , the radial inflow U, and VMAX (i.e., the last term in the brackets) in Eq. (8), which are all pronounced in the PBL near the RMW. Given the fact that C_D ranges from 10⁰ to 10⁻³ (see

Holton 1992) and $H \approx 10^3$ m, κ may vary from 10^{-3} to 10^{-6} m^{-1} . For $\kappa = 10^{-4} \text{ m}^{-1}$, $U \approx 10 \text{ m s}^{-1}$, $R \approx 50 \text{ km}$, and $V \approx 70 \text{ m s}^{-1}$, the coupled RMW-frictional term could contribute up to about a 47-hPa pressure drop, which is large compared to the contribution from the second terms in the two paired brackets in Eq. (8). Note that for a typical TC, $V \gg U$, and the coupled RMWfrictional contribution is roughly linear in VMAX, like the Coriolis-related terms. This helps explain why the linear contribution of VMAX plays an important role in the regressional PWRs, even after considering the impacts of surface friction. This suggests that the simple constant recursive coefficient for the linear VMAX term tends to oversimplify the PWR for weak TCs, or during their early development stage. In contrast, for strong TCs with small sizes in which the radial flows are large, the frictional term can no longer be approximated as a linear function of VMAX. In addition, it is evident from Eq. (8) that the RMW and VMAX should be treated as being coupled rather than independent predictors. This coupling of the RMW and VMAX is essential as it differs from the current functional forms used for best fitting the PWR (see KZ07).

Consider next a double-eyewall pattern as sketched in Fig. 3. Assuming that the double eyewalls are represented by dual RMWs (with dual VMAXs) and that they contract slowly, an integration of Eq. (3) for each region gives

$$\begin{split} \delta p_1 &= \int_0^{R_1} \rho \bigg(\Omega_1^2 - \omega_1^2 + f \Omega_1 + \kappa \omega_1 \sqrt{\Omega_1^2 + \omega_1^2} r \bigg) r \, dr \\ &\approx \overline{\rho}_1 \bigg[\frac{(V_1^2 + f V_1 R_1 - U_1^2)}{2} + \frac{\kappa |U_1| R_1 \sqrt{V_1^2 + U_1^2}}{3} \bigg], \end{split}$$

$$\begin{split} \delta p_2 &= \int_{R_1}^{R_2} \rho \Biggl(\frac{\Omega_2^2}{r^3} + \frac{\omega_2^2}{r^3} + \frac{f\Omega_2}{r} + \frac{\kappa \omega_2 \sqrt{\Omega_2^2 + \omega_2^2}}{r^2} \Biggr) dr \\ &\approx \overline{\rho}_2 \Biggl[\frac{(V_1^2 + U_1^2)}{2} \frac{(R_2^2 - R_1^2)}{R_2^2} + fV_1 R_1 \ln \biggl(\frac{R_2}{R_1} \biggr) \\ &+ \kappa |U_1| \sqrt{V_1^2 + U_1^2} \frac{R_1 (R_2 - R_1)}{R_2} \Biggr], \end{split}$$

$$\begin{split} \delta p_3 &= \int_{R_2}^{R_3} \rho \bigg(\Omega_3^2 - \omega_3^2 + f \Omega_3 + \kappa \omega_3 \sqrt{\Omega_3^2 + \omega_3^2} r \bigg) r \, dr \\ &\approx \overline{\rho}_3 \Bigg[\frac{(V_2^2 + f V_2 R_2 - U_2^2)}{2} \frac{(R_3^2 - R_2^2)}{R_2^2} \\ &+ \frac{\kappa |U_2| \sqrt{V_2^2 + U_2^2}}{3} \frac{(R_3^3 - R_2^3)}{R_2^2} \Bigg], \quad \text{and} \end{split}$$



FIG. 3. A schematic description of the double-eyewall configuration with dual RMWs during the eyewall-replacement process. Numbers 1–10 denote the contributions of individual terms on the rhs of Eq. (10) to the central pressure drop from four different radial ranges, i.e., $[0, R_1], \ldots$, $[R_3, R_\infty]$. The shaded region denotes the contribution from the outer eyewall.

$$\begin{split} \delta p_4 &= \int_{R_3}^{R_{\infty}} \rho \! \left(\frac{\Omega_4^2}{r^3} + \frac{\omega_4^2}{r^3} + \frac{f\Omega_4}{r} + \frac{\kappa \omega_4 \sqrt{\Omega_4^2 + \omega_4^2}}{r^2} \right) dr \\ &\approx \overline{\rho}_4 \! \left[\frac{(V_3^2 + U_3^2)}{2} + fV_3 R_3 \ln \! \left(\frac{R_{\infty}}{R_3} \right) \right. \\ &+ \kappa |U_3| R_3 \sqrt{V_3^2 + U_3^2} \bigg], \end{split}$$

inner and outer eyewalls, respectively, and V_2 and R_2 are the minimum tangential wind and its radius, respectively, between the two eyewalls (see Fig. 3). Following the same steps as derived earlier for the single-eyewall case, we obtain finally

$$\Delta p \approx \rho_e \Pi \left(1 + \frac{\Pi}{p_e} \right), \tag{9}$$

where V_1 and V_3 are the local maximum tangential winds (i.e., VMAXs) at R_1 and R_3 (i.e., RMWs) in the

where

$$\Pi = \frac{(V_1^2 + fV_1R_1 - U_1^2)}{2} + \frac{\kappa |U_1|R_1\sqrt{V_1^2 + U_1^2}}{3} + \frac{(V_1^2 + U_1^2)}{2} \frac{(R_2^2 - R_1^2)}{R_2^2} + fV_1R_1\ln\left(\frac{R_2}{R_1}\right) \\ + \kappa |U_1|\sqrt{V_1^2 + U_1^2}\frac{R_1(R_2 - R_1)}{R_2} + \frac{(V_2^2 + fV_2R_2 - U_2^2)}{2}\frac{(R_3^2 - R_2^2)}{R_2^2} + \frac{\kappa |U_2|\sqrt{V_2^2 + U_2^2}}{3}\frac{(R_3^3 - R_2^3)}{R_2^2} \\ + \frac{(V_3^2 + U_3^2)}{2} + fV_3R_3\ln\left(\frac{R_\infty}{R_3}\right) + \kappa |U_3|R_3\sqrt{V_3^2 + U_3^2}.$$
(10)

Note that the PWR(9) [PWR in Eq. (9)] will be identical to the PWR(8) if one sets $R_3 = R_2 = R_1$, $V_3 = V_2 = V_1$, and $U_3 = U_2 = U_1$ in Eq. (10). It is evident from the expression in Eq. (10) that the formation of dual VMAXs will enhance Δp by an amount mostly given by the sum of the 6th and 7th terms on the rhs of Eq. (10). Although the 8th–10th terms contain information about the outer eyewall, most of their contributions have been compensated by the 6th and 7th terms (see Fig. 3 for illustration). To estimate the magnitude of this outereyewall contribution, we take some data from the simulated Wilma with $V_2 = 65 \text{ m s}^{-1}$, $U_2 = 10 \text{ m s}^{-1}$, $R_2 = 32 \text{ km}$, and $R_3 = 43 \text{ km}$, and find that the outer eyewall could account for about 19 hPa, which is large compared to the root-mean-squared error from the regressional PWR (~5.8 hPa in KZ07).

Table 1 quantifies the contributions of each region to the total pressure drop from the 42-h simulation, valid at

TABLE 1. Contribution of pressure drops, as calculated from Eq. (10), from regions 1–4 (see Fig. 3) to the total central pressure drop using the 42-h simulation, valid at 1800 UTC 19 Oct 2005.

	Radius intervals (km)	$\frac{\text{VMAX}}{(\text{m s}^{-1})}$	Radial wind U (m s ⁻¹)	Pressure drop, δp (hPa)
Region 1	0-12	90	-18	39
Region 2	12-32	65	-11	37
Region 3	32-43	75	-14	17
Region 4	43-1000	0	0	59

1800 UTC 19 October 2005, at which time the doubleeyewall configuration is most evident (see Fig. 1b). Region 1 (i.e., the inner core of Wilma) contributes 39 hPa to the total pressure deficit (about 26%). The most significant contribution of 59 hPa is, however, from the outermost region (i.e., region 4), accounting for about 38% of the total pressure drop. The unexpected proportions could be attributed to the small convectively active annulus in region 1 (0-12 km) compared to the large area coverage of the latent heating in the outer region (R = 43 km and beyond), which is consistent with the observation of Willoughby (1998). Note from the above analysis that the contribution of the double eyewall is roughly 19 hPa, which is about 12% of the total pressure drop. As seen in Table 1, the sum of the pressure deficits from regions 1-4 is 152 hPa, which corresponds to a minimum sea level pressure of 858 hPa as compared to the simulated 864 hPa in Fig. 1a, indicating the applicability of Eq. (10) to some real-data cases.

Although little information about the dual VMAXs or the radial inflows could be provided from the current observing platforms (except for the availability of aircraft reconnaissance fixes), the above result indicates that the outer eyewall (or spiral rainbands) could have significant contributions to the central pressure drop in the innercore region. Note that this result does not contradict the findings of Hack and Schubert (1986), which showed that the smaller radius at which latent heating occurs, the more significant contribution to the central pressure fall is. Here, the outer region contributes 59 hPa to PMIN compared to a total drop of 93 hPa from the inner region (i.e., R <43 km). But this result explains why both KZ07's and H08's regression curves exhibit unexpected fluctuating behavior for Hurricane Wilma, exhibiting a well-organized outer eyewall during the replacement process (see Fig. 2). It should be mentioned that in principle the effects of the outer eyewall can be incorporated into KZ07's PWR by redefining the size parameter S, for example, by using the radius of 200 km instead of 500 km for the calculation of S for small TCs. But this would require the least squares best fit to be performed again, which is beyond the scope of the present study.

3. Effects of intensity change

Although the PWRs in Eqs. (8) and (9) could capture the balanced dynamics of VMAX and PMIN reasonably well, they neglect the temporal dependence of TCs through intensity changes. KZ09 present an analytical model for the rapid intensification of TCs in which the inclusion of a time-dependent factor results in different patterns of behavior for the rotational flows and pressure drop. By assuming the linear growth of the top-hat-shaped vertical motion within the inner core of the TCs,

$$w(r, z, t) = \begin{cases} W_0 \sin(\lambda z) e^{\beta t} & r \le \text{RMW} \text{ (region I)} \\ 0 & r > \text{RMW} \text{ (region II)} \end{cases},$$
(11)

a class of exact time-dependent solutions for the primary circulations of TCs are obtained, which capture several observed dynamical structures in both the core and outer regions and the rapid growth of the TCs. They include the following: (a) the rotational flows in the inner-core region grow at much faster rates than those in the outer region, (b) the amplification rates of the primary circulations differ profoundly from those of the secondary circulations, (c) the rotational flows tend to grow from the bottom upward with the fastest growth occurring at the lowest levels, and (d) the TC growth rates depend critically on the vertical structure of tangential flows, with a faster rate for a lower-level VMAX. Note that the exponential form of w, as given by Eq. (11), can be treated as a linear function of time for a small value of β (i.e., 10^{-6} – 10^{-5} s⁻¹), and it is used here to ease the derivations of analytical solutions.

Of importance is that KZ09's analytical model also provides a dynamically consistent framework for deriving the PWR of TCs. As shown in KZ09, the analytical solutions for the tangential wind and geopotential perturbation in the parametric form are given as follows:

$$V(r, z, t) = K(z, t)r,$$
(12)

$$\phi_1(r, z, t) = \phi_2(R, z, t) - \left(K^2 + fK - Q\beta e^{\beta t} - Q\kappa - Q^2 e^{2\beta t} - He^{2\beta t} \frac{dQ}{dz}\right) \frac{(R^2 - r^2)}{2}, \text{ and}$$
(13)

$$\phi_{2}(r, z, t) = e^{\beta t} R^{2} Q(\beta + \kappa) \ln \frac{R_{\infty}}{r} - \frac{e^{2\beta t} R^{4} Q^{2}}{2} \left(\frac{1}{r^{2}} - \frac{1}{R_{\infty}^{2}}\right) - \frac{C^{2}}{2} \left(\frac{1}{r^{2}} - \frac{1}{R_{\infty}^{2}}\right) - fC \ln \frac{R_{\infty}}{r}, \qquad (14)$$

where ϕ_1 and ϕ_2 are the geopotential perturbations in the inner-core and outer regions, respectively, and the

Parameters	Remarks	Values
а	Radius of the cloud disk or the RMW (R)	20 km
β	Growth rate parameter	$10^{-6} - 10^{-5} \text{ s}^{-1}$
f	The Coriolis parameter at 10°N	$2 \times 10^{-5} \text{ s}^{-1}$
H_0	Depth of the troposphere	20 km
$H_{\rm PBL}$	Depth of the PBL	1 km
λ	Inversed depth of the troposphere $(=\pi/H_0)$	$1.7 \times 10^{-4} \text{ m}^{-1}$
κ_0	Frictional drag coefficient at $z = 0$	$5 \times 10^{-5} \mathrm{s}^{-1}$
R_m	The outer radius of a TC beyond which the ambient environment is at rest	2000 km
S	Stratification parameter ($S \equiv N^2/g$)	10^{-5} m^{-1}
W_0	Area-averaged vertical motion within inner-core region	$2 \times 10^{-2} \mathrm{~m~s^{-1}}$
$\partial V / \partial t$	Tendency of tangential wind during the intensification	20 m s ⁻¹ in 24 h

implicit functions C(z, t), Z(z), Q(z), H(z), and K(z, t) are given by

$$\begin{split} C(z,t) &= \left(\frac{-e^{\beta t}QfR^2}{\beta + \kappa} + Ze^{-\kappa t}\right),\\ Z(z) &= \left[K(z,0) + \frac{Qf}{\beta + \kappa}\right]R^2,\\ Q(z) &= -\frac{W_0[\lambda\cos(\lambda z) - S\sin(\lambda z)]}{2} \end{split}$$

$$K(z,t) = 2G_0 \cos^2\left(\frac{\lambda z}{2}\right) e^{-Sz} \left\{ \exp\left(\frac{W_0 \lambda}{\beta} e^{\beta t}\right) + \epsilon \frac{\exp(W_0 \lambda e^{\beta t}/\beta) - \tan(\lambda z/2)}{W_0 \lambda e^{\beta t}/\beta - \ln[\tan(\lambda z/2)]} \right\} - \frac{f}{2}, \text{ and}$$

 $H(z) = W_0 \sin(lz).$

Table 2 lists the definitions and implications of some parameters. Because at the surface (i.e., z = 0) U = -Q(z = 0)R, V = C(z = 0, t)/R, and $\Delta p = -\rho(\phi_1 + \phi_2)$, we have at r = 0:

$$\Delta p = \overline{\rho} \left[e^{\beta t} UR(\beta + \kappa) \ln \frac{R_{\infty}}{R} + \frac{e^{2\beta t} U^2}{2} + \frac{V^2}{2} + f VR \ln \frac{R_{\infty}}{R} + \frac{1}{2} (V^2 + f VR + UR\beta e^{\beta t} + UR\kappa - U^2 e^{2\beta t}) \right]$$
$$= \overline{\rho} \left[V^2 + f VR \left(\frac{1}{2} + \ln \frac{R_{\infty}}{R} \right) + e^{\beta t} UR\beta \left(\frac{1}{2} + \ln \frac{R_{\infty}}{R} \right) + UR\kappa \left(\frac{1}{2} + \ln \frac{R_{\infty}}{R} e^{\beta t} \right) \right], \tag{15}$$

and

$$V = \left[2G_0 \exp\left(\frac{W_0 \lambda}{\beta} e^{\beta t}\right) - \frac{f}{2}\right] R.$$
 (16)

The time-dependent factor $e^{\beta t}$ in Eq. (15) can be found by solving Eq. (16):

$$e^{\beta t} = \ln \left[\frac{1}{2G_0} \left(\frac{V}{R} + \frac{f}{2} \right) \right] \frac{\beta}{W_0 \lambda}.$$

So we have the nonlinear form of the PWR:

$$\Delta p = \overline{\rho} \left\langle V^2 + f V R \left(\frac{1}{2} + \ln \frac{R_{\infty}}{R} \right) \right. \\ \left. + \ln \left[\frac{1}{2G_0} \left(\frac{V}{R} + \frac{f}{2} \right) \right] \frac{U R \beta^2}{W_0 \lambda} \left(\frac{1}{2} + \ln \frac{R_{\infty}}{R} \right) \right. \\ \left. + U R \kappa \left\{ \frac{1}{2} + \ln \frac{R_{\infty}}{R} \ln \left[\frac{1}{2G_0} \left(\frac{V}{R} + \frac{f}{2} \right) \right] \frac{\beta}{W_0 \lambda} \right\} \right\rangle.$$
(17)

If one sets $\beta = 0$, implying no intensity change, and takes $\kappa = \kappa_0 \sqrt{(V^2 + U^2)}$, the PWR(17) will be identical to the PWR(8), except for the logarithm factor $\ln(R_{\alpha}/R)$ in the frictional term due to the use of the first-order friction (see KZ09). To express the PWR(17) in a more familiar form involving the intensity change (i.e., $\partial V/\partial t$), as is often used in the previous statistical PWRs, we take the time derivative of (12) at z = 0 and get

$$\frac{\partial V}{\partial t} = 2G_0 R W_0 \lambda e^{\beta t} \exp\left(\frac{W_0 \lambda}{\beta} e^{\beta t}\right).$$
(18)

Note that

$$V|_{z=0} = \left[2G_0 \exp\left(\frac{W_0 \lambda}{\beta} e^{\beta t}\right) - \frac{f}{2}\right] R.$$
 (19)

So,



FIG. 4. Distribution of the central pressure drop (hPa) with respect to the RMW and VMAX for (a) the centrifugal forcing, (b) the Coriolis forcing, (c) the TC tendency $\partial V/\partial t$, and (d) the frictional forcing, using the PWR(22) and the parameters given in Table 2. See the text for more details.

$$2G_0 \exp\left(\frac{W_0 \lambda}{\beta} e^{\beta t}\right) = \frac{V}{R} + \frac{f}{2}.$$
 (20)

Substitution of Eq. (20) into Eq. (18) leads to

$$e^{\beta t} = \frac{\partial V}{\partial t} \left[RW_0 \lambda \left(\frac{V}{R} + \frac{f}{2} \right) \right]^{-1}.$$
 (21)

Thus, we finally obtain the nonlinear PWR equation with the TC tendency included:

$$\begin{split} \Delta p &= \overline{\rho} \left\langle V^2 + f V R \left(\frac{1}{2} + \ln \frac{R_{\infty}}{R} \right) \right. \\ &+ \frac{\partial V}{\partial t} \left[W_0 \lambda \left(V + \frac{f R}{2} \right) \right]^{-1} U R \beta \left[\frac{1}{2} + \ln \left(\frac{R_{\infty}}{R} \right) \right] \\ &+ U R \kappa \left\{ \frac{1}{2} + \frac{\partial V}{\partial t} \left[W_0 \lambda \left(V + \frac{f R}{2} \right) \right]^{-1} \ln \left(\frac{R_{\infty}}{R} \right) \right\} \right\rangle. \end{split}$$

$$(22)$$

Figure 4 shows the distributions of Δp associated with individual terms on the rhs of Eq. (22), which represents the centrifugal effect, Coriolis forcing, TC tendency, and frictional forcing, respectively. Obviously, the pressure drop associated with the centrifugal effect is the most weighted, which could reach 90 hPa for VMAX = 90 m s⁻¹ (Fig. 4a), whereas the linear contributions of VMAX associated with both $\partial V/\partial t$ and the Coriolis forcing are insignificant (Figs. 4b and 4c); the latter is consistent with the momentum budget of Zhang et al. (2001) showing that the tangential flows in the innercore regions can be approximated by the cyclostrophic relation. In particular, unlike the previous PWRs, in which the contribution of $\partial V/\partial t$ is considered only as a linear addition (e.g., see H08), we see different dependences of Δp on $\partial V/\partial t$ from the PWR(22). That is, while the direct contribution of $\partial V/\partial t$ to Δp [i.e., the third term on the rhs of Eq. (22)] is negligible (Fig. 4c), its indirect contribution associated with the frictional effects [i.e., the fourth term on the rhs of Eq. (22)] is pronounced (see Fig. 4d) due to the drag coefficient κ



FIG. 5. As in Fig. 4d but with $\partial V/\partial t = 30 \text{ m s}^{-1} (24 \text{ h})^{-1}$.

that is greater in magnitude than β in the last two terms. Depending upon the magnitude of the drag coefficient, this coupled friction-intensity tendency could account for 10–50 hPa of the pressure drop. For instance, if we take $\kappa = 10^{-4}$ m⁻¹ and $\partial V/\partial t = 30$ m s⁻¹ in 24 h, this indirect contribution could also drastically change the quadratic functional form of the PWR (see Fig. 5). This result is physically expected since a more intense storm tends to produce stronger radial inflows. As a result, the frictional effects become more significant in determining the linear contribution of VMAX to Δp for intense storms.

While KZ07's PWR does not explicitly incorporate the TC tendency as a direct predictor, it has been implicitly included in the size parameter S (Knaff et al. 2007). Namely, intensifying TCs were found by KZ07 to have smaller sizes and to be located at higher latitudes, which offset somewhat the direct size contribution to the pressure drop. This is more or less consistent with our Eq. (22), since the TC tendency contribution is always coupled with the RMW (i.e., the product of $\partial V/\partial t$ and *R*). Apparently, the impacts of the TC tendency are allowed to be compensated for by the smaller TC size, as found statistically.

As could also be expected from the balanced model presented in section 2, the PWR(22) indicates that the TC size should be coupled with VMAX and the TC intensity change (i.e., $\partial V/\partial t$) rather than being treated linearly as in KZ07. Although the indirect contribution of the TC intensity change can be approximated as a linear function of VMAX at the limit of $V \gg U$, as is often the case (because $\kappa \sim C_d V/H$), the TC intensity change should still be coupled with the RMW rather than acting as an independent predictor.

It is of interest to note that Eq. (22) shows the dependence of the PWR on the depth of the troposphere (i.e., through the λ parameter). As the depth of the troposphere decreases with latitude, one can see some dependence of the PWR on latitude through $\partial V/\partial t$. Such a latitude dependence of the PWR is different from that of the Coriolis forcing, and it appears to be consistent with the recent report of Kossin and Velden (2004), who showed a bias in the PWR with latitude. While this bias could be related to the Coriolis parameter, its dependence on latitude implies that there must be some dynamical reason behind it, and our PWR(22) captures this well.

4. Concluding remarks

In this study, the dynamical constraints between VMAX and PMIN in the PWR are examined. The Rankine vortex is used to demonstrate that the linear contribution of VMAX to the pressure drop through the frictional effect in the PBL has to be included in the PWR, particularly when TCs are strong or the eye size is small such that the radial inflows are no longer negligible. This indicates that the simple treatment of a constant regressional coefficient for the linear VMAX term as presently employed in various statistical PWRs should be employed with caution when being applied to strong TCs with small eye sizes. An examination of the double-eyewall configuration reveals that the formation of an outer eyewall or spiral rainbands complicates the PWR. Our analysis of a cloud-resolving simulation of Hurricane Wilma (2005) shows that the outer eyewall could result in the deepening of PMIN even with a constant VMAX with time. This outer-eyewall contribution becomes increasingly important when the TC size is too small for the statistical PWRs to capture the inner-core processes. An application of KZ09's analytical model to the rapid intensification of TCs shows further that the inclusion of the tangential wind tendency can make significant contributions to the central pressure drop when coupled with the frictional forcing. Unlike the simple linear addition often assumed in the previous regressional PWRs, our analysis shows that the contribution of the tangential wind tendency varies with the magnitude of radial inflows, which could even change the functional form of the PWR when the eye sizes are small or intensity changes are pronounced.

It should be pointed out that there are some limitations with the PWR(22) due to the assumed axisymmetry, and the neglect of storm translation and some environmental factors. Nevertheless, our results suggest that (i) the TC size should be coupled with VMAX, (ii) the TC tendency $\partial V/\partial t$ should be at least coupled linearly with the RMW rather than being treated independently, and (iii) the radial wind in the PBL is of equal importance to the linear contribution of VMAX. Based on the above analysis, we suggest modifying the statistical PWR as follows:

$$\Delta p = a_0 + a_1 V + a_2 S + a_3 \Phi + a_4 \frac{\partial V}{\partial t} + a_5 V^2 + a_6 \frac{\partial V}{\partial t} S + a_7 V S, \qquad (23)$$

where all notations follow the conventions of KZ07, and a_i with i = 1, ..., 7 are the regressional coefficients that could be obtained from the least squares best-fit approach. This will be investigated in the future using some available observations including the Atlantic basin Hurricane Database (or HURDAT).

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APPENDIX A

Two Most Representative PWRs

The most recently revised PWR by Knaff and Zehr (2007) is given as follows:

$$\Delta p = 23.286 - 0.483 V_{\rm srm} - \left(\frac{V_{\rm srm}}{24.254}\right)^2 - 12.587S - 0.483\Phi, \tag{A1}$$

where $\Delta p = \text{PMIN} - P_{\text{env}}$ is the pressure drop and V_{srm} is the storm-relative maximum surface wind speed that is estimated from the maximum surface wind V and the translational speed c as

$$V_{\rm srm} = V - 1.5c^{0.63}.$$
 (A2)

The size parameter S in Eq. (A1) is defined as the ratio of the average tangential flows, V_{500} , and the climatology tangential wind, V_{500c} (i.e., $S = V_{500}/V_{500c}$), where

$$V_{500c} = V \left(\frac{R}{500}\right)^x$$
, where
 $x = 0.1147 + 0.0055V - 0.001(\Phi - 25),$ (A3)

and

$$R = 66.78 - 0.09102V + 1.0619(\Phi - 25).$$
 (A4)

Given the maximum surface wind V, the latitude Φ , the translational speed c, and the tangential wind V_{500} that is averaged within an annulus of 400–600 km of a TC, the PWR in (A1) can be used to estimate the pressure drop accordingly. The root-mean-square error for (A1) is 5.8 hPa.

Holland (2008) proposed a different parametric form for the PWR that allows one to compute VMAX, given Δp , and it is recapitulated as follows:

$$V = \left(\frac{b_s}{\rho e}\Delta p\right)^{0.5},\tag{A5}$$

where

$$b_s = -4.4 \times 10^{-5} \Delta p^2 + 0.01 \Delta p + 0.03 \frac{\partial p_c}{\partial t}$$
$$-0.014\Phi + 0.15c^x + 1.0$$
(A6a)

and

$$x = 0.6 \left(1 - \frac{\Delta p}{215} \right). \tag{A6b}$$

Given the pressure drop Δp , the latitude Φ , the translational speed *c*, and the tangential flow tendency, the PWR in (A5) can be used to estimate VMAX parametrically. The root-mean-square error for (A1) is 3.5 m s⁻¹.

APPENDIX B

The Gradient-Balanced PWR

Consider the gradient balance approximation:

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{V^2}{r} + fV \tag{B1}$$

To find a PWR from this approximation, we need to know the profile of V(r). Let us use the Rankine vortex model to derive the PWR as follows:

region I (inner core), $V = \Omega r$,

$$\delta p_I = \int_0^R \rho(\Omega^2 + f\Omega) r \, dr$$

= $\overline{\rho} \int_0^R (\Omega^2 + f\Omega) r \, dr = \overline{\rho} \frac{(\Omega^2 + f\Omega)R^2}{2}$, and
= $\overline{\rho} \frac{(V^2 + fVR)}{2}$
(B2)

region II (outer core), $V = K/r^{\alpha}$ where $\alpha \ge 1$,

$$\delta p_{II} = \int_{R}^{\infty} \rho \left(\frac{K^2}{r^{2\alpha+1}} + \frac{fK}{r^{\alpha}} \right) dr = \overline{\rho} \int_{R}^{\infty} \left(\frac{K^2}{r^{2\alpha+1}} + \frac{fK}{r^{\alpha}} \right) dr = -\overline{\rho} \left[\frac{1}{2\alpha} \frac{K^2}{r^{2\alpha}} + \frac{1}{(\alpha-1)} \frac{fK}{r^{\alpha-1}} \right]_{R}^{\infty} = \overline{\rho} \left[\frac{V^2}{2\alpha} + \frac{fVR}{(\alpha-1)} \right]. \tag{B3}$$

So for $\alpha > 1$,

$$\delta p = \delta p_I + \delta p_{II} = \overline{\rho} \left[\frac{V^2}{2} \left(1 + \frac{1}{\alpha} \right) + f V R \left(\frac{1}{2} + \frac{1}{\alpha - 1} \right) \right].$$
(B4a)

For $\alpha = 1$, we integrate the pressure deficit in the outer region from *R* to some finite value R_{∞}

$$\delta p = \delta p_I + \delta p_{II} = \overline{\rho} \left\{ V^2 + f V R \left[\frac{1}{2} + \ln \left(\frac{R_{\infty}}{R} \right) \right] \right\}.$$
(B4b)

The mean density $\overline{\rho}$ is estimated from

$$\overline{\rho} \approx \frac{p_e + p_c}{2RT_e} = \frac{2p_e - \Delta p}{2RT_e} = \rho_e \left(1 - \frac{\Delta p}{p_e}\right). \quad (B5)$$

So for $\alpha > 1$,

$$\begin{split} \delta p &= \rho_e \bigg[\frac{V^2}{2} \bigg(1 + \frac{1}{\alpha} \bigg) + f V R \bigg(\frac{1}{2} + \frac{1}{\alpha - 1} \bigg) \bigg] \\ &\times \bigg\{ 1 + \frac{1}{p_e} \bigg[\frac{V^2}{2} \bigg(1 + \frac{1}{\alpha} \bigg) + f V R \bigg(\frac{1}{2} + \frac{1}{\alpha - 1} \bigg) \bigg] \bigg\}, \end{split} \tag{B6a}$$

and for $\alpha = 1$,

$$\begin{split} \delta p &= \rho_e \left\{ V^2 + f V R \left[\frac{1}{2} + \ln \left(\frac{R_{\infty}}{R} \right) \right] \right\} \\ &\times \left\langle 1 + \frac{1}{p_e} \left\{ V^2 + f V R \left[\frac{1}{2} + \ln \left(\frac{R_{\infty}}{R} \right) \right] \right\} \right\rangle, \end{split} \tag{B6b}$$

where $\rho_e \approx 1.1 \text{ kg m}^{-3}$, $p_e \approx 1.01 \times 10^5 \text{ Pa}$, and $R_{\infty} \approx 1000 \text{ km}$.

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