Hurricane Wind–Pressure Relationship and Eyewall Replacement Cycles

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ABSTRACT

The relationship between minimum central surface pressure and the maximum sustained surface wind in tropical cyclones has been studied for many years, motivated by the fact that minimum pressure is generally easier to measure, but maximum wind is a much more relevant metric when considering tropical cyclone risk and potential impacts. It is well understood that tropical cyclone wind is closely related to the radial gradient of pressure through gradient or cyclostrophic balance assumptions, and not to a single point value of the minimum pressure near the storm center. But it is often the case that the maximum wind must be inferred from this single value. To accomplish this, a number of statistical relationships have been documented, such as those used in the Dvorak technique for estimating tropical cyclone intensity from satellite imagery. Here, the relationship between tropical cyclone maximum wind and minimum pressure is explored during eyewall replacement cycles (ERCs) that have been observed in North Atlantic hurricanes. It is shown that the wind–pressure relationship (WPR) can vary substantially during an ERC and generally moves away from the statistically fitted WPR used by the Dvorak technique in that basin. The changes in WPR during an ERC can be quite different depending on the intensity of the hurricane at the start of the ERC.

1. Introduction

Maximum sustained surface wind in the tropical cyclone eyewall is difficult to measure directly, even when low-level aircraft reconnaissance data are available, in part because the tropical cyclone wind field can be highly azimuthally variable (i.e., the wind can be far from axisymmetric) as well as highly variable in the vertical, and aircraft typically travel along radial legs at roughly fixed azimuths and altitudes (Kossin and Schubert 2001; Kossin and Eastin 2001; Franklin et al. 2003). The surface pressure field is generally less spatially variable (smoother) because it is related to the integral of the wind, and the minimum pressure is typically easier to locate near the storm center, particularly in hurricanes with eyes. The minimum pressure is also generally easier to measure using a variety of instruments such as dropwindsondes from aircraft (Franklin et al. 1988) or via hydrostatic integration of atmospheric temperature soundings estimated from satellites (Kidder et al. 2000). Minimum pressure can be used directly as a measure of hurricane intensity, but it is not as physically relevant as wind, which is the metric directly responsible for storm surge and, of course, wind damage. However, the tangential swirling wind at any distance from the storm center is most closely related to the local radial gradient of pressure through gradient or cyclostrophic balance assumptions, and not to a single point value of the minimum pressure near the storm center. Thus, there is not a one-to-one relationship between minimum central pressure in the eye and maximum wind in the eyewall, and empirical relationships and statistical fits are typically constructed to estimate wind from pressure (Knaff and Zehr 2007).

The tropical cyclone wind–pressure relationship (WPR) has been found to depend on a number of factors such as regional environmental climatology and storm latitude, size, and intensity (Kossin and Velden 2004; Brown et al. 2006; Knaff and Zehr 2007). The relationship between WPR and storm size in particular raises questions about WPR variability during tropical cyclone eyewall replacement cycles (ERCs) since ERCS are typically associated with large and rapid changes in storm size (Willoughby et al. 1982; Kossin and Sitkowski 2009, 2012; Sitkowski et al. 2011), as well as with marked changes in the radial pressure gradients within the eye and eyewall (Sitkowski et al. 2012). Here, WPR variability during ERC events in Atlantic hurricanes is
identified and documented, and a modified WPR is introduced that could potentially be applied, either operationally or in postmortem analysis, to post-ERC hurricanes.

2. Data and results

Using a large collection of low-level aircraft reconnaissance data, Sitkowski et al. (2011) documented 24 ERC events that were well sampled throughout their entire cycle by multiple aircraft sorties. They found that the evolution of the structure and intensity of the wind field during an ERC could be naturally divided into three distinct phases separated by four distinct points (Fig. 1). The beginning of an ERC (point 1) is identified by a persistent, coherent secondary wind maximum observed at flight level. This marks the beginning of the intensification phase (I) of the ERC. During this phase, both the primary (inner) and secondary (outer) wind maxima are increasing and contracting radially inward toward the storm center. During the weakening phase (II), which starts at point 2, the primary wind maximum decreases while the secondary maximum increases as it continues to contract. The end of the weakening phase (point 3) is identified when both wind maxima are equal. Beyond point 3, the outer wind maximum has exceeded the inner and has become the primary maximum. During the reintensification phase (III), the outer wind maximum continues to contract inward while intensifying. The ERC is completed (point 4) when there is no longer an observed inner wind (local) maximum.

The mean radii of maximum wind (RMW) at points 2 and 4 in Fig. 1 are 28 and 50 km, respectively (Sitkowski et al. 2011; Kossin and Sitkowski 2012), which demonstrates the rapid expansion of the wind field during an ERC. Additionally, Sitkowski et al. (2012) showed that the radial pressure gradient becomes flatter in the hurricane eye and steeper in the eyewall (near the RMW) as an ERC progresses, due in part to the persistence of high inertial stability near the eye center (referred to as a relict inner eyewall) and the influence that this has on the local transverse circulation patterns (Willoughby 1988; Schubert et al. 2007; Rozoff et al. 2008; Schubert and McNoldy 2010). The expansion of the wind field and changes in the pressure gradient can cause substantial changes in the WPR.

Differences in WPR between the beginning periods of an ERC (points 1 and 2 in Fig. 1) and the ending periods of an ERC (points 3 and 4) are shown in Fig. 2a [1 mb = 100 Pa; 1 knot (kt) = 0.51 m s⁻¹)]. Here, and in subsequent figures, maximum wind and minimum pressure are taken from the 6-hourly North Atlantic hurricane database (HURDAT) interpolated to the times at which points 1–4 occurred in each ERC event. These values are strongly influenced by the presence of low-level aircraft reconnaissance throughout each ERC but are somewhat smoother in time than the raw aircraft reconnaissance data.
At the beginning of an ERC (red points in Fig. 2a), the observed WPR tends to be near the WPR used by the Dvorak technique in the Atlantic (Dvorak 1975; Velden et al. 2006; Knaff and Zehr 2007). Toward the end of an ERC, however, there has been a clear migration of the WPR away from the Dvorak WPR (blue points in Fig. 2a) and toward a significant weak bias in the wind. That is, for a given minimum pressure the associated maximum wind is significantly weaker, in general, at the end of an ERC than at the start. Following Knaff and Zehr (2007), a second-order polynomial is fit to the values from points 1 and 2 (red dashed line) and from points 3 and 4 (blue dashed line) are shown. (b) Changes in WPR from point 1 (red) to 4 (blue). The WPR used by the Dvorak technique in the Atlantic is shown by the black dashed curves.

Table 1. WPR used by the Dvorak technique in the Atlantic and the observed best-fit WPR toward the end of an ERC.

<table>
<thead>
<tr>
<th>Max wind (kt)</th>
<th>Dvorak (Atlantic)</th>
<th>Post ERC</th>
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</thead>
<tbody>
<tr>
<td>65</td>
<td>987</td>
<td>982</td>
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<td>906</td>
<td>887</td>
</tr>
<tr>
<td>170</td>
<td>890</td>
<td>867</td>
</tr>
</tbody>
</table>

Fig. 2. (a) Contemporaneous max wind and min pressure around the start (red; points 1 and 2 in Fig. 1) and end (blue; points 3 and 4 in Fig. 1) of 24 Atlantic ERC events. The best quadratic fit to values from points 1 and 2 (red dashed line) and from points 3 and 4 (blue dashed line) are shown. (b) Changes in WPR from point 1 (red) to 4 (blue). The WPR used by the Dvorak technique in the Atlantic is shown by the black dashed curves.

At the beginning of an ERC (red points in Fig. 2a), the observed WPR tends to be near the WPR used by the Dvorak technique in the Atlantic (Dvorak 1975; Velden et al. 2006; Knaff and Zehr 2007). Toward the end of an ERC, however, there has been a clear migration of the WPR away from the Dvorak WPR (blue points in Fig. 2a) and toward a significant weak bias in the wind. That is, for a given minimum pressure the associated maximum wind is significantly weaker, in general, at the end of an ERC than at the start. Following Knaff and Zehr (2007), a second-order polynomial is fit to the values from points 1 and 2 (red dashed line in Fig. 2a) and from points 3 and 4 (blue dashed line). Utilizing the fit shown by the blue dashed line, a comparison of the Dvorak Atlantic WPR table (Dvorak 1975) and the WPR observed toward the end of an ERC is shown in Table 1. Knaff and Zehr (2007) fit the tabulated Atlantic WPR of Dvorak (1975) as \( P = aV^2 + bV + c \), where \( P \) is minimum surface pressure (mb), \( V \) is maximum sustained surface wind (kt), and \( (a, b, c) = (-0.0025, -0.36, +1021.36) \). The post-ERC WPR given by the blue dashed line uses \( (a, b, c) = (-0.0030, -0.39, +1019.85) \), which can be employed to expand Table 1 as needed.

As noted above, the WPR can vary with the latitude of the storm center. Since hurricanes tend to track westward and northward in the Atlantic, this can also contribute to the changes shown in Fig. 2a, as the storms will generally move north during the duration of an ERC. However, the mean latitude at the start (point 1) and end (point 4) of the 24 ERC events considered here differ by only 2° (21° and 23°N, respectively), and the difference is not statistically significant. This suggests that it is the change in storm structure during an ERC, and not the environment, that causes the WPR to change.

The migration of the WPR observed from point 1 to 4 in Fig. 1, for each of the 24 ERC events, is shown in Fig. 2b. It is seen that, during some events, the migration is roughly parallel to the Dvorak WPR curve. That is, storm intensity varies, but the WPR follows near the climatological WPR documented in Dvorak (1975). Most events, however, cause a significant deviation away from the Dvorak WPR. Another interesting feature seen in Fig. 2b is an apparent separation between WPR changes in storms that begin an ERC with maximum winds less than around 100 kt and those that begin at greater than 100 kt. The weaker hurricanes typically intensify during the ERC, while the stronger hurricanes typically weaken. The mean WPR change from the beginning periods of an ERC, based on averaging the values at points 1 and 2 in Fig. 1, to the ending periods, based on averaging the values at points 3 and 4, is shown in Fig. 3 for hurricanes that begin the ERC with maximum winds under 100 kt and for those that begin the ERC at greater than 100 kt.
Around the start of an ERC, both the weaker and stronger hurricanes have a mean WPR close to the Dvorak WPR, but both exhibit a weak bias in the maximum wind. The weaker hurricanes have a mean maximum wind around 7 kt less than would be assigned by the Dvorak WPR based on the mean minimum pressure, and the stronger hurricanes have a mean maximum wind around 4 kt less. At the end of an ERC, the mean WPR for both the weaker and stronger hurricanes has moved farther from the Dvorak WPR, and the weaker hurricanes have a mean maximum wind around 4 kt less. At the end of an ERC, the mean WPR for both the weaker and stronger hurricanes has moved farther from the Dvorak WPR, and the weaker hurricanes have a mean maximum wind around 17 kt less than would be assigned by the Dvorak WPR based on the mean minimum pressure, while the stronger hurricanes have a mean maximum wind around 14 kt less. On average, the weaker hurricanes intensify by only 8 kt while their central pressures decrease by 15 mb, and the stronger hurricanes weaken by 10 kt while their central pressures increase by only 2 mb.

### 3. Summary and discussion

Eyewall replacement cycles (ERCs) can have a rapid and substantial effect on the wind–pressure relationship (WPR) in hurricanes. This is caused by the expansion of the radius of maximum wind and changes in the radial pressure gradient in the eye and eyewall during an ERC. During the evolution of an ERC, the WPR migrates, on average, away from the climatological WPR used by the Dvorak technique and toward weaker maximum wind for a given minimum pressure. This is found to be true for all hurricanes considered here, although the migration of the WPR during an ERC is quite different for hurricanes that begin an ERC with intensity less than about 100 kt versus hurricanes that begin an ERC with intensity greater than 100 kt. On average, the weaker hurricanes intensify by only 8 kt while their central pressures decrease by 15 mb, and the stronger hurricanes weaken by 10 kt while their central pressures increase by only 2 mb. A modified WPR that can be applied to hurricanes that have undergone an ERC is provided in Table 1, which can be expanded as needed using the polynomial coefficients provided above.

There are a number of implications of these results. For example, when aircraft reconnaissance data are not available following an ERC, it is likely that operational satellite-based Dvorak technique intensity estimates will overestimate the maximum wind speed. For hurricanes that make landfall after an ERC, postmortem wind assessments that use available land-based surface pressure measurements and existing WPRs may also overestimate wind speed. A caveat to the results presented here is that they are based on a limited sample size. The requirement that each phase of each ERC be observed by low-level aircraft reconnaissance results in only 24 ERC events, and the second-order polynomials shown in Fig. 2a are fit using only 48 points each. This makes the values in Table 1, and particularly the extrapolated values (i.e., maximum wind >150 kt), somewhat uncertain. As data continue to be collected, however, it is likely that individual ERC events will occasionally be well sampled during their evolution, as in the events used here, and the sample size is expected to increase in time.

It is unclear how closely the results presented here would apply to tropical cyclones in other ocean basins. There are comparatively few ERCs observed in the eastern North Pacific (Kossin and Sitkowski 2009) but ERCs are quite common in the western North Pacific and have been observed in the Southern Hemisphere (Hawkins et al. 2006). Western North Pacific tropical cyclones, in particular, can experience a dramatic expansion of the eyewall during an ERC that is much greater than observed during Atlantic ERCs (Lander 1999). It seems quite plausible that a greater expansion would cause the post-ERC WPR to deviate further from the mean WPR, leading to even greater potential for overestimation of the maximum winds. Testing this will be a challenge though, as it will require efforts to compile the necessary data in a region where aircraft data are only occasionally collected.

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REFERENCES


