Reply

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ABSTRACT

Veerasamy has made several comments concerning the results and methods presented in a recent article by the authors titled "Reexamination of Tropical Cyclone Wind–Pressure Relationships." One comment concerns the terminology and definition of the environmental pressure. Another comment suggests the merits of a simpler approach developed by Veerasamy in 2005 that utilizes the radius of 1004 hPa to determine the "proper" wind–pressure relationship. The third comment concerns the performance of the Knaff and Zehr wind–pressure relationship [their Eq. (7)] during the well-observed North Atlantic Hurricanes Katrina, Rita, and Wilma during 2005. The final comment suggests that the techniques discussed in Knaff and Zehr are more difficult to apply than an operational method developed by Veerasamy and used in Mauritius. These comments are addressed individually along with some of the lessons learned since the publication of the Knaff and Zehr methodology that are important to the tropical cyclone community.

1. Introduction

A recent article (Knaff and Zehr 2007, hereinafter KZ07) revisited the topic of tropical cyclone (TC) wind–pressure relationships (WPRs) using 15 yr of minimum sea level pressure (MSLP) estimates, numerical analysis fields, and best-track intensities, mostly collected in the North Atlantic. The purposes of that paper were to examine the influences of operationally measurable factors (i.e., TC size, environmental pressure, latitude, TC motion, and intensification trend) on the relationship between maximum surface winds (MSWs) and MSLP and to develop unified methods to estimate MSLP given MSW and MSW given MSLP. Using these new WPRs and the large modern dataset (3801 cases), various WPRs used globally in operational centers and those used for historical reanalyzes of TC intensities were examined and compared.

Our colleague Veerasamy (2008, hereinafter V08) makes several specific comments on our earlier work. One comment concerns the terminology and definition of environmental pressure. V08 also suggests a simpler MSLP estimation approach (Veerasamy 2005, hereinafter V05) that utilizes the 1004-hPa isobar radius and the WPR tables in Dvorak (1984). Furthermore, V08 remarks on the performance of the KZ07 WPR during Hurricanes Katrina, Rita, and Wilma. Finally, V08 suggests the methods in KZ07 are more difficult to use than the method described in V05. In addition to these comments, other correspondence with various members of the TC user community (A. Burton, J. Courtney, and D. Duncalf 2007, personal communications) have indicated that the KZ07 methods use TC size and environmental pressure estimates that are quite different than the traditional operational measures of these quantities and that the KZ07 methods perform poorly at very low latitudes. The V08 comments will be addressed individually in sections 2–5 followed by a discussion of lessons learned since the publication of KZ07 that are relevant to the TC user community in section 6. Table 1 lists several nonstandard acronyms used in the text of this reply.

2. Comments on estimating environmental pressure

It is acknowledged that the term for "environmental pressure" (P_{env}) used in KZ07 could be confused with

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TABLE 1. A list of nonstandard acronyms and definition used in this manuscript is provided.

Acronym	Definition
MSLP	Minimum sea level pressure
MSW	Maximum surface wind
WPR	Wind–pressure relationship
P_{env}	Environmental pressure measured as an average in a 800–1000-km annulus from the TC center and defined in KZ07
P_E	Environmental pressure defined as the average radius of an outer closed cyclonic isobar as defined in Wang (1978) and Holland (1980)
R4	Average radius of the 1004-hPa isobar
WNP D-WPR	The tabular wind–pressure relationship given in Dvorak (1984) for use in the western North Pacific
NA D-WPR	The tabular wind–pressure relationship given in Dvorak (1984) for use in the North Atlantic
AH77 WPR	The wind–pressure relationship developed in Atkinson and Holliday (1977, 1975)

previous work by Wang (1978) and Holland (1980), and that the naming convention may have caused some unnecessary confusion. In the context of KZ07, however, the P_{env} parameter is well defined and accounts for the variations of the environmental pressure between our samples and more importantly allows the estimation of the pressure deficit (ΔP) from the environment. V08 also points out that the measurement of the P_{env} in KZ07 is much easier to estimate in an operational setting because it is defined by a fixed, rather than variable, radius—something KZ07 wanted to achieve. The measurement of environmental pressure (P_E) used in Wang (1978) and Holland (1980) is defined as the average radius of an outer closed cyclonic isobar, which is not only variable, but in a case of large asymmetries or rapid translation may be difficult to calculate accurately.

It is also acknowledged that isobaric measurements of tropical cyclone characteristics can be used to evaluate the combined effects of TC size and environmental pressure. V08 points out that Cocks and Gray (2002) and Veerasamy (2005, hereafter V05) advocate the use of the average radius of the 1004-hPa isobar (R4) as a proxy for size. From the results given in V05 this approach seems reasonable, especially for the cases listed in Table 1 of V08. Cocks and Gray however found that R4 was not always the best proxy of TC size, and developed an equivalent R4 that accounted for the variations of the pressure associated with the outer closed isobar. For KZ07 using R4 was not practical because 1) the environmental pressure in the North Atlantic is much higher than that of the western North Pacific and apparently the SWIO TC basins, 2) one of the primary motivations of KZ07 was to isolate influences of the environmental pressure and TC size in determining the WPR and a fixed isobar combines both these effects, 3) storm motion and semidiurnal pressure variations add noise to the estimates of R4, and 4) the radius of the outer closed isobar and/or R4 currently is manually/subjectively determined. This reasoning however does not diminish the contributions of Cocks and Gray (2002) or V05, which have found R4 (or equivalent measures of R4) to be a useful metric of TC size in operational settings.

3. Suggestion to use the Veerasamy (2005) methodology

KZ07 did not address the technique discussed in V05, where R4 is used to determine which WPR, either the North Atlantic Dvorak WPR (NA D-WPR) table or the western North Pacific Dvorak WPR (WNP D-WPR) table published in Dvorak (1984), is more appropriate. The ideas presented in V05 are quite good, as the R4, at least in the SWIO, appears to discriminate both the tropical cyclone size and the environmental pressure in a single term. If a storm is either in an anomalously high sea level pressure environment or the circulation is small, the value of R4 will be small ($<3.3°$ latitude) and the V05 findings suggest the NA-WPR relationship is more appropriate. Similarly, if R4 is greater than 4.5° latitude, WNP D-WPR gives superior results and, in the case $3.3 < \mathrm{R4} < 4.5$, an average of NA and WNP D-WPR is applied. To us, R4 seems like a reasonable TC size metric and the V05 method produces results similar to the discrete tabular version of KZ07 (i.e., see their appendix B).

However, a concern we have with the V05 methodology is the validity of the WNP D-WPR. Our reservations stem from KZ07's finding that conclusively shows that the WPR developed by Atkinson and Holliday (1977, hereinafter AH77 WPR), and thus WNP D-WPR, was improperly fit to the Atkinson and Holliday (1975) data. This improper fit to the raw data ultimately results in a low MSLP bias for high values of MSW (>80 kt; 1 kt $= 1.852$ km h^{-1}). Also while the studies of Atkinson and Holliday (1975, 1977) were not referenced in Dvorak (1984), the WNP D-WPR is identical to AH77 WPR as noted independently by Harper (2002). Furthermore, the studies used to justify the AH77 WPR, namely Shewchuk and Weir (1980) and Lubeck and Shewchuk (1980), offer little proof of the reliability or accuracy of the AH77 WPR. The foundation of this statement was not discussed in KZ07, but deserves some elaboration here. The Shewchuk and Weir study relied on best-track intensities within 24 h of aircraft observations for validation. However, when aircraft were observing the storm, the best-track data intensities, by the authors' own acknowledgment, were heavily weighted to MSW determined by using the AH77 WPR. Lubeck and Shewchuk (1980) examined the fit of AH77 using a mere 13 independent cases. Their conclusion that the AH77 WPR was not statistically different from an independently derived WPR—and therefore accurate—is not surprising given the number of cases. Nonetheless, AH77 WPR was then adopted by Dvorak (1984) for use in the western North Pacific following the recommendation of Shewchuk and Weir (1980) with no reference to these other studies. Later the WNP D-WPR from Dvorak (1984) was adopted by the World Meteorological Organization (WMO) for use in the southwest Indian Ocean.

The reliance on WNP D-WPR however can be avoided. To demonstrate that similar MSLP estimates can easily be created without the use of the WNP D-WPR in the SWIO, an example of how the KZ07 methods can be applied is now offered. Instead of the full KZ07 unified equations, the tables provided in appendix B of KZ07 can be applied using the size criteria already developed in V05. For instance, if R4 is less than 3.3° latitude, it would be considered small sized; if $3.3^\circ < \mathrm{R4} < 4.5^\circ$, the storm would be considered average sized; and if R4 is larger than 4.5° latitude, the storm would be considered large sized. This example makes use of the R4 and MSLP observations provided in Table 1 of V08. Because these observations were all taken at approximately 20°S, it is assumed the appropriate ΔP value is an average of the <20° table and the 20°–30° table in appendix B in KZ07, though this is not necessary. If a representative environmental pressure of 1012 hPa (i.e., from Sadler et al. 1987) is assumed, the results for the MSLP observations given in Table 1 of V08 become 954, 954, 962, 976, 958, 970, and 968, respectively. The bias for this independent sample is 0.4 hPa with a mean absolute error (MAE) of 3.0 hPa and root-mean-square error (RMSE) of 3.4 hPa. For comparison, the method of V05 produces a bias of −0.9 hPa, an MAE of 1.7 hPa, and an RMSE of 4.0 hPa for the same, but in this case, developmental sample.

TABLE 2. Comparison of error statistics associated with Hurricanes Katrina, Rita, and Wilma. Shown are errors associated with the KZ07 WPR, NA D-WPR, and WNP D-WPR. Bias, MAE, and RMSE are given in terms of hPa. The number of cases (N) is given along with the storm name(s).

Katrina (N = 50)			
WPR	Bias (hPa)	MAE (hPa)	RMSE (hPa)
KZ07	4.31	4.68	6.67
NA D-WPR	10.62	10.67	12.86
WNP D-WPR	−6.63	7.55	8.85
Rita (N = 81)			
WPR	Bias (hPa)	MAE (hPa)	RMSE (hPa)
KZ07	12.70	14.01	17.60
NA D-WPR	−5.35	9.95	11.79
WNP D-WPR	2.04	12.27	12.76
Wilma (N = 64)			
WPR	Bias (hPa)	MAE (hPa)	RMSE (hPa)
KZ07	1.95	2.86	11.51
NA D-WPR	9.17	10.33	13.48
WNP D-WPR	−9.36	10.69	13.08
Katrina, Rita, and Wilma (N = 195)			
WPR	Bias (hPa)	MAE (hPa)	RMSE (hPa)
KZ07	4.84	7.97	10.68
NA D-WPR	11.01	11.94	15.19
WNP D-WPR	−7.00	9.58	11.58

4. Performance of wind–pressure relationships during Hurricanes Katrina, Rita, and Wilma

V08 states that a single WPR often performs poorly on individual TC cases and we agree. Similar observations were one of the key motivations for the KZ07 study and the justification for developing unified WPRs. However KZ07 did not examine all of the factors that influence the WPR of a given storm. An analysis of the Katrina, Rita, and Wilma cases suggests that factors not considered in KZ07 may be related to some of the errors associated with the application of various WPRs. It is also noteworthy that the use of Eq. (7) in KZ07, which considers variations of P_{env} (as defined in KZ07), latitude, and TC size, results in statistically significant improvements in the estimation of MSLP versus the NA D-WPR and WNP D-WPR for these storm cases, as shown in Table 2.

Figure 1 shows the aircraft-based time series of pressure for Hurricanes Katrina, Rita, and Wilma along with MSLP estimates created using KZ07, NA D-WPR, and WNP D-WPR. WPR-based MSLPs are estimated using best-track intensity estimates interpolated to the time of the MSLP observation. These time series plots show the relevant issues discussed in section 4 of V08. Indeed there are periods of time where one WPR outperforms the others. The KZ07 WPR however appears to do a good job, with a few exceptions.

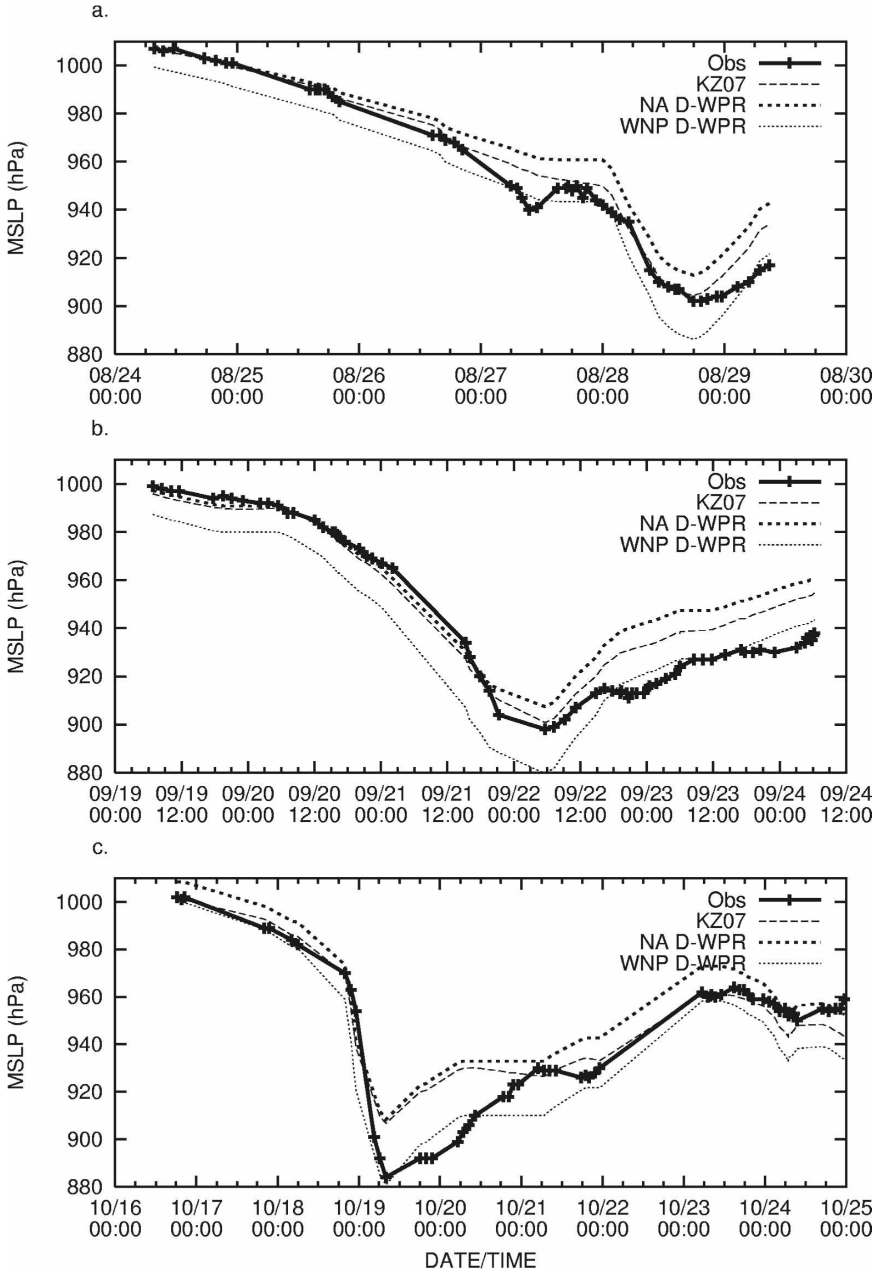

FIG. 1. Time series of observed and estimated MSLPs associated with Hurricanes (a) Katrina, (b) Rita, and (c) Wilma. Shown are the observed MSLP (Obs), where the times are indicated by the points along the line, and estimates of MSLP using the KZ07 WPR, the NA D-WPR, and the WNP D-WPR.

In the following discussion it is argued that much of the success and failure of the different WPRs can be explained by environmental and storm-scale factors. Figure 2 shows the environmental pressure (i.e., P_{env}) time series as defined in KZ07, and Fig. 3 shows the normalized TC size parameter (S in KZ07) and the observed eye diameter. The time axes for these figures are identical to those in Fig. 1. In the following discussions, the MSW estimates reported in the best-track dataset are interpolated to the time of the MSLP observation and used as ground truth.

a. Hurricane Katrina

Hurricane Katrina was a near-average Atlantic tropical cyclone from 24 August through late on 26 August with environmental pressure (P_{env}) slightly greater than

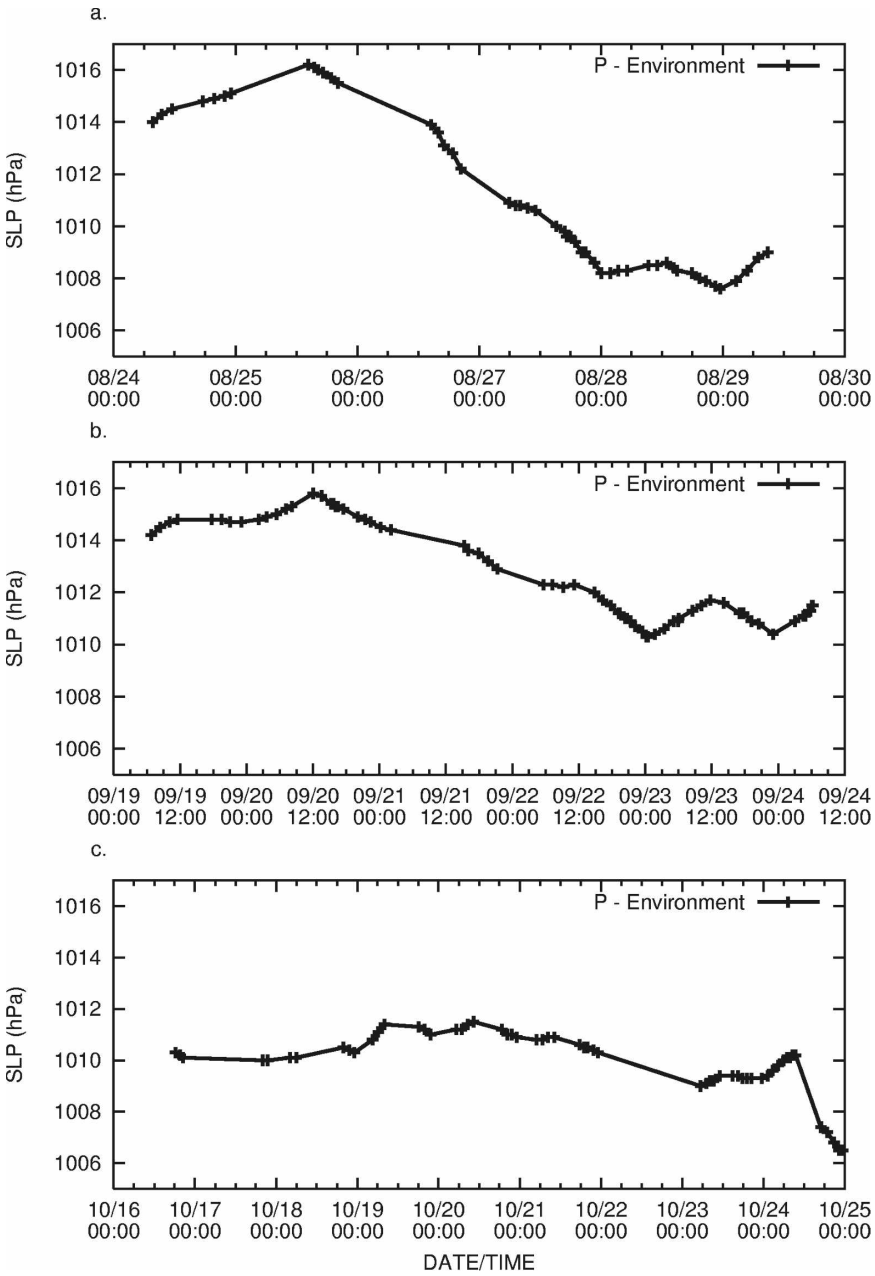

FIG. 2. The time series of environmental pressure (P − environment) for Hurricanes (a) Katrina, (b) Rita, and (c) Wilma. Environmental pressure is defined in KZ07 as the average value in an annulus between 800 and 1000 km from the center of a tropical cyclone.

or equal to 1013 hPa (Fig. 2a); eye diameters of 10–20 n mi (1 n mi = 1.852 km; Fig. 3a), which is less than the major hurricane average (Zehr and Knaff 2007); and a normalized size parameter close to the mean value (0.49) reported in KZ07 (Fig. 3a). During this period the NA D-WPR and KZ07 WPR provide good estimates of MSLP based on MSW (Fig. 1a). From approximately 1200 UTC 26 August until 0000 UTC 28 August the P_{env} drops from ~1013 to ~1008 hPa where it remains until Katrina makes landfall. During this time the storm also went through an eyewall replacement cycle (Knabb et al. 2005a), and the eye diameter grew from 10 to 30 n mi, which also remained fairly constant until landfall on 29 August. Following the eyewall replacement, the normalized size parameter increased dramatically, reaching a peak at 1200 UTC 28 August. Both the changes in TC size and in environmental pressure were accounted for in the KZ07 WPR,

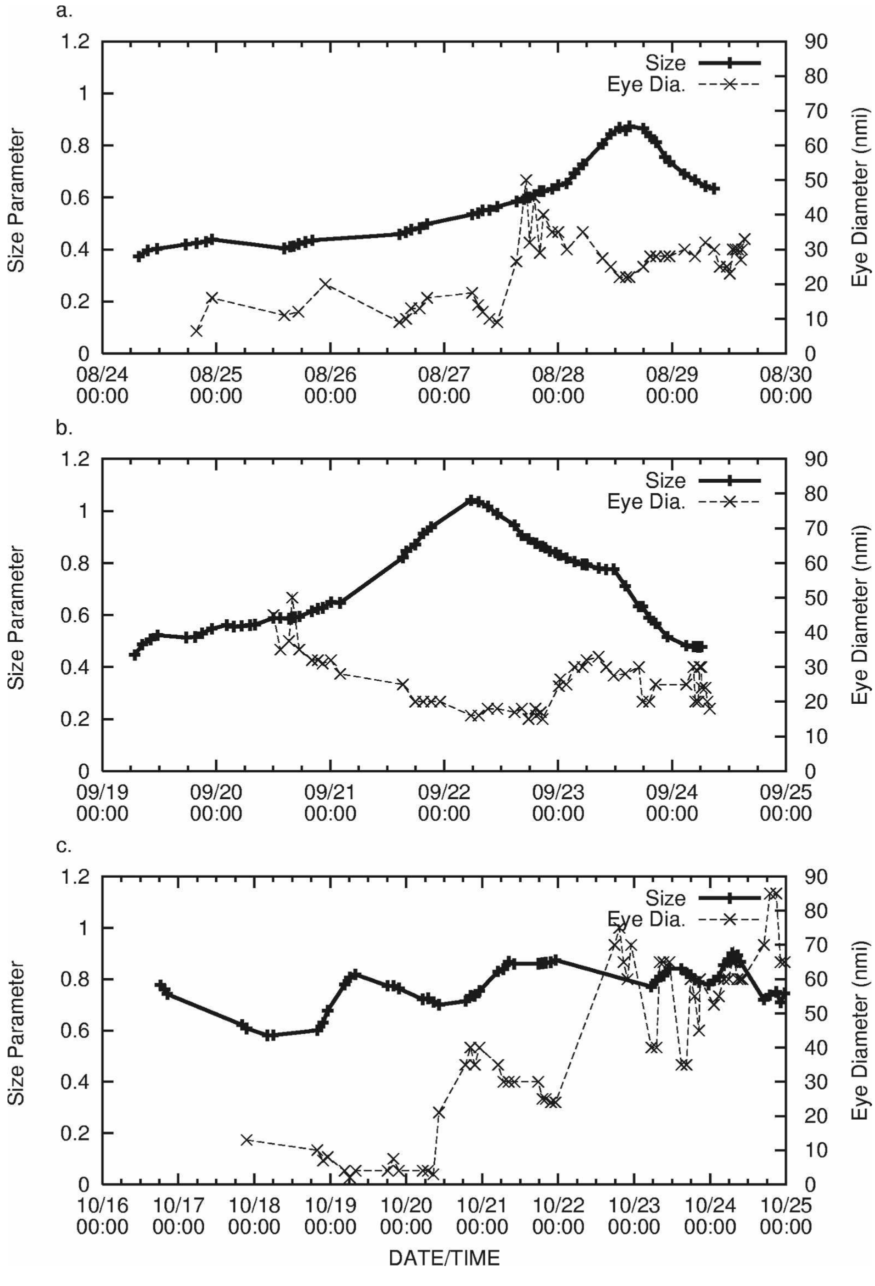

FIG. 3. The time series of the normalized tropical cyclone size parameter (Size) and of the reported eye diameter (Eye Dia.) for Hurricanes (a) Katrina, (b) Rita, and (c) Wilma. The normalized tropical cyclone size parameter is defined in KZ07 and the eye diameter comes from the values reported by reconnaissance aircraft. In the case of elliptical or concentric eyes, when two diameters are reported, the average is plotted.

which captured the MSLP trace prior to and at peak intensity of 150 kt at 1800 UTC on 28 August (Beven et al. 2008). As Katrina approached the coast, the normalized size parameter decreased, causing the KZ07 WPR to be biased high with respect to MSLP. The outer winds however did not decrease during this time as noted in Knabb et al. (2005a). This poor TC size estimation seems to be due to the use of wind speeds over land and is one of the lessons learned since the publication of KZ07, which is highlighted in section 6.

It appears that the NA D-WPR did an adequate job and the KZ07 WPR captured MSLP variations due to size and environmental pressure quite well. It is noteworthy that the WNP D-WPR creates superior estimates of MSLP only during the eyewall replacement cycle and just prior to landfall, rather than over a continuous long-lasting time period.

b. Hurricane Rita

The intensity evolution of Hurricane Rita was similar in many regards to that of Katrina. The MSLP estimates of the various WPRs are shown in Fig. 1b. The NA D-WPR and the KZ07 WPR show fairly good agreement with the observed pressure until about 1800 UTC 22 September. At this point, the observed MSLP agrees best with the WNP D-WPR, as pointed out in V08, which reported several MSLP and MSW observations including the following: 1) the 973 hPa reported at 2007 UTC 20 September with an estimated 88-kt MSW; 2) 898 hPa reported at 0538 UTC 22 September with a 154-kt MSW; 3) 927 hPa reported at 0831, 1007, and 1143 UTC 23 September with a 115-kt MSW; and 932 hPa reported at 0300 UTC 24 September with a 103-kt MSW, where MSW is interpolated from the 6-hourly best track. Indeed, report 1 agrees well with NA D-WPR, report 2 is closer to an average of WNP D-WPR and NA D-WPR, while reports 3 and 4 are best estimated by the WNP D-WPR. While the observations are interesting, there may be some physical reasons for the pressures in Rita remaining so low from 1800 UTC 22 September to landfall at ~1200 UTC 24 September.

The initial P_{env} on 19 September was close to the Atlantic mean reported in KZ07 and remained fairly constant until approximately 1200 UTC 20 September (Fig. 2b). From that point onward, P_{env} decreased slowly to values close to 1011 hPa on 23 September and remained at those values until landfall. Hurricane Rita also began as a fairly large TC and grew into an even larger TC. The normalized size parameter associated with this storm (Fig. 3b) shows Rita growing until ~22 September. After that time the size parameter indicates the storm was shrinking while a report (Knabb et al. 2005b) suggests the storm's outer wind field continued to expand. At the same time the surface winds, estimated and measured, suggested that the MSWs were weakening much faster than would be indicated by the pressure increase (Beven et al. 2008; Knabb et al. 2005b). For about 48 h prior to landfall, the outer winds increased, the eye diameter remained rather constant (~30 n mi), the MSW were observed to decrease from 155 to 100 kt, and the pressure increased from 897 to 935—only 38 hPa. The only physical explanation, one well supported by the observations, is that the wind field associated with Hurricane Rita was large and decreased rather slowly with increasing radius. It appears that the reason for the very low pressures was the size of the wind field associated with Rita as it approached the Texas coast.

To determine the poor performance of the KZ07 WPR during period 48 h prior to landfall, one only needs to examine the normalized size parameter and its assumptions. The normalized size parameter (Fig. 3b) did not accurately depict the size of Rita. The climatological model generally increases the outer wind profile as storms weaken and move north. This is accomplished by decreasing the size parameter x in Eq. (5) of KZ07 and increasing the radius maximum wind in Eq. (6) of KZ07. This was not the case in Hurricane Rita whose eye diameter remained fairly steady for the 48 h prior to landfall. Also noteworthy is the abrupt, exponential-like, decrease in the normalized size parameter as Rita approached land, which also occurred to a lesser extent with Hurricane Katrina. This again is likely due to using unrepresentative (of the gradient wind balance) near-surface wind estimates over the land areas located north and west of Rita.

c. Hurricane Wilma

In the case of Hurricane Wilma, the performance of NA D-WPR (Fig. 1c) was handicapped by the low P_{env} (Fig. 2c), which is more indicative of the reference value used in the western North Pacific. However, it is interesting to note that the overall performance of the NA D-WPR is similar to that of the WNP D-WPR for Wilma (Table 2). At the first time discussed in V08, 0433 UTC 19 October, the pressure is 901 hPa and the best-track intensity interpolated to that time is 143 kt, which corresponds to 894 hPa using the WNP D-WPR. The second data point mentioned in V08 is 0801 UTC 19 October, with a 884-hPa MSLP and a 153-kt best-track MSW estimate, which corresponds to a 881-hPa MSLP using the WNP D-WPR. So why during the period 0600 UTC 19 October through 1200 UTC 20 October did the WNP D-WPR appear to provide superior MSW estimate? Fig. 3c shows that Hurricane Wilma had a very small eye diameter (<7 n mi) during this time. Such conditions are uncommon. The major hurricane average eye diameter is 34 n mi with a standard deviation of 16 n mi (Zehr and Knaff 2007). In fact, Pasch et al. (2006) remarks that the observed 2 n mi eye diameter and coincident 882-hPa MSLP estimate in the best track are both climatological records for the North Atlantic Basin. This is the only time when the WNP D-WPR provides superior MSLP estimates. At approximately 1200 UTC 20 October, the eye diameter increased when an eyewall replacement ensued. The evidence suggests that the very low MSLP coincided with the period when the radius of maximum wind was anomalously small and thus the eye-to-eyewall pressure gradient very steep. Following the eye replacement, Wilma exhibited eye diameters that are more typical of very strong hurricanes (20–40 n mi) and the KZ07 WPR once again becomes the superior MSLP estimate. The observed small eye diameters provide a physically based explanation for why such low MSLPs were observed in Wilma and why the KZ07 WPR produced poor MSLP estimates during that time.

5. The methods of Knaff and Zehr are difficult to apply in operations

V08 and others in the operational TC forecasting community have suggested that the KZ07 methods are too difficult or require significant additional effort to apply in an operational setting. Such assertions are rather disheartening in that great care was given in the development of the KZ07 unified WPR equation to consider only those factors that could be easily measured in a modern TC forecast office. The KZ07 methods to estimate TC size and environmental pressure are quite different than the traditional measures of TC size such as radius of gales or an outer-closed isobar, but are quite easily calculated by hand and can easily be automated. As defined in KZ07, P_{env} can be measured directly from sea level pressure analyses with as few as four equally spaced observations at a radius of 900 km (8° latitude) from the TC center. Similarly, the tangential wind around a cyclone can be estimated from the surface wind fields, by simply averaging the cyclonic wind components at 500 km from the cyclone center; it would be easiest to make this calculation at four points that were north, east, south, and west of the TC center. The normalized TC size parameter can then be calculated on a hand calculator. Translation speed and latitude are routinely estimated. Once these factors are known, the calculation of MSLP or MSW is trivial using Eqs. (7) and (8) in KZ07. If one prefers, the tabular form can also be applied to create an estimate of MSLP as has been demonstrated in section 3.

6. Lessons learned

V08 brings up some simple oversights in our reporting as well as some interesting perspectives from an operational TC forecast center. Hopefully, the comments of V08 have been addressed and the KZ07 recommendations are better understood.

Since the publication of KZ07, various users have tried and applied our methods. Some have encountered difficulties applying our methodology. We now comment on some lessons learned during this process.

1) There is a desire by forecast centers to use quantities already routinely measured to estimate tropical cyclone size. Such quantities include the average radius of gales and the radius of an outer closed isobar. We did not anticipate this issue, but rather assumed that because digital surface analyses are readily available, that this more objective information would be desirable. Nonetheless there are ways that the KZ07 WPR can utilize other measures of TC size and environmental pressure. In this paper, we have suggested a way to use an isobaric measure of size. We have also worked with other groups and determined that the data in Fig. 8 of KZ07 could be utilized to estimate the parameter V500 from the radius of gales (R34), using an equation of the form V500 $\approx$ R34/9 $-$ 3 and applying a minimum of 0.2 to the normalized size parameter (S in KZ07) at lower latitudes. Another yet explored, and more preferable, option is a size measurement based on features available solely from IR imagery.
2) Because the KZ07 dataset did not contain any TCs equatorward of 10° latitude, there are some unforeseen problems in Eqs. (7) and (8) as provided by KZ07. Positive values of ΔP can occur for weak storms at low latitude (J. Courtney and D. Duncalf 2007, personal communications). Thus, those equations may not always be valid equatorward of 10° latitude. This was an oversight on our part and we are working to develop WPRs that perform well at very low latitudes. Preliminary results suggest that there is almost no pressure variation with latitude equatorward of ~15°. Using the data equatorward of 18°, we found that an equation of the form $\mathrm{MSLP} = 5.962 - 0.267V_{\mathrm{srm}} - (V_{\mathrm{srm}}/18.26)^2 - 6.80S + P_{\mathrm{env}}$, where V_{srm} and S are defined in KZ07, is a good compromise to Eq. (7) in KZ07 at these very low latitudes.
3) The estimation of V500 from the model fields can be biased low when the averaging annulus contains a large percentage of overland exposure. This effect is also evident in a few landfalling cases at higher latitude (~30° and poleward) in our dataset and those that occur in the boreal autumn rather than summer. Apparently, the low-level winds are reduced over land, but winds at a slightly higher level are not affected by the frictional boundary layer and result in the maintenance (via gradient wind balance) of lower MSLPs. As a result, the estimated MSLPs for some landfalling and near-land cases may be higher than observed. We will investigate the use of gradient-level wind fields for size estimation, but in the meantime, forecasters should be aware that the nor-

malized size parameter rarely decreases while a TC is slowly decaying.

The shortcomings discussed above are the foundation of future improvements to the KZ07 methodology. Specifically, future work will concentrate on efforts to estimate ΔP solely from routine satellite and operational information. It is also noteworthy that development of satellite-based and observation-based tropical cyclone diagnosis and forecast techniques are currently hampered by the lack of low-latitude tropical cyclone reconnaissance observations. We therefore suggest that a concerted national and international effort be explored to make quality TC reconnaissance fights in low-latitude areas where tropical cyclones form (e.g., western North Pacific, north of Australia).

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