

Adapting the Knaff and Zehr wind-pressure relationship for operational use in Tropical Cyclone Warning Centres

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A methodology to implement a new operational mean sea-level pressure versus maximum mean near-surface wind relationship (hereafter wind-pressure relationship) based on a modified version of the approach recently developed by Knaff and Zehr is presented. This method incorporates latitude, size, storm motion and environmental pressure. In this formulation tropical cyclone size is expressed in terms of the radius of gales, environmental pressure is expressed in terms of the pressure of the outer closed isobar – parameters that are already routinely available in the operational setting. The resulting wind speed is also converted from a one-minute mean to a ten-minute mean. In addition, a correction is introduced for a weakness in the original Knaff and Zehr formula for storms located at low latitudes.

The resulting algorithm is able to be integrated into the operational software to assist in the efficient calculation of the central pressure. Other Tropical Cyclone Warning Centres are encouraged to use this derivation. The new approach also presents the potential to reanalyse past tropical cyclone events to create a more homogeneous data-set. Some historical variations in intensity derivation in the Australian region are also presented.

Differences between Atlantic basin best-track reconnaissance data and Dvorak-based data relied upon in other tropical cyclone basins result in some biases associated with the determination of the maximum wind. Dvorak-derived maximum wind corresponds well with the reconnaissance-derived maximum wind for non-weakening systems with intensities associated with Dvorak current intensity (CI) numbers of 3.5 and higher (i.e. greater than ~50 knots). At weaker intensities the Dvorak intensity underestimates the maximum wind. As a result the calculated pressure via a wind-pressure relationship, which is strongly influenced by reconnaissance-based intensity estimates, may result in higher pressures than is actually the case.

Introduction

The issue of the relationship between the central mean sea-level pressure (P_c) and maximum mean near-surface wind*

(the wind-pressure relationship, hereafter WPR) in a tropical cyclone (TC) has been the subject of ongoing debate for many decades and a number of relationships have been developed during this period. This is demonstrated by the fact that the three Australian Tropical Cyclone Warning Centres (TCWCs) have each used a different WPR: Perth used the method of Atkinson and Holliday (1977) (hereafter A&H), Darwin used Love and Murphy (1985) (hereafter L&M) and Brisbane used a method based upon an unpublished study

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* Throughout this paper, 'wind' refers to the mean wind at a standard 10 metre elevation above the ocean surface. The averaging period of 1 minute or 10 minutes is specified.

by Crane, circa 1985, as discussed in Harper (2002). These are different again from the Dvorak Atlantic (Dvorak 1975) used in the Atlantic and central and eastern Pacific by the US National Hurricane Center (NHC) and Central Pacific Hurricane Center, and the Koba et al. (1991) method used in the northwest Pacific by the Tokyo Regional Specialized Meteorological Center (RSMC). La Reunion RSMC use A&H while Fiji RSMC applies the Crane method consistent with the Brisbane TCWC. These WPRs were based on data-sets of varying quality in different basins to arrive at a unique value of the wind for a particular pressure deficit.

Existing approaches to determine P_c involve lookup tables based on the A&H (Perth), L&M (Darwin) and Crane (Brisbane) methods combined with estimates of environmental pressure. In the case of Crane, this has the added criterion of assessing whether a TC is 'small' or 'average' with the potential for a marked shift in estimates when there is a change between the two.

Harper (2002) provided a comprehensive review into the various WPRs and advocated a standard approach making several recommendations in consideration of its development. For reasons of consistency alone there has long been the need to standardise the approach to the WPR issue amongst TCWCs.

The current WPRs are primarily based on the pioneering work of Dvorak (1972, 1973, 1975, 1982, 1984, 1995) that began in the early 1970s. Aside from the development of WPRs, Dvorak developed a technique to assess cyclone intensity. Cyclone intensity is given by the current intensity (CI) estimates that can be determined subjectively or objectively us-

ing both visible and infrared satellite imagery. The CI , which ranges from 1.0 to 8.0 is then directly related to a wind speed. The wind speeds assigned to each CI and the corresponding lookup tables from the various TCWCs are shown in Table 1. The Dvorak method has withstood the test of time and to this day remains the primary intensity analysis tool as documented in Velden et al. (2006), especially in basins without aircraft reconnaissance information. Even with the advent of other observing methods, it has proven remarkably robust (e.g. Guard 2004) with relatively minor alterations (e.g. Brown and Franklin 2002, 2004) being made to its practice.

The variation in the application of the Dvorak technique and the use of different methods to estimate winds given an observed pressure has contributed to significant systematic inconsistencies in historical tropical cyclone best track intensities. This inhibits any meaningful study of historical intensity changes, an issue that is important for planning and climate change investigations in particular. It is also an issue for storm surge calculations for forecasting and mitigation measures.

The Knaff and Zehr wind-pressure relationship

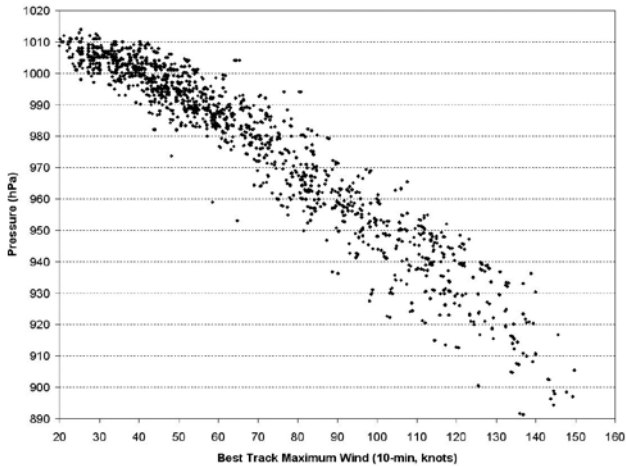
The most accurate central pressure and maximum wind data upon which to develop a WPR is the recent Atlantic best track data based upon aircraft reconnaissance, particularly since GPS dropwindsondes were introduced. Figure 1 shows a plot of the maximum winds and minimum pressure from

Table 1. Dvorak CI numbers, maximum winds and ΔP values corresponding to the various wind-pressure relationships used by TCWCs.

<i>Dvorak</i>	<i>Maximum Wind (knots)</i>		<i>ΔP (hPa)</i>				
	<i>One-Minute</i>	<i>Ten-Minute</i>	<i>A&H</i>	<i>L&M</i>	<i>Crane (large)*</i>	<i>Crane (small)*</i>	<i>Dvorak Atlantic*</i>
2.0	30	26	-10	-10	-11	-11	-7
2.5	35	31	-13	-13	-13	-13	-11
3.0	45	40	-19	-19	-20	-20	-16
3.5	55	48	-26	-25	-25	-25	-22
4.0	65	57	-34	-31	-30	-30	-29
4.5	77	68	-44	-38	-45	-35	-37
5.0	90	79	-56	-46	-58	-40	-46
5.5	102	90	-69	-54	-73	-53	-56
6.0	115	101	-83	-62	-85	-65	-68
6.5	127	112	-96	-70	-90	-70	-81
7.0	140	123	-112	-80	-110	-90	-95
7.5	155	136	-131	-90			-110
8.0	170	150	-152	-100			-126

*Based on an environmental pressure of 1016 hPa (Dvorak Atlantic) and 1010 hPa (Crane).

Fig. 1 Scatter diagram of the maximum ten-minute mean wind versus the minimum pressure from reconnaissance-based best track data, Atlantic basin, 1998-2007.



reconnaissance-based best track data in the North Atlantic from 1998 to 2007. The plot shows considerable variation about a line of least-squares best fit as discussed in Brown et al. (2008). With such scatter it should come as no surprise that WPRs based upon more limited datasets would arrive at different WPR formulations.

The challenge to formulate a new approach to the WPR issue was undertaken by Knaff and Zehr (2007) (hereafter K&Z). They used sixteen years of information (1989-2004) in the North Atlantic and Central and East Pacific basins including aircraft reconnaissance data, National Hurricane Center’s best track estimates and numerical weather prediction (NWP) analysis fields from the National Centers for Environmental Prediction (NCEP). Minimum sea-level pressure was estimated from aircraft reconnaissance or measured from dropwindsondes, and maximum wind speeds were interpolated from best track maximum one-minute wind speed estimates. The aircraft data were collected primarily in the Atlantic but also include eastern and central North Pacific cases. This represented the most accurate assemblage of data to date to assess the WPR issue.

Five factors were identified to account for the scatter: environmental pressure, storm motion, latitude, size and intensity trend. However, intensity trend did not add to the skill when latitude and size were included as predictors and was not used further. A unified WPR to predict the minimum pressure (P_c) was derived using a multiple regression approach to arrive at the following equation:

$$P_c = 23.286 - 0.483V_{srm1} - \left(\frac{V_{srm1}}{24.254}\right)^2 - 12.587S - 0.483\Phi + P_e \quad \dots 1$$

where, V_{srm1} is the one-minute mean maximum winds adjusted for storm motion in knots,

$$V_{srm1} \approx V_{max1} - 1.5C^{0.63} \quad \dots 2$$

where V_{max1} is the one-minute mean maximum wind in knots and C is storm motion in knots.

S is related to storm size using NWP-derived parameters and is a function of latitude and the maximum wind:

$$S = \frac{V500}{V500_c} \quad \dots 3$$

where $V500$ is the tangential wind in the 400-600 km annulus in knots, $V500_c$ is the climatological tangential wind 500 km from the centre in knots

Φ is latitude, and P_e is the environmental pressure. K&Z also derived a separate equation to estimate V_{max1} given P_c .

In addition K&Z provide background material on current WPRs used in TCWCs including those in Australia (see Fig. 2) and discusses limitations on the current array of relationships. Verification data showed that the Dvorak Atlantic relationship performed reasonably well on the data-set, a conclusion supported by Brown et al. (2008), and the L&M WPR was valid for small, low latitude systems. However, the K&Z WPR proved superior to any of the existing WPRs being used including the three methods used in the Australian region. In particular it was noted that A&H WPR was unsupported by the data. K&Z showed that P_c can be estimated from the maximum wind within 5-6 hPa and the wind can be estimated from the P_c within 7-8 knots. The K&Z WPR was also successfully tested with data from the 2005 Atlantic season.

Other contemporary approaches

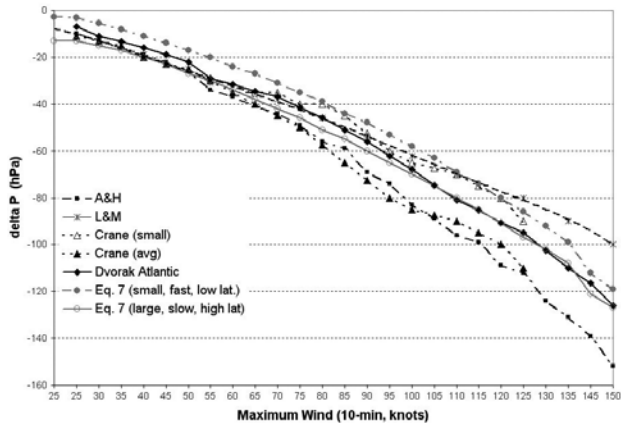
The Weber wind-pressure relationship

Weber (2008) devised a WPR model using 2000-2004 global operational TC advisory (ATCF) data from the Joint Typhoon Warning Center using position, central pressure, maximum wind, radius of maximum winds, radius of gales, and the radius and pressure of the outer closed isobar (POCI). This approach was able to account for some of the spread in the maximum wind-central pressure plot, and was able to produce estimates of all the above TC parameters for a given pair of size and intensity parameters. This approach also has the added advantage of considering the radius of maximum wind in the WPR calculation. However, the quality of the originating data is inferior to the Atlantic best track dataset and at the time of writing this method was not available for operational use. Further testing would be required to assess whether there is any added skill over the Knaff and Zehr approach.

The Holland wind-pressure relationship

Holland (2008) proposed an alternative WPR model based upon a Dvorak CI -to-pressure-to-wind approach on the basis that pressure is a more ‘robust’ parameter having less scatter than the wind. Certainly, this approach has merit on scientific grounds, particularly where pressure observations are reliably observed and estimated, as in the case where

Fig. 2 Comparison of wind-pressure relationships: Atkinson and Holliday; Love and Murphy; Crane (small and average); Dvorak Atlantic; and Eqn 7 for a small ($R_{34} = 60$ nm), fast moving (15 knots), and low latitude (12°) TC; and for a large ($R_{34} = 150$ nm), slow moving (5 knots), and high latitude (25°) TC.



dropsonde or reconnaissance data are available. In a similar manner to the operational application of the K&Z WPR discussed later, the Holland WPR could also be implemented via an algorithm in operational software. However, operational warning centres adopt a wind-to-pressure approach and, until such time as there is general agreement amongst the centres to change to a pressure to wind approach, it would be unnecessarily complicating matters even further should a warning centre adopt the Holland approach. Furthermore, from an operational perspective it is not desirable to have the maximum wind fluctuate on short time-scales especially if that results in fluctuating cyclone categories for a constant *CI*.

Operational application of the Knaff and Zehr WPR

The demonstrated superiority of the K&Z WPR over other WPRs in the Atlantic basin suggests that it should be considered as the operational WPR used by TCWCs not just in the Atlantic but in other basins. There are a number of factors to consider before this can be done.

Size

The size parameter *S* in Eqn 1 is from NWP-derived parameters that are not readily available in operations. Appendix B in K&Z tabulates more useful operational values comparing the Dvorak *CI* against ΔP (the difference between the central pressure P_c and the environmental pressure P_e) for low latitude ($\Phi = 15^\circ$), ‘mid’ latitude ($\Phi = 25^\circ$) and ‘high’ latitude ($\Phi = 33^\circ$) using small, medium and large systems.

Given that the radius of gales (R_{34}) is a key size parameter estimated for operational requirements, the size was expressed in terms of R_{34} with units of nautical miles (nm) for three different latitude bands.

0-20° : Small $R_{34} < 55$ nm, large $R_{34} > 110$ nm

20-30° : Small $R_{34} < 60$ nm, large $R_{34} > 120$ nm

30°+ : Small $R_{34} < 70$ nm, large $R_{34} > 140$ nm

For operations this would require a total of nine lookup tables to account for the three sizes across three latitude bands. However, it is preferable to have a single formula approach to deriving the central pressure.

Using models from the Global Forecast System (GFS), National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) reanalysis and the Navy Operational Global Atmospheric Prediction System (NOGAPS), the model-estimated V_{500} can be related to the radius of gales via:

$$V_{500} = \frac{R_{34}}{9} - 3 \quad \dots 4$$

where R_{34} is in nm

and from K&Z

$$V_{500} = V_{max1} \left[\frac{(66.785 - 0.09102V_{max1} + 1.0619(\Phi - 25))^{(0.1147 + 0.0055V_{max1} - 0.001(\Phi - 25))}}{500} \right] \quad \dots 5$$

However, for systems below gale force intensity V_{500} goes to -3 and the *S* value is negative causing erroneous pressure values. Similarly for small TCs *S* can also become negative. Examining tropical lows and small systems showed that *S* is approximately 0.4. Hence a minimum value for *S* of 0.4 is used.

Maximum wind

K&Z expresses the maximum wind as a one-minute mean, consistent with practices in the USA. However, the maximum wind is expressed as a ten-minute wind in other areas outside the North Atlantic and Central and East Pacific basins including the Australian region. The standard conversion (Bureau of Meteorology 1978; Sampson et al. 1995) is:

$$V_{max10} = 0.88V_{max1} \quad \dots 6$$

In a preliminary report into wind speed time averaging conversions for tropical cyclones, Harper et al. (2008) recommend that the open sea conversion factor from one-minute to ten-minute winds be 0.93. If this was to be adopted then the ten-minute winds derived via the Dvorak process would be about five per cent higher than current values. Until such time as this becomes the accepted practice, the current standard 0.88 conversion factor should be used.

Low latitudes

For low latitude systems the calculated difference between P_C and P_e , (ΔP) using Eqn 1 approaches zero or changes sign. Unfortunately the Atlantic data-set has few systems equatorward of 10° . To overcome this problem a separate equation was developed that better reflected the scatter in pressure and wind equatorward of 18° .

Hence, the modified version of Eqn 1 can be expressed as the following:

For $\Phi < 18^\circ$

$$\Delta P = 5.962 - 0.267 V_{srm1} - \left[\frac{V_{srm1}}{18.26} \right]^2 - 6.8 S \quad \dots 7a$$

For $\Phi > 18^\circ$

$$\Delta P = 23.286 - 0.483 V_{srm1} - \left(\frac{V_{srm1}}{24.254} \right)^2 - 12.587 S - 0.483 \Phi \quad \dots 7b$$

where V_{srm1} is expressed in terms of V_{max10} and C from Eqns 2 and 6. S is in terms of R_{34} , V_{max10} and Φ from Eqns 3, 4, 5 and 6 and has a minimum value of 0.4.

Table 2 is a sample lookup table for ΔP based on the combination of Eqns 2 to 7 (hereafter abbreviated as Eqn 7) with varying values of intensity, latitude, radius of gales and motion. As there are multiple variables, it is difficult to plot Eqn 7 against other WPRs. Given that a greater ΔP is determined from high values of R_{34} and latitude and a low value of storm motion, indicatively small and large ΔP plots are shown in Fig. 2 using the following inputs to Eqn 7:

- (a) small ($R_{34} = 60$ nm), fast moving (15 knots), and low latitude (12°); and
- (b) large ($R_{34} = 150$ nm), slow moving (5 knots), and high latitude (25°).

This shows that A&H and Crane (average) lie outside the two Eqn 7 plots. Equation 7(a) has a noticeably smaller ΔP , particularly at the weaker end of the scale. For intense systems, where the maximum wind exceeds 110 knots (57 m s^{-1}), L&M has the smallest ΔP .

Validating against Australian data

To assess the validity and promote acceptance of this method in the Australian region, Eqn 7 was tested on available Australian data. The details of the limited sample from seven TC events are given in the Appendix. A key issue with all of these cyclone events is whether observations captured the maximum wind and the minimum central pressure. For example, the pressure gradients near the centre can be high, e.g. measured at 5.5 hPa/km in TC *Tracy*, while it is unlikely that a single anemometer can capture the maximum wind, especially if it is not sampling continuously.

The calculated central pressures for all seven TCs is higher than the observed pressures, although for six of these events the difference ranges from just two to seven hecto-

Table 2. Sample lookup table for ΔP based on Eqn 7 with varying values of intensity, latitude, radius of gales and motion. The A&H ΔP is added for comparison purposes. Winds are rounded to the nearest five.

CI	Latitude	R_{34} nm	ΔP (Eqn 7) hPa		ΔP (A&H)
			motion 5 knots	motion 15 knots	
1.0	12	60	-2.8	-1.3	
		150	-8.5	-8.8	
		60	-3.4	-1.2	
1.5	12	150	-12.8	-13.8	
		60	-5.0	-3.3	
		150	-9.3	-8.6	
2.0	25	60	-6.6	-4.2	
		150	-13.3	-12.8	
		60	-5.0	-3.3	
2.5	12	150	-9.3	-8.6	
		60	-6.6	-4.2	
		150	-13.3	-12.8	-10
3.0	25	60	-7.4	-5.6	
		150	-10.8	-9.6	
		60	-9.8	-7.4	-13
3.5	12	150	-15.0	-13.7	
		60	-13	-11	
		150	-15	-14	-19
4.0	25	60	-17	-14	
		150	-20	-18	
		60	-19	-17	
4.5	12	150	-21	-19	
		60	-24	-21	-26
		150	-27	-24	
5.0	25	60	-23	-20	
		150	-24	-22	
		60	-28	-25	-34
5.5	12	150	-30	-28	
		60	-34	-31	
		150	-36	-33	-44
6.0	25	60	-40	-37	
		150	-42	-39	
		60	-42	-39	
6.5	12	150	-44	-41	
		60	-49	-45	-56
		150	-51	-47	
7.0	25	60	-52	-48	
		150	-54	-50	
		60	-58	-54	-69
7.5	12	150	-60	-56	
		60	-62	-58	
		150	-64	-60	-83
8.0	25	60	-67	-64	
		150	-70	-66	
		60	-73	-69	
8.5	12	150	-76	-71	
		60	-77	-73	-96
		150	-80	-76	
9.0	25	60	-91	-86	
		150	-94	-90	
		60	-93	-89	-112
9.5	12	150	-97	-92	
		60	-103	-99	
		150	-108	-103	-131
10.0	25	60	-104	-100	
		150	-108	-104	
		60	-124	-119	
10.5	12	150	-130	-124	
		60	-121	-117	-152
		150	-127	-122	

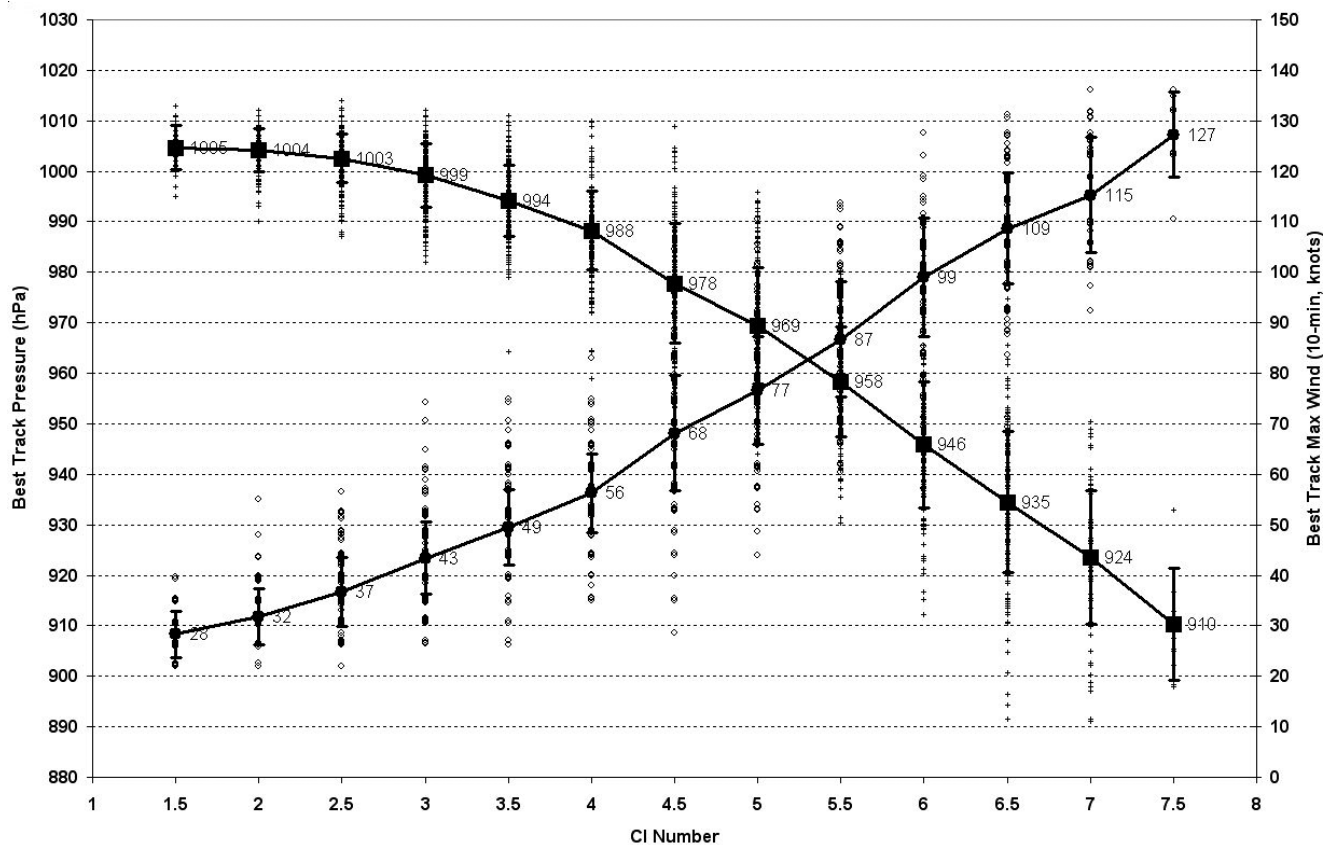
pascals (hPa). This is within the bounds of the defined accuracy of the K&Z WPR. While these data may suggest a modification to the formula given the consistent positive bias, a more likely reason for the discrepancy is the likelihood that the maximum wind is higher than the observed values given the limitations of the observations.

Tropical cyclone *Orson* demonstrates the greatest difference, the observed pressure of 905 hPa being considerably less than the calculated 935 hPa from Eqn 7 based on a maximum wind of 105 knots (54 m s^{-1}), reduced from an observed wind of 121 knots (62 m s^{-1}) at a height of 36.4 m. While this suggests that for large and intense systems A&H may be superior to K&Z, caution is warranted in making conclusions based upon a single event as evidenced by the scatter in Fig. 1. Similarly large differences were also found with Atlantic hurricanes *Wilma* and *Rita* in 2005, which is further elaborated upon in Knaff and Zehr (2008), and also in hurricane *Ike* in 2008. As suggested by K&Z, the consideration of radius of maximum winds (RMW) in a regression equation could improve the WPR to account for cases such as these.

Calculations of the maximum wind (Dvorak)

As noted, the maximum wind is primarily derived from the Dvorak technique in basins without aircraft reconnaissance information. It is of interest to determine whether the maximum wind determined from aircraft reconnaissance correlate with the Dvorak-derived maximum wind. Figure 3 shows the scatter of Atlantic 1998-2007 best track maximum wind and pressure against the operational Dvorak estimates from the Satellite Analysis Branch (SAB), Tropical Analysis and Forecast Branch (TAFB) and US Air Force Weather Agency (AFWA) whenever there was a reconnaissance within three hours of the fix. The statistics of these data are shown in Table 3 and they highlight the considerable scatter in both pressure and wind for Dvorak CI categories. Certainly, a significant amount of this scatter may be accounted for by considering the limitations of the Dvorak technique as summarised in Velden et al. (2006). While some of this scatter may be a result of inaccuracies in the operational Dvorak assessment, it is a realistic picture of the variations in inten-

Fig. 3 Comparison of Atlantic (1998-2007) aircraft reconnaissance pressure and best track maximum wind (ten-minute) against Dvorak CI number. Crosses indicate pressures and circles indicate wind speeds. The mean wind and pressure with associated standard deviation as error bars are also displayed.



sity based on the Dvorak method in the operational environment. Were it to be readily available, incorporating the environmental pressure to provide a ΔP would also likely reduce the scatter in the pressure somewhat.

The scatter in the maximum wind is only marginally greater than that of pressure, and is actually less at Dvorak *CI* of 4.5 and higher (c.f. Table 1). For example for a *CI* of 4.0, the maximum ten-minute wind ranges from 35 to 83 knots (18–43 m s⁻¹), averaging 56 knots (29 m s⁻¹) with a standard deviation of 7.8 knots (4.0 m s⁻¹) while the pressure ranges from 959 to 1010 hPa averaging 988 hPa with a standard deviation of 7.8 hPa. The following discussion will show results based solely on ten-minute maximum winds.

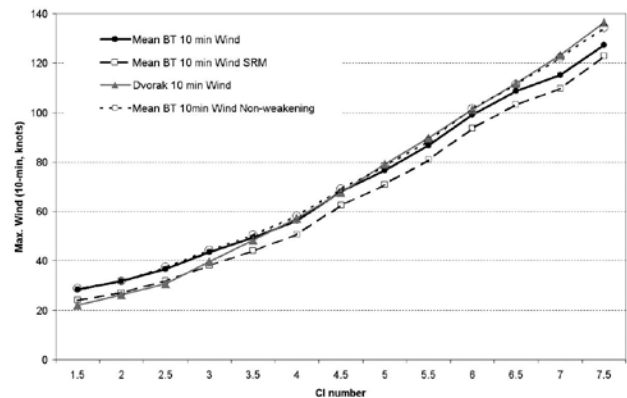
Many previous studies (e.g. Harper 2002; Velden et al. 2006; Holland 2008) have noted the deviations from observations of Dvorak-derived maximum winds. In a comparison of three years of Atlantic best track and reconnaissance data, Harper (2002) concluded that there is evidence of a systematic overestimation of the maximum wind in the Atlantic best track data-set as a direct result of Dvorak intensity influence, a claim supported by Holland (2008) particularly for intense TCs. Using a more homogeneous and representative sample, Brown and Franklin (2002, 2004) compared Dvorak estimates with reconnaissance-based best track data. Their results indicated that Dvorak-estimated winds were lower by about 3 to 5 knots (1.5–2.6 m s⁻¹) for tropical cyclones with maximum winds of 65 knots (34 m s⁻¹) or less.

Figure 4 shows the mean best track maximum wind, storm relative maximum wind (SRM) and maximum wind for non-weakening cases, plotted against the Dvorak *CI* number based on the Atlantic best track 1998–2007. This shows that the best track winds are consistent with the Dvorak maximum wind for intensities of *CI* 3.5 to 6.5 but are higher for intensities of *CI* 3.0 and less, and lower at the other end of the scale at *CI* 7.0 to 7.5.

Brown and Franklin (2002, 2004) also found a slight high bias in the Dvorak estimates of slow-moving TCs and a low bias for fast moving TCs. Holland (2008) claims that Dvorak underestimates the impact of translation on intensity, causing an underestimate of wind that is most apparent for weaker TCs. The mean storm motion shown in Table 3 shows that the average storm motion is slower at weaker intensities – 7–9 knots at *CI* 1.5–3.0 compared to 10–11 knots at *CI* >3.5. However, the relative contribution of storm motion to the maximum wind is still significant at the weaker end of the intensity scale. When the maximum wind was calculated relative to storm motion, the bias in the mean was removed at low intensities, although this introduced a low bias in the best track estimates at remaining intensities, as shown in Fig. 4.

Brown and Franklin (2002) demonstrated that the intensities of weakening TCs are overestimated by the Dvorak technique by about 5 to 6 knots (~3 m s⁻¹) suggesting that the Dvorak *CI* constraint to hold the *CI* number for 12 hours during initial weakening is too limiting during a TC's weakening phase. Subsequently TCWCs have introduced more lenient constraints during this phase. As shown in Fig. 4, removing

Fig. 4 Comparison of Atlantic (1998–2007) mean best track (BT) maximum wind, BT storm-relative maximum wind, BT maximum wind for non-weakening cases and Dvorak maximum wind. All winds are presented in a ten-minute format.



the weakening cases removes the high bias of the Dvorak estimates at intensities of *CI* 7.0 to 7.5. Holland (2008) may have revised his conclusion that the Dvorak technique overestimates maximum winds had this been considered.

Indeed the mean best track maximum winds for non-weakening TCs demonstrate remarkable agreement with the Dvorak maximum wind at all *CI*s of at least 3.5. This agreement may appear suspicious and undoubtedly, there is some 'contamination' in that analysts have access to reconnaissance data when making operational Dvorak estimates, thereby creating an artificial bias. Also, as suggested by Harper (2002) and Holland (2008), the Dvorak estimate can be applied to determine the best track maximum wind even when aircraft reconnaissance is available. However, as commented by Brown and Franklin (2004), themselves NHC forecasters responsible for performing best track analyses, Dvorak intensity estimates are not relied upon when reconnaissance data are present.

Of particular interest for the present study is the underestimation of the Dvorak ten-minute mean maximum wind at weaker intensities (i.e. *CI* ≤ 3.5). The average best track maximum wind for a *CI* value of 2.5 is 37 knots (19 m s⁻¹), an increase of 6 knots (3 m s⁻¹) from the standard Dvorak-derived wind. That systems, on average, are at gale force intensity for a *CI* of 2.5 has significant implications for TCWC operations and would affect the number of named TCs, introducing a bias in best track numbers.

Koba et al. (1991) in a study of typhoons from 1981 to 1986 also concluded that the Dvorak Method underestimated the intensities of weak tropical cyclones. Those findings led to the Japanese Meteorological Agency (JMA) adopting an alternative Dvorak scale where tropical cyclone intensity (ten-minute mean wind of less than 34 knots (18 m s⁻¹)) is assigned from a *CI* of 2.5 rather than 3.0 as is the practice in other TCWCs.

Table 3. Atlantic 1998-2007 tropical cyclone best track (BT) maximum wind and central pressure statistics in relation to the operational Dvorak estimates from the Satellite Analysis Branch (Washington D.C.), Tropical Analysis and Forecast Branch (TAFB, Miami) and US Air Force (Omaha) whenever there was aircraft reconnaissance within three hours of the fix. All winds converted to ten-minute from one-minute means using a factor of 0.88.

Dvorak				All cases			BT pressure (hPa)			Non-weakening cases	
CI	Max. wind (knots)	Count	Motion (knots)	BT max. wind (knots)		Mean SRM	Mean	Stand. dev.	Count	BT max. wind (knots)	
				Mean	Stand. dev.					mean	Stand. dev.
1.5	22	64	7.2	28.3	4.6	24.2	1004.7	4.4	33	28.8	5.0
2.0	26	139	7.9	31.8	5.5	27.2	1004.2	4.2	92	31.9	5.9
2.5	31	332	7.7	36.7	7.0	32.1	1002.5	4.8	244	37.5	7.4
3.0	40	372	9.2	43.4	7.2	38.2	999.2	6.3	294	44.3	7.7
3.5	48	286	9.5	49.5	7.6	44.2	994.1	7.0	210	50.5	8.0
4.0	57	228	10.3	56.2	7.8	50.7	988.2	7.8	161	58.1	8.0
4.5	68	267	10.7	68.1	11.4	62.5	977.8	11.9	178	69.1	11.9
5.0	79	242	11.0	76.6	10.6	70.9	969.4	11.6	146	78.3	11.1
5.5	90	165	10.7	86.7	11.4	80.9	958.3	10.9	105	88.4	12.4
6.0	101	188	10.7	99.1	11.7	93.5	945.9	12.5	113	101.6	11.8
6.5	112	207	10.0	108.7	11.0	103.2	934.5	13.9	118	111.3	12.0
7.0	123	84	10.4	115.3	11.4	109.6	923.5	13.2	41	122.2	10.3
7.5	136	15	7.0	127.2	8.4	122.8	910.2	11.1	6	134.2	2.2

It should be noted that the Dvorak technique is based upon patterns of storm organisation from which the maximum wind speed near the centre is inferred. For storms with maximum winds in the 20-50 knot ($10\text{-}26\text{ m s}^{-1}$) range there are several different cloud patterns that correspond to such intensities. With improving observing systems including microwave, scatterometry, radar and Stepped Frequency Microwave Radiometer (SFMR), it is apparent that strong variations exist in both deep convection and in the wind fields near the centre and local wind maxima can vary considerably from the mean maximum wind in the annulus about the centre. This can be most apparent in weaker systems where, for example, the mean flow around the centre may be on the order of 20-30 knots ($10\text{-}15\text{ m s}^{-1}$) but enhanced convection may drive local wind maxima in excess of 34 knots (18 m s^{-1}) in a particular quadrant. The inherent uncertainty in associating the cloud patterns to a particular maximum wind is reflected in the modification by Dvorak (1995) to allow discretion in assigning intensity in the 2.5-3.5 CI range using the shear pattern.

As noted by Velden et al. (2006) TC motion is not explicitly taken into account when estimating the maximum winds via the Dvorak process. A mean TC motion (based on Dvorak's sample) is implicit in the technique; however, nearly stationary or very fast-moving TCs (>15 knots (8 m s^{-1})) will inherit small biases in the estimated maximum winds.

This underestimation of the maximum winds and consideration of storm motion is significant when considering the WPR. K&Z adopted an approach based on the maximum wind being storm-relative, on the basis that the maximum wind is enhanced by forward motion. The maximum winds used in K&Z were based on best track cases where aircraft observations determined the intensity estimate and the pressure, and thus were much less influenced by the previously

discussed Dvorak-based intensity biases that result when maximum wind is estimated solely by the Dvorak technique. By reducing the Dvorak-derived maximum wind to a storm-relative value prior to calculation ignores the fact that there is a mean TC motion implicit in the technique.

Another potential underestimation of the maximum wind results from the conversion factor from one-minute to ten-minute winds. Should the recommendation from Harper et al. (2008) be adopted to change the open sea conversion factor from one-minute to ten-minute winds to 0.93 instead of the current value of 0.88, then the ten-minute winds derived via the Dvorak process would be about five per cent higher than current values.

Operational methodology

There are several reasons why an algorithm-based wind to pressure approach is appropriate for operations.

Consistency of the warning message.

The ultimate objective of operational intensity estimates is to ensure public safety, which is related more to the maximum wind than it is to pressure. The maximum wind needs to be consistent with general messages of developing, weakening or not changing. Public confidence would be eroded if the maximum wind were to vary on short time-scales, especially if it meant fluctuating between categories on successive warnings. For example when the Dvorak CI number remains the same but other parameters vary, it is preferable for the maximum wind to remain the same and for the pressure to vary subtly, rather than for the pressure to stay the same and for the maximum wind to vary. This is in contrast to the Holland (2008) approach.

While it is tempting to exclude central pressure from warning products to avoid confusion in the perception of cyclone intensity, as noted in Callaghan and Smith (1998), this would undoubtedly provoke a negative response from users who are familiar with using central pressure.

Efficiency in the forecast process.

The estimation of the intensity parameter, in this case maximum wind, and the subsequent derivation of central pressure needs to be done as quickly and reliably as possible to make the warning process timely and accurate. Existing techniques based on look-up charts are susceptible to transcription errors and where there is some interpretation required subject to user variation. In contrast, a methodology using an algorithm is quick and standardised and thus reduces the chance for errors.

Figure 5 shows the operational methodology for calculating the intensity parameters implemented in Australian TCWCs for the 2008/09 season. The analyst is required to derive the maximum mean wind via the Dvorak technique and any other methods such as surface observations, scatterometry, and, where available, aircraft reconnaissance data. The environmental pressure is derived from the calculated POCI plus 2 hPa. Estimates of *CI*, maximum mean wind, latitude, radius of gales, and POCI at the analysis time are input to the software package TC Module used in Australian TCWCs (Kelly et al. 2004). Storm motion is automatically derived from fix positions in the previous six to twelve hours. The program then calculates P_c based on Eqn 7. In the event of other information being available this can be overwritten. Similarly once the forecast parameters for the maximum winds, latitude, radius of gales and POCI are determined the forecast P_c values can be readily calculated via the equation. In the event of program failure the algorithm can be run via a spreadsheet.

While it is possible to calculate the pressure to the precision of a decimal point, it is considered more desirable to present operational values in publicly available products to the nearest even integer for pressures of 980 hPa and above and then to the nearest 5 hPa below 980 hPa. In the absence of defining

accuracy figures, this provides a more realistic indication of precision given the inherent inaccuracies in the derived value. For the purposes of the best track and forecast verification, calculations to the nearest integer can be retained.

The Eqn 7 algorithm was successfully introduced into Australian TCWCs for the 2008/09 season and while the output could not be verified, the process was received favourably by forecasters.

Implications for best track data

The change to a new WPR introduces an artificial bias in best track archives. However, given that three different WPRs are currently used in Australian TCWCs (four if including the two variants of the Crane method), it presents the opportunity to standardise pressure estimates and to extend the use in other TCWCs outside the Australian region. There is also the opportunity to revise historical pressure estimates to assist in creating a more homogeneous data-set, although there are a range of issues involved in reanalysing the best track archive. The use of the new algorithm should be noted in the metadata in any best track archive, as should be the case with any wind-pressure relationship.

To illustrate the change a comparison of the pressure from the best track and Eqn 7 is shown in Fig. 6 for three recent significant TCs in each of the three regions: *George* (March 2007) in the western region, *Monica* (April 2006) in the central region and *Larry* (March 2006) in the eastern region. Unfortunately, there are no pressure and wind observations available to verify a WPR for these systems. For *George* the A&H-based best track pressure is noticeably lower than pressures from Eqn 7, up to 19 hPa lower at the peak intensity of 110 knots (57 m s^{-1}). While there is a similar pattern for *Monica* at pressures above 960 hPa, the L&M-based best track pressure is higher by up to 14 hPa at the peak intensity at 135 knots (70 m s^{-1}) when Eqn 7 indicated 905 hPa. Extrapolations from pressure observations near the eye suggest a pressure of about 920 hPa at peak intensity is more likely. This suggests that either the actual maximum winds were

Fig. 5 Operational methodology for estimating maximum wind speeds and minimum pressure.

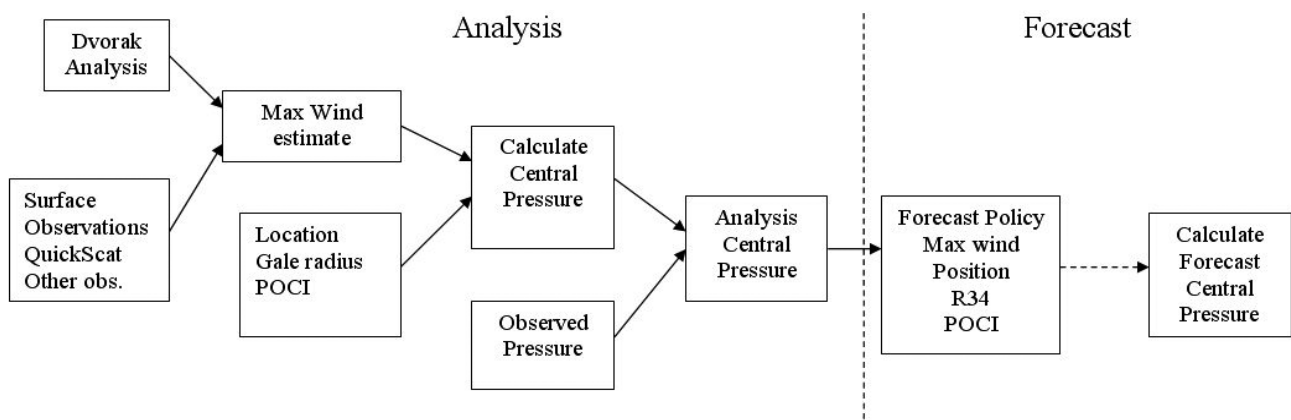


Fig. 6(a) Comparison of central pressure for TC *George* (March 2007) between the Australian best track and Eqn 7 in the western region (Perth TCWC) where Atkinson and Holliday (1977) is used.

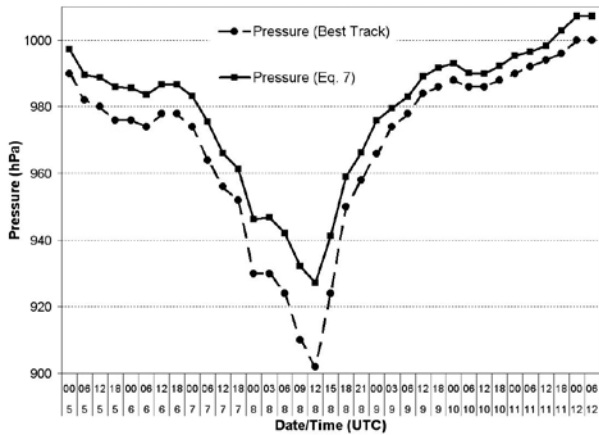


Fig. 6(b) Comparison of central pressure for TC *Monica* (April 2006) between the Australian best track and Eqn 7 in the central region (Darwin TCWC) where Love and Murphy (1985) WPR is used.

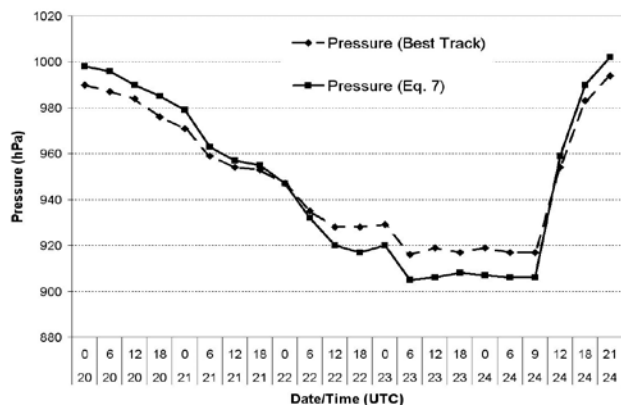
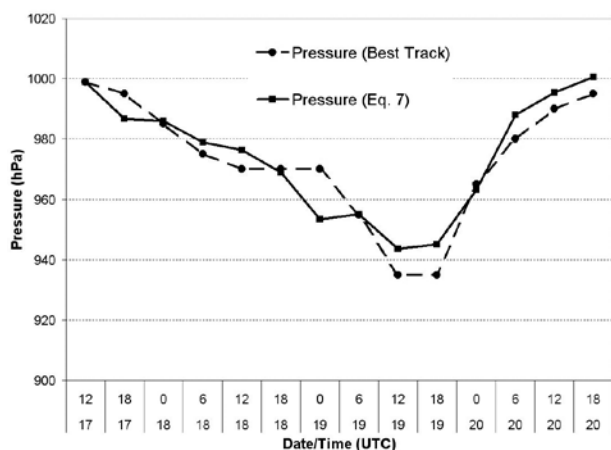


Fig. 6(c) Comparison of central pressure for TC *Larry* (March 2006) between the Australian best track and Eqn 7 in the eastern region (Brisbane TCWC) where the Crane WPR is used.



less (a 920 hPa pressure corresponded to a 120 knot (62 m s⁻¹) wind from Eqn 7) or that the L&M WPR is more appropriate in this case. Given that *Monica* was a midget cyclone having a RMW of only 10 nm and a gale radius of 40-55 nm during peak intensity, inclusion of the RMW in Eqn 7 may provide a more accurate WPR as discussed earlier for *Wilma* and *Rita*. For *Larry* in the eastern region there are general similarities between the Crane-based best track pressures and pressures from Eqn 7 although the Eqn 7 pressures are higher during the most intense phase. It appears the best track pressures follow the mid-point of the two Crane method curves and are presumably influenced by the observed pressure at landfall.

Summary and future work

The most reliable data source of tropical cyclone maximum wind and minimum pressure is that of the reconnaissance-based best track data in the Atlantic ocean. The approach of Knaff and Zehr (2007) to account for the scatter in this dataset using the additional parameters of environmental pressure, storm motion, latitude and size represents the most complete WPR devised thus far. Their equation has been modified to be expressed in terms of the radius of gales, POCI (for environmental pressure) and as a ten-minute mean wind speed. A separate equation has been developed to account for low-latitude TCs.

Using a small sample of historical data in the Australian region, the calculated pressure was generally consistent with the observed pressure. The fact that the calculated pressure was generally higher than the observed pressure may be a reflection of the observed winds underestimating the actual maximum wind. TC *Orson* was an outlier but it is difficult to make conclusions based upon just one event.

For basins without access to aircraft reconnaissance data the determination of intensity and use of a WPR is strongly linked to the Dvorak technique. The comparison of the Dvorak intensity with reconnaissance-based data shows that the Dvorak-derived maximum wind corresponds well with the reconnaissance-derived maximum wind for non-weakening systems at intensities of 3.5 (*CI*). The combined use of Dvorak to determine the maximum wind, and Eqn 7 may produce higher pressures than is actually the case.

In relation to the Dvorak technique the following points should be noted.

- At weaker intensities Dvorak underestimates the maximum wind. A *CI* of 2.5 corresponds to the mean maximum wind of gale force strength consistent with the findings of Koba et al. (1991) and the practice at JMA. For many systems at this intensity, the occurrence of gale force winds may be confined to one or two quadrants, in regions of enhanced convection or related to storm motion. In this sense the Australian practice of requiring gales to extend more than half-way around near the centre before a TC is declared may correspond to a *CI* of 3.0.

- The reduction of the Dvorak-derived maximum wind to account for storm motion in the K&Z WPR process ignores the fact that there is a mean TC motion implicit in the Dvorak technique.
- The standard conversion factor from one-minute to ten-minute winds of 0.88 is less than the 0.93 suggested by Harper et al. (2008). Should the higher figure be adopted then the ten-minute winds derived via the Dvorak process would be about five per cent higher than the current values. Harper et al. (2008) also recommends the use of different conversion factors for different exposures.

With these and similar issues in mind, the quantification of the biases and errors associated with the Dvorak intensity estimates are the subject of ongoing and future work.

As discussed in K&Z, the WPR could be improved with the inclusion of the RMW to take into consideration inner-core features rather than the overall size. Although RMW is now being recorded in the best track, it remains difficult to estimate for all cases. Furthermore, in order to incorporate this effect into a regression-based equation, historical RMW values are needed. The inclusion of RMW information would likely improve the capability of matching the more extreme cases such as hurricanes *Wilma* and *Rita* in 2005, and *Tracy* (1974) and possibly *Monica* (2006) in the Australian region.

The adoption of this new WPR will assist in standardising published wind and pressure data between TCWCs. Should all the necessary input parameters be available in best track data-sets, the new algorithm will assist the creation of a more homogeneous best track intensity data-set.

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Appendix

Validating the method against Australian data

To assess the validity of use in the Australian region, Eqn 7 was tested on available data. However, there are very few reliable observations of concurrent central pressure and maximum ten-minute wind speeds. Table A1 lists observed parameters along with the calculated pressure and maximum winds from Eqn 7 for seven TC events in the Australian region. Details of each TC are discussed below and in more detail in Harper (2002), Callaghan and Smith (1998) and in TC reports for *Tracy* (Bureau of Meteorology 1977), *Kathy* (Bureau of Meteorology 1984), *Orson* (Bureau of Meteorology 1992a) and *Ian* (Bureau of Meteorology 1992b). TCs *Ada* (1970), *Joan* (1975), *Kerry* (1979), *Olivia* (1996) and *Vance* (1999) have been excluded from this analysis owing to incomplete data.

A key issue with all of these cyclone events is whether observations captured the maximum wind and the minimum central pressure. The pressure gradients near the centre can be high, e.g. measured at 5.5 hPa/km in *Tracy*, while it is unlikely that a single anemometer can capture the maximum wind especially if it is not sampling continuously.

Agnes, 6 March 1956 (Callaghan and Smith 1998). A minimum pressure of 961 hPa was registered as *Agnes* passed over Townsville on 6 March 1956. The anemograph showed a maximum wind gust (three-second) of 73 knots (38 m s⁻¹) which reduces to a mean wind of 52 knots (27 m s⁻¹) using a gust factor of 1.4. *Agnes* is described as large with gales extending for more than 500 km. Cairns recorded gusts to 79 knots (41 m s⁻¹), higher than at Townsville although terrain effects are likely to have enhanced winds in the Cairns area. Given the frictional influences overland and that localised severe damage was reported in the vicinity of the Townsville Meteorological Office, the maximum mean winds are conservatively estimated at 60 knots (31 m s⁻¹) over open water although it is possible the maximum winds were higher.

The calculated pressure of 963 hPa is consistent with the observed pressure of 961 hPa. Indeed, the calculated maximum wind of 62 knots (32 m s⁻¹) may be a better reflection of the maximum wind over water.

Tracy, 25 December 1974. *Tracy* passed near Darwin on Christmas Day 1974 and remains Australia's most iconic TC. A minimum pressure of 950 hPa was measured at Darwin but the anemometer was destroyed after measuring a gust of 217 km/h. A Bureau of Meteorology report (Bureau of Meteorol-

ogy 1977, p.45) suggested that 'peak gusts associated with *Tracy* were most likely in the range of 217-240 km/h corresponding to maximum mean winds over Darwin of 140 to 150 km/h'. This calculation was based on 'anemometer readings, pressure gradients, and satellite data'. Interestingly this suggests a gust ratio of 1.55-1.6 which is higher than the standard 1.4 factor as discussed in Harper et al. (2008). The mean wind of 140-150 km/h corresponds to 76-81 knots (39-42 m s⁻¹).

A maximum wind of 81 knots (42 m s⁻¹) would equate to a calculated pressure of 962 hPa, well above the observed pressure. However, there are many factors suggesting the maximum wind was higher than this in addition to the level of destruction as suggested by Walker (personal communication). In an unpublished study one of the present authors (Courtney) discusses these meteorological factors concluding that the maximum wind is more likely to have been on the order of 95 knots (49 m s⁻¹) which is consistent with the calculated pressure of 949 hPa.

Kathy, 23 March 1984. *Kathy* was a small TC that passed near Centre Island in the Gulf of Carpentaria on the morning of 23 March 1984. Centre Island recorded a minimum pressure of 940 hPa and a maximum wind gust of 125 knots (64 m s⁻¹) prior to instrument failure. The Bureau of Meteorology (1984) report quotes the mean maximum wind as 100 knots (51 m s⁻¹) presumably from an assessment of the Dines wind trace. However Harper (2002) derives a value of 90 knots (46 m s⁻¹) based on the maximum wind gust using a 1.4 gust factor and concludes that it is reasonable to assume that the peak winds were probably sampled despite instrument failure.

Accepting the maximum wind value of 100 knots (51 m s⁻¹) equates to a calculated pressure of 946 hPa which is above the observed value of 940 hPa. The calculated maximum wind corresponding to the observed pressure is 106 knots (55 m s⁻¹) which is not unreasonable especially as the Dvorak intensity was assessed as 6.5 (110 knots (57 m s⁻¹)).

Orson, 22 April 1989. *Orson* passed over the North Rankin gas platform on 22 April 1989. Privately operated instruments recorded a minimum pressure of 905 hPa and a maximum ten-minute wind of 121 knots (62 m s⁻¹) at a height of 36.4 m with a non-coincident gust of 148 knots (76 m s⁻¹). This equates to a 10 m wind of approximately 103 knots (53 m s⁻¹) using a 0.85 conversion, although Harper (2002) uses a greater reduction factor arriving at a 10 m wind of 90 knots (46 m s⁻¹). Harper (2002) also suggests that previously discounted higher gusts may be valid possibly indicating the presence of mesoscale vortices.

Based upon a maximum wind of 105 knots (54 m s⁻¹), the calculated pressure of 935 hPa is significantly higher than the observed 905 hPa. The calculated maximum wind from the observed pressure is 131 knots (67 m s⁻¹). The Bureau of Meteorology (1992a) report indicates the Dvorak intensity was 6.5 as it passed North Rankin corresponding to a maximum wind of 110-115 knots (57-59 m s⁻¹). It is possible that the actual maximum wind may have been at this level or

Table A1. Comparison of observed pressure with modified Knaff and Zehr methodology (calculated via Eqn 7) pressure for selected Australian region TCs.

TC Name	Date	Latitude	Gale radius nm	Observed		Pe hPa	Press. hPa	Calculated		Comments
				Motion knots	Max. wind knots			Press. hPa	Max. wind knots	
<i>Agnes</i> *	6 Mar 1956	19.2	300	10	60 (52)	1002	961	963 (968)	62	Max. wind estimate.
<i>Tracy</i> **	25 Dec 1974	12.5	30	3	95 (81)	1004	950	949 (962)	94	Max. wind estimate.
<i>Kathy</i>	23 Mar 1984	15.6	40	5	100	1010	940	946	106	Max. wind before instrument failure.
<i>Orson</i>	22 Apr 1989	19.2	200	12	105	1008	905	935	131	Max. wind derived from measurement at 36 m.
<i>Ian</i>	2 Mar 1992	20.8	45	6	80	1010	960	964	84	Max. wind sampled at 5 minutes.
<i>Oliver</i>	7 Feb 1993	17.1	100	3	90	1010	950	957	97	Limited sampling of max wind.
<i>Olivia</i>	10 April 1996	20.3	200	12	105	1008	927	926	105	Varanus I. pressure; Barrow I. max. wind.
<i>Rachel</i>	7 Jan 1997	20.3	100	6	70	1010	971	973	72	Port Hedland pressure; Bedout I. max. wind.

* Maximum wind value is an open water estimate; lower value in parenthesis is based on the conversion of observed gusts to mean winds.

** Maximum wind is an estimate based upon reanalysis by one of the present authors (Courtney), the lower value in parenthesis is from Bureau of Meteorology (1977).

even near the 36.4 m observed wind of 121 knots (62 m s^{-1}) especially as debate still surrounds the reduction factors of peak winds. Nevertheless, it is still difficult to match with the observed pressure using most of the standard WPRs. The A&H-derived pressure for a maximum wind of 105 knots (54 m s^{-1}) is 920 hPa is closest to the observed pressure, while the A&H-derived maximum wind for an observed 905 hPa of 117 knots (60 m s^{-1}) is plausible given the Dvorak intensity.

Ian, 2 March 1992. *Ian* was a small TC that passed over Barrow Island on 2 March 1992. Pressure and five-minute mean winds were recorded by privately operated instruments. The minimum pressure (adjusted) was 960 hPa and the highest mean winds were 80 knots (41 m s^{-1}). Although mean winds measured over five minutes are slightly higher statistically than those averaged over ten minutes, an 80 knot five-minute mean wind equates to 80 knot ten-minute mean using rounded values to the nearest 5 knots.

The calculated pressure of 964 hPa is consistent with the observed pressure of 960 hPa. Indeed, the calculated maximum wind of 84 knots (43 m s^{-1}) based on the 960 hPa observed pressure, happens to be the same value as the Dvorak-influenced best track value.

Oliver, 7 February 1993. *Oliver* passed over Lihou Reef on 7 February 1993. The maximum measured wind speed was 91 knots (47 m s^{-1}) and the lowest pressure was 950 hPa, although the automatic weather station (AWS) only records a single ten-minute observation per hour and failed to report when it experienced the strongest convection in the eye wall.

Based on the 91 knot observation, the calculated pressure of 957 hPa is above the observed pressure of 950 hPa. The calculated maximum wind is 97 knots (50 m s^{-1}) based on the 950 hPa observed pressure which is quite possible given the variations in convection in the eye wall. This is also consistent with the Dvorak *CI* of 6.0 which corresponds to a maximum wind of 100 knots.

Rachel, 7 January 1997. A minimum pressure of 971 hPa and a maximum ten-minute wind of 65 knots (34 m s^{-1}) were registered as *Rachel* passed over Port Hedland at 3pm 7 January 1997. Bedout Island to the north registered a maximum wind of 69 knots (36 m s^{-1}) and this wind (rounded to 70 knots) is used for this analysis to account for land frictional effects at Port Hedland. The calculated pressure of 973 hPa is consistent with the observed pressure of 971 hPa.

