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Deriving Tropical Cyclone Central Pressures for Reanalyses

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Abstract

Surface pressure observations have been found to be useful for historical reanalyses of sparse observational networks. To provide additional pressure data for such reanalyses, minimum central pressure values for tropical cyclones (TCs) have been derived from wind speed estimates contained in the National Climatic Data Center's International Best Track Archive for Climatic Stewardship (IBTrACS). Three TC wind speed/pressure relationships have been evaluated: the cyclostrophic equation, our gradient wind equation (GWE), and the Holland (2008) model. Between the three methods, only minor significant differences were found in overall root-mean-square errors of central pressures. However, the GWE was found to be the least biased method, especially in higher intensity TC categories. Coefficients for the GWE have been calculated separately for all TC basins to obtain minimum central pressure estimates from IBTrACS winds. The derived pressures and associated estimated errors may be useful for improving the assimilation of tropical cyclones in historical reanalyses.

1. Introduction

The earliest Atlantic tropical cyclone (TC) observations in the HURDAT dataset, a comprehensive North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea tropical storm and hurricane dataset by the NOAA Atlantic Oceanographic Meteorological Laboratory, start in 1851 (Landsea et al. 2004). Most of these early TC observations contain only wind speed estimates. Wind speed is useful for evaluating TC strength and destructiveness; the Saffir-Simpson scale has been used successfully to describe TC destructiveness for many years[2]. However pressure is also useful for several purposes, including assimilation into historical reanalyses extending back to the 19th Century (Whitaker et al. 2004; Compo et al. 2006). In the absence of direct observations of tropical storm pressures, wind speed/pressure relationships can be used to derive pressure from wind estimates (e.g., Dvorak 1975; Holland 1980; Love and Murphy 1985; Knaff and Zehr 2007; Holland 2008, hereafter HOLLAND08).

Hart et al. (2008) found that the increased availability of TC observations in the past few decades has greatly improved the representation of TCs in reanalysis datasets. In particular, they found that the size and the location of TCs are more influential in reanalysis quality than is TC intensity. Improving the representation and utility of intensity data may require a different approach than used in many of the existing reanalysis datasets, which rely heavily on ship and station observations that happen to be close to TCs. The National Centers for Environmental Prediction Climate Forecast

[2] Recently, Emanuel (2005) proposed a physically-based index to describe possibly increasing TC destructiveness due to the global warming.

System Reanalysis employed a storm relocation technique (Liu et al. 1999) to "move" vortices to the observed location before the data assimilation system combined other observations (Saha et al. 2010). Recently, the Japan Reanalysis 25 (Onogi et al. 2007) assimilated synthetic wind profiles (Fiorino 2002) to improve the representation of TCs. Both of these efforts improved many of the characteristics of TCs in the reanalysis fields compared to earlier datasets (Schekel 2010). Assimilation of central pressure observations might be one way to bring about further improvement. However, an analysis of the records in a new tropical cyclone dataset, the National Climatic Data Center (NCDC) International Best Track Archive for Climatic Stewardship (IBTrACS, Kruk et al. 2009; Knapp et al. 2010) shows that before the 1950s few TC records contain both wind and pressure values. Even in the last decade, more than 400 records have only wind. Thus, to take advantage of an improvement in the representation of TC intensity that might be made from the assimilation of pressure, it will be necessary to derive central pressure values from wind estimates to reanalyze earlier decades.

Several algorithms exist to derive pressure from TC wind speed estimates. Most empirical wind speed/pressure models use the "cyclostrophic equation" (e.g., Fujita 1971; Atkinson and Holliday 1977; Harper 2002), which requires only an estimate of the wind speed and empirical parameters appropriate for a particular region or basin. This algorithm is an integral part of the Dvorak (1975) satellite cloud image analysis technique to arrive at simultaneous wind speed and pressure estimates. Most widely used in operations recently is the Knaff and Zehr (2007) algorithm, which uses wind speed and additional environmental factors in the form of a second-order polynomial approximating the gradient wind. For data assimilation, this algorithm may be difficult to use because it relies on environmental pressure and wind field information in 6-hourly intervals from the NCEP-NCAR reanalysis dataset (Kalnay et al. 1996). Using derived central pressure values that include existing reanalysis input may introduce a covariance between the errors in the individual values and may also propagate biases from the utilized reanalysis fields to any future assimilation effort. Additionally, the Knaff and Zehr (2007) algorithm is limited to the present range of the NCEP-NCAR reanalysis dataset, 1948-2010. A different algorithm is used in the HOLLAND08 model, which can also derive central pressure from wind speed and several additional storm and environmental factors. The HOLLAND08 model is a successor to that of Holland (1980), the first theoretically based gradient wind model. This updated algorithm appears to be applicable generally to the full time range of historical TC data and may be suitable for use in reanalysis applications.

For these reasons, three wind speed-to-pressure relationships are studied here. The approximation to the cyclostrophic wind equation and the HOLLAND08 model are compared. Additionally, an approximation to the gradient equation with similarities to that of Knaff and Zehr (2007), but with fewer parameters, is also investigated. We refer to this as the gradient wind equation (GWE). In all three wind speed-pressure relationships, coefficients are determined empirically.

In this paper, we would like to reserve the word “estimate” for central pressure values that can be found in the original dataset, while “derived” is used for pressure values determined from a wind speed-pressure relationship. For an historical account of hurricane intensity estimates, see Landsea et al. (2004). Note, too, that even in the satellite era intensity is estimated, e.g., by the Dvorak satellite cloud image technique (Velden et al. 2006).

The structure of the paper is as follows. The data used in this paper are described in Section 2. The three wind speed/pressure relationships are described and their performance is evaluated by comparing root-mean-square (RMS) errors and mean biases for North Atlantic TC central pressure estimates in Section 3. In Section 4, the GWE is applied to the other basins. A discussion is given in Section 5. Conclusions are presented in Section 6.

2. Data

Two different observational tropical cyclone datasets were used in this paper. Initially, the HURDAT dataset (Landsea et al. 2004) was used to evaluate the methods. The HURDAT dataset is the official record of tropical storms and hurricanes in the Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea since 1851. The HURDAT dataset contains not only wind speeds and pressures but also translation speeds and wind directions. Its time resolution is 6 hourly. Wind speeds are reported as 1-minute averages at an elevation of 10 meters above the surface.

Unfortunately, HURDAT is limited to the North Atlantic Ocean. To extend our study globally, a new best track compilation, the NCDC IBTrACS dataset (Kruk et al. 2009; Knapp et al. 2009), was used to derive central pressures and to estimate the associated expected error. Version v01r01 was used here. IBTrACS incorporates HURDAT as a data source for North Atlantic basin, however, it does not include HURDAT's translation speeds and wind directions. The time resolution is 6 hourly. In the compilation process of IBTrACS several adjustments were made, e.g., all maximum sustained wind estimates were normalized to the 10-minute average and all minimum central pressure estimates of all reported observations for each provided record were averaged (for additional details see Kruk et al. 2009; Knapp et al. 2010).

IBTrACS includes nine different non-overlapping sub-basins for delineating TC identity: EPCP (East Pacific/Central Pacific); EPEP (East Pacific); NA (North Atlantic); NI (North Indian); SI (South Indian); SIWA, (South Indian/West Australia); SPEA (South Pacific/East Australia); SPSP (South Pacific), and WP (West Pacific). Figure 1 illustrates the locations of central pressure data in all nine sub-basins during 2000. The number of TC observations (pressure and/or wind speed estimates) available in each basin is presented in Table 1 as a function of Saffir-Simpson category. Outside the North Atlantic and West Pacific basins, Category 5 storms are exceedingly rare or absent altogether, and Category 4 storms only slightly more common. The impact of satellite data is seen very clearly when these TC observations are presented in decadal bins, without regard to basin or Saffir-Simpson category (Figure 2); the number of wind-only observations per decade increases sharply in the 1950's and continues to rise through the 1990's. (Less than 10 years of data are available for the final decade plotted.)

3. Comparison of methods for deriving pressure from wind speed

a. The three wind-pressure relationship approximation methods

Three different methods to approximate central pressures from wind speed data are examined: the cyclostrophic equation, the GWE, and the HOLLAND08 model.

The cyclostrophic equation as used for TC wind-to-pressure relationships can be placed in the form,

$$V = c\left(P_{ref} - P_c\right)^n \tag{1}$$

where V is the wind speed, P_{ref} is the reference or environmental pressure, P_c is the minimum central pressure, and c and n are empirical constants with n between 0 and 1. When n = 0.5, the dynamical cyclostrophic equation is recovered (Holton 1992). For application to TCs, the parameters c and n differ from one basin to another. The cyclostrophic equation for the Atlantic basin is given by

$$V_{cyl} = 8.354\left(1015.8 - P_c\right)^{0.6143} \tag{2}$$

where V_{cyl} is in units of knots and P_c is in hPa (Brown et al. 2006). The fit period for the basin-specific variables is between 2000 and 2005.

Like the dynamical cyclostrophic equation, the full gradient wind equation also has pressure dependent on squared wind speed. The relationship can be cast as a second order polynomial. Such an approach simplifies that of Knaff and Zehr (2007) who incorporated latitude dependence and several other factors, including storm movement. For this simpler model, consider the gradient wind equation in coordinates relative to the horizontal flow (Holton 1992):

$$\frac{V^2}{R} + fV = -\frac{1}{\rho}\frac{\partial P}{\partial n} \tag{3}$$

where R is the radius of curvature, f is the Coriolis parameter, P and ρ are the air pressure and density, respectively, and n is in the direction normal to the horizontal velocity.

Approximating $-\frac{\partial P}{\partial n}=\frac{\Delta P}{\Delta n}=\frac{\mathrm{P}_{ref}-P_c}{R}$ and collecting terms, we can express P_c in terms of three parameters in the GWE:

$$P_c = P_{ref} - \alpha V - \beta V^2 \tag{4}$$

where P_{ref}, α, and β are coefficients that will be determined empirically; V is units of m s^{-1} and P_c is in hPa.

The last wind speed-to-pressure relationship evaluated is the HOLLAND08 model. This model improves upon the representation of the scatter in wind speed and pressure by elaborating on the scaling parameter b used in Holland (1980). The b parameter provides the advantage of representing a radial wind profile that can be more peaked than is assumed in Eq. (1) (Holland 1980; Love and Murphy 1985; HOLLAND08). The HOLLAND08 model determines V_m, the 1-minute mean wind speed at 10-m elevation, as

$$V_m = \left(\frac{b}{\rho \exp}\Delta P\right)^{0.5} \tag{5}$$

where V_m is in units of m s^{-1}, ρ is in units of kg m^{-3}, exp is Euler's constant, and ΔP is in units of hPa. The parameter b is determined from

$$b = -4.4 * 10^{-5}\Delta P^2 + 0.01\Delta P + 0.03\frac{\partial P_c}{\partial t} - 0.014\varphi + 0.15 v_t^x + 1.0 \tag{6}$$

with the exponent

$$x = 0.6\left(1 - \frac{\Delta P}{215}\right),$$

ϕ being the absolute value of latitude in degrees, and v_t being the TC translation speed in m s^{-1}. Eq. (6) allows the maximum winds to vary for a given central pressure according to the prior intensity change, latitude, translation speed, and surface air density. HOLLAND08 estimated the parameters from 2000-2005 Atlantic hurricane data. Appendix A contains additional details of its implementation in this study.

Our evaluation of these three models uses HURDAT. This is partly because the IBTrACS dataset does not contain the translation speed information needed by HOLLAND08. Observations over land are excluded from performance evaluation, since the HOLLAND08 model explicitly requires sea surface temperature (SST, see Appendix A). In addition, the first observation of each cyclone was excluded, since it does not have translation speed information. For the remaining records, a MySQL database system was employed to choose a common subset of events/observations that had all the variables needed to estimate the parameters.

b. Comparison

Figure 3 illustrates the mean bias and the root-mean-square (RMS) error of the models. Derived and HURDAT central pressures in the Atlantic are compared as a function of Saffir-Simpson Category/Strength using data from the 30-year period (1977-2006). In this and subsequent categorized figures, the Saffir-Simpson Category is based on the wind estimate. Total counts of the tropical storm and hurricane observations used are in Table 2. For the GWE, a jackknife method (Quenouille 1949, 1956; Tukey 1958) with a three-year interval was used to provide cross-validated statistics to avoid overconfidence in the estimated bias and RMS. With this method, the parameters were calculated every three years using data from the remaining years. For the HOLLAND08 model, statistics were based on the results obtained by using pressure tendencies, calculated from two consecutive observed pressure estimates. If two consecutive observed pressure estimates were not available for a given observed central pressure estimate, that datum was excluded from the study.

The results show that overall biases are generally small[3] and similar for the HOLLAND08 model, GWE, and cyclostrophic equation (Fig. 3a). Examining the biases as a function of category, they are generally small for the weaker categories. The GWE has the smallest magnitude bias for Category 4 and 5 hurricanes, while HOLLAND08 has the largest. The HOLLAND08 model has a negative bias in Categories 3-5 while the cyclostrophic equation has a positive bias for Categories 4 and 5. Attribution of the cause of these biases is beyond the scope of this paper.

All of the methods also performed similarly in terms of overall RMS errors (Fig. 3b). Distinguishing differences can be seen for Categories 2 to 5. The cyclostrophic equation and the GWE have very similar errors except for Category 5, while the HOLLAND08 model RMS is larger than both as hurricane strength increases from Category 2 to 5. The GWE appears to have slightly better performance for Category 5 hurricanes compared to the cyclostrophic equation.

Though none of the wind speed/pressure approximation methods performed better than others in terms of overall RMS error, the GWE is found to be the least biased method, to have the smallest RMS error for Category 5, and to have comparable errors to the cyclostrophic equation for other categories. Thus we focused on the GWE to study the characteristics of derived pressures in other basins.

[3] The overall bias is roughly 0.1% 'small', when pressures are 1000 hPa and the bias is only ~ 1hPa.

4. Derived TC central pressures

As in the Dvorak technique (Harper 2002), regionally specific values of the GWE parameters in (4) were calculated for all nine IBTrACS sub-basins, using data from 1979-2007. The year 1979 was chosen as an arbitrary cut-off to capture most of the satellite period, with the years prior to 1979 reserved as an independent period. Table 3 shows the GWE coefficients of (4) for each sub-basin. The resulting wind speed/pressure curves together with verifying P_c and wind observations from the independent period are shown in Figures 4-6 for the three basins with many central pressure estimates available for comparison: the Atlantic (Fig. 4), Eastern Australian (Fig. 5), and West Pacific (Fig. 6). Corresponding RMS errors are shown in Table 4, together with the RMS values from the dependent period. The GWE curves for the Atlantic and Eastern Australian regions show good agreement to the dependent wind speed and pressure estimates used to calculate the GWE parameters (Table 3) and to the observations from the independent period. The GWE curve for the West Pacific region also shows good agreement to the dependent data (Table 3 and Fig. 6a), but not to the observations from the pre-1979 independent period (Fig. 6b). Because of an issue with the homogeneity of historical TC data (Harper and Callaghan 2006; Kossin et al. 2007), GWE curves generated using 1979-2007 data might not be expected to correspond well with estimates from the pre-1979 period. This appears to be the case for the West Pacific data. This issue will be further examined in section 5.

The calculated region-specific GWE parameters were used to derive TC pressures from all available TC wind speed estimates in the IBTrACS dataset. The number of IBTrACS observations in each basin which contained only pressure estimates, both pressure and wind estimates, and only wind estimates, are listed in Table 1; this encompasses all years. Figure 7 shows RMS errors of the GWE derived pressure values compared to TC central pressure estimates for all nine sub-basins. RMS errors were calculated as function of the TC category using independent data from the period 1958 to 1978. These years were chosen to capture a time period with significant satellite observations that was not used to calculate the parameters; information on data availability for 1958-1978 is presented in Table 5. RMS values computed from fewer than 40 values are omitted from Fig. 7. For most sub-basins, errors increase with increasing intensity. An exception to this occurs for the South Indian sub-basin. The highest error value pooling all categories ("Overall") is about 15 hPa for the Central Pacific sub-basin. The lowest is ~4 hPa for the East Australian sub-basin.

Our derived TC data complements the existing central pressure data both temporally and spatially. Table 1 shows the total number of both estimated and derived TC central pressures for each basin when all available IBTrACS data are used, and also shows basin counts for each Saffir-Simpson category. As an example of the supplementary nature of the derived pressure values, the geographical distribution of both derived and estimated values in the 1960s and 1970s are shown in Figures 8a-d. The most striking feature of this four-way comparison is that derived central pressures for the 1960s (Fig. 8b) occur mostly in regions with few estimated TC central pressures (Fig. 8a) in the Eastern Pacific, Central Pacific, South West Pacific/East Australian, and South Indian basins. In the 1990s, both estimated (Fig. 8c) and derived (Fig. 8d) TC central pressures show similar distributions except in the North Atlantic where most IBTrACS records contain TC central pressure estimates.

While additional derived central pressures themselves may be useful, data assimilation systems such as used in reanalysis require an estimate of the observation error for each observation (e.g., Daley, 1991). The RMS errors calculated with independent data (c.f. Fig. 7) could be used to determine this value for the GWE- or cyclostropic-derived pressures. Figure 7 further shows that that such observation errors should probably vary with TC category. The improved coverage and associated error estimates may be useful for future reanalysis efforts.

5. Discussion

The larger RMS values of the GWE derived central pressures in the Western Pacific (Fig. 7) warrant a discussion. First, note that Fig. 6b shows a large spread in the Western Pacific data, suggesting that more than one population may be contained in the distribution. In fact, at least three different TC tracks have been identified in the Western Pacific (Elsner and Liu 2003). It may therefore be surprising that the data points in the West Pacific basin for the 1979-2007 period have a remarkably different character that appears to be well-represented by the GWE fit (Fig. 6b). In contrast, central pressure estimates from more intense wind speeds prior to 1979 appear overestimated relative to the curve (Fig. 7a). This may indicate a problem in the homogeneity of IBTrACS data in this region. Kruk et al. (2009) cite inter-agency variability as a major source of inhomogeneity and suggest that reanalysis data sets provide some adjustment. Other than normalizing all non-10 minute winds to the WMO standard 10-minute average, the NCDC IBTrACS has not been adjusted to achieve long-term homogeneity.

Inhomogeneities of the tropical cyclone historical records are a well known issue (Harper and Callaghan 2006; Kossin et al. 2007). For example, Black (1993) attributes the inconsistent typhoon data in the Pacific basin to two different wind speed approximation methods. The effect of introducing inhomogeneous tropical cyclone data to reanalyses efforts is yet to be known.

An additional homogeneity concern is the issue of undetected cyclones in the pre-satellite periods. The rapid increase in the number of central pressure estimates in Fig. 2 shows the lack of satellite technology before the 1950s. For example, Chang and Guo (2007) and Mann et al. (2007) showed an undercount bias for tropical cyclones in the North Atlantic basin in earlier periods (see also, Landsea et al., 2010). Vecchi and Knutson (2008) estimated the expected number of Atlantic tropical cyclone missed by the pre-satellite observing system (1878-1965). This undercount bias may also be related to the poor correspondence in the Western Pacific basin for the earlier period (1949-1979) (Fig. 6b).

In general, the GWE shows a good correspondence with the central pressure values in IBTrACS (Figures 5-7). This is not a surprising result because the first portion of our study found the GWE was the least biased method among the three methods compared.

6. Conclusions

The present study has investigated the potential for enhancing the database of estimated central pressures in IBTrACS with additional derived central pressures. It appears feasible to derive TC central pressure values with appropriate error estimates. Three TC wind speed/pressure relationships, the cyclostrophic equation, the GWE, and the HOLLAND08 model, have been evaluated by studying RMS error and mean bias. In the

Atlantic, although there was virtually no difference in overall RMS errors among the three wind speed/pressure approximation methods, the GWE was the least biased method. The GWE method was then applied to create derived TC pressures in all eight sub-basins around the globe. The associated errors in these basins were studied by direct comparison with estimated pressures.

In this study, almost 65 000 derived TC central pressures have been synthesized from wind speed estimates in eight different basins between 1851-2007. From a total of 191 443 global TC records, 64 201 derived central pressures could be added to the IBTrACS data set. This increase represents about half of the total number of estimated central pressures (Table 1). In the period prior to satellites, most of the central pressure values are derived (Fig. 1). Additionally, derived central pressures provide significant coverage in several sub-basins that would otherwise have none (Fig. 1). With these new values, together with the 127,242 central pressure estimates already included in IBTrACS, we anticipate that improvement in the representation of tropical cyclones continues in future reanalysis efforts.

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APPENDIX

Implementation details of HOLLAND08

Several quantities are needed to utilize the HOLLAND08 model (6). The central pressure tendency $\partial P_c/\partial t$ was calculated from two consecutive pressure estimates. As in HOLLAND08, near-surface air temperature was estimated as 1.0 K below the sea surface temperature (SST). Monthly SST values HadISST (Rayner 2003) were used for this purpose. Also, as in HOLLAND08 the environmental pressure = 1015 hPa (HOLLAND08).

Additionally, the following thermodynamical quantities were used.

The surface virtual air temperature,

$$T_{vs} = (T_s + 273.15)(1 + 0.81 q_m),$$

where

$$q_m = 0.9 \frac{3.802}{P_{rmw}} e^{17.67 T_{s/(243.5+T_s)}},$$

was used to calculate the equation of the state where T_s is the surface temperature, q_m is the vapor pressure at an assumed relative humidity of 90 percent and P_{rmw} is the pressure at the radius of maximum wind (HOLLAND08). The dry air gas constant, R_d, is set to

287.05 J kg^{-1} K^{-1}. A pressure derived from Eq. (1) from a given wind speed was used as an initial guess and perturbed subsequently, as the Holland (2008) equations were iterated to a specified error tolerance of the target wind speed.

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FIG. 6. (Top) Estimated Gradient Wind Equation (GWE) curve for the Western Pacific based on parameters fit using 27 957 IBTrACS data points from 1979-2007, shown as open circles. (Bottom) Same GWE curve, with open circles showing all the available IBTrACS simultaneous estimates of wind speed and central pressure before 1979.

FIG. 7. RMS error of the GWE-derived central pressure compared to IBTrACS central pressure estimates from the period 1958 to 1978, shown as function of TC intensity, for the nine sub-basins defined in Fig. 1. GWE parameters were calculated separately for each sub-basin using IBTrACS estimates of wind speed and pressure from the period 1979-2007. RMS values with N below 40 are omitted.

FIG. 8. Estimated (top) and derived (bottom) TC central pressures during the 1960s (left) and 1990s (right).

TABLE 1. Total number of IBTrACS central pressure estimates in each basin as a function of Saffir-Simpson category, together with counts of the number of central pressure estimates available in the IBTrACS dataset and the number derived from IBTrACS winds. Basin abbreviations are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Pacific), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

	Saffir-Simpson category							**Estimates**			**Derived**	**Estimates + Derived**
Basin	**Tropical storm**	**Cat 1**	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**		**Pressure + wind**	**Pressure only**	**Total**		
EPCP	2882	382	120	84	34	0		1141	269	1410	2361	3771
EPEP	14 900	2451	615	554	65	3		7575	0	7575	11 013	18 588
NA	29 952	5963	2006	1140	284	19		13 367	0	13 367	25 997	39 364
NI	4281	173	70	48	19	0		2212	42	2254	2379	4633
SI	17472	1355	587	337	47	0		10 604	190	10 794	9194	19 988
SIWA	9356	730	270	170	24	1		9068	1896	10 964	1483	12 447
SPEA	5308	365	108	48	10	3		4848	1767	6615	994	7609
SPSP	10 305	828	360	118	49	0		8737	266	9003	2923	11926
WP	49 873	7570	3201	2447	1043	272		56 549	8711	65 260	7857	73 117
Total	144 329	19 817	7337	4946	1575	298		114 101	13 141	127 242	64 201	191 443

TABLE 2. Total number of 1977-2006 HURDAT observations used (c.f. Figure 3) as a function of Saffir-Simpson Category, 1977-2006 (Figures 3 and 4), together with the speed range associated with each category.

	Wind speed (kt)	**Wind speed (m s^{-1})**	**HURDAT observations**
Overall			8356
Non Hurricane Cyclones	< 64	< 32.9	5696
Category 1	64 - 82	32.9 - 42.2	1430
Category 2	83 - 95	42.7 - 48.9	557
Category 3	96 - 113	49.4 - 58.4	412
Category 4	114 - 135	58.6 - 69.5	196
Category 5	> 135	> 69.5	65

TABLE 3. Gradient wind equation (GWE) coefficients calculated for each sub-basin using all (V, P_c) observations, 1979-2007. Sub-basins are shown in Fig. 1: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Pacific), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

	EPCP	**EPEP**	**NA**	**NI**	**SI**	**SIWA**	**SPEA**	**SPSP**	**WP**
P_{ref}	1017.74	1016.17	1018.42	1001.87	1014.38	1016.31	1014.55	1013.53	1012.85
A	-0.533 429	-0.529 944	-0.734 988	0.135 548	-0.919 901	-1.238 93	-1.014 78	-0.933 561	-0.653 169
B	-0.015 144 9	-0.015 567 6	-0.012 598 2	-0.022 834	-0.013 062 8	-0.007 411 85	-0.010 073 1	-0.012 698 6	-0.017 715 6
# obs	1018	7442	10 595	2192	9864	5793	2850	6559	27 957

TABLE 4. RMS error in hPa of the Gradient wind equation (GWE) for the North Atlantic, South Pacific/East Australia, and West Pacific region for the periods spanning the start of estimates in IBTrACS through 1978 and also from 1979 to 2007. Numbers in parentheses are the total number of central pressure estimates used to calculate the error.

	RMS (Number of central pressure estimates)		
	North Atlantic	**South Pacific/ East Australia**	**West Pacific**
Before 1978	9.47 (2772)	4.06 (1998)	12.27 (28 592)
1979-2007	6.46 (10 595)	4.02 (2850)	3.91 (27 957)

TABLE 5. Total number of IBTrACS central pressure estimates from 1958-1978 (see also Fig. 7) in each basin as a function of Saffir-Simpson category, together with counts of the number of central pressure estimates available in the IBTrACS dataset and the number derived from IBTrACS winds. Basin abbreviations are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Pacific), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

	Saffir-Simpson category							**Estimates**			**Derived**	**Estimates + Derived**
Basin	**Tropical storm**	**Cat 1**	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**		**Pressure + wind**	**Pressure only**	**Total**		
EPCP	742	112	33	23	2	0		92	105	197	820	1017
EPEP	4653	836	100	111	10	0		131	0	131	5579	5710
NA	4862	720	280	228	51	4		2259	0	2259	3886	6145
NI	382	49	17	6	0	0		18	20	38	436	474
SI	6163	412	101	45	11	0		740	69	809	5992	6801
SIWA	3064	208	50	29	4	0		3173	580	3753	182	3935
SPEA	2169	134	18	0	0	0		1970	253	2223	351	2574
SPSP	3620	229	75	1	0	0		2150	92	2242	1775	4017
WP	16 844	2588	1072	904	601	190		21 612	4685	26 297	587	26 884
Total	42 499	5288	1746	1347	679	194		32 145	5804	37 949	19 608	57 557

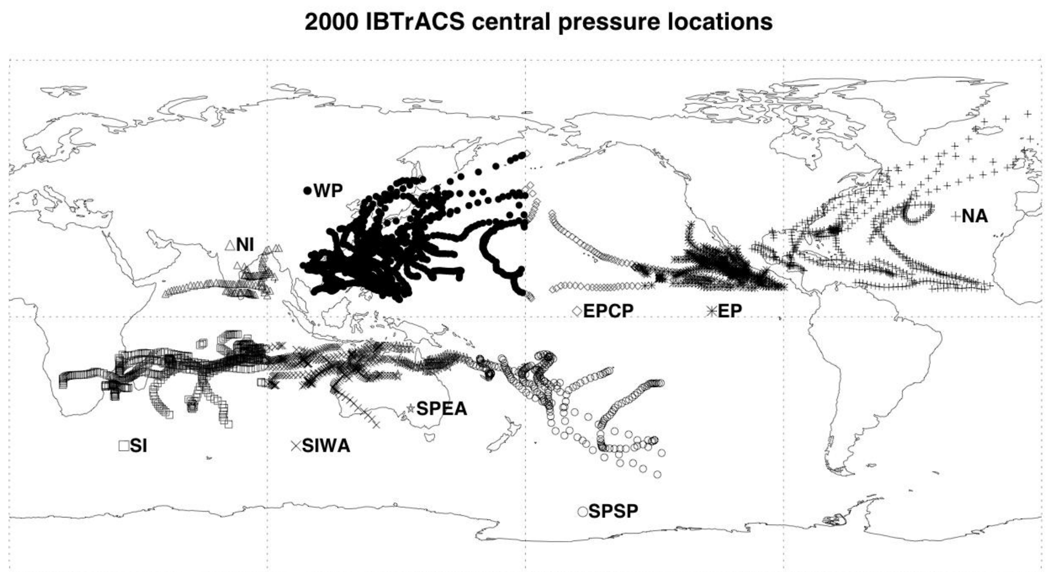

FIG. 1. IBTrACS central pressure locations during the year 2000 for nine different sub-basins. The main basin sub-basin abbreviation combinations that have been adapted from IBTrACS are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Australia), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

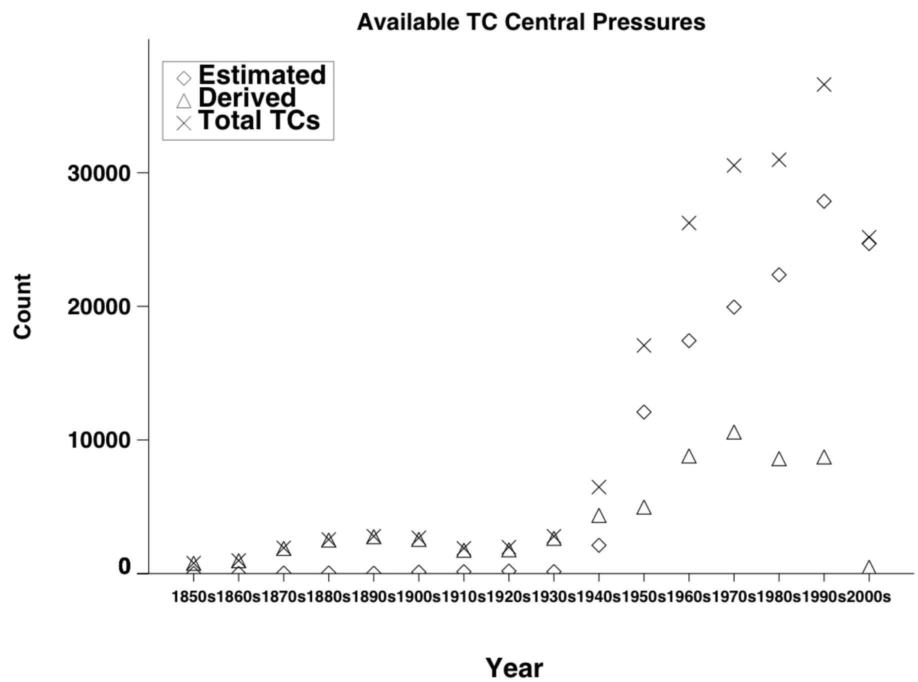

FIG. 2. Total number of estimated and derived TC central pressure values from IBTrACS data in ten-year intervals. Central pressure values were derived from wind speed estimates whenever estimated central pressures were not available.

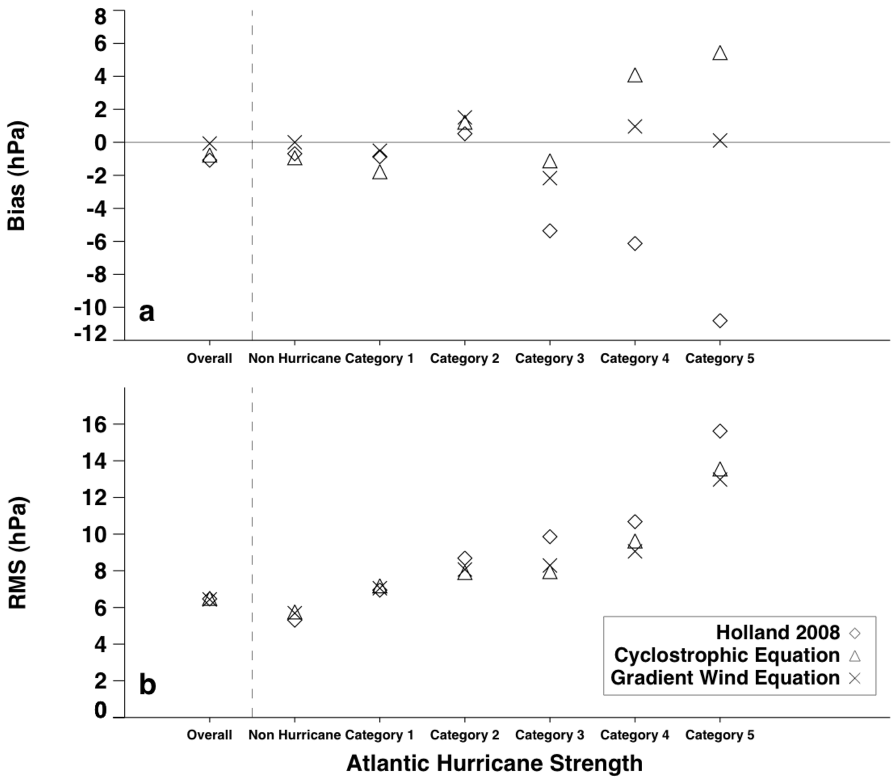

FIG. 3. 1977-2006 mean bias (a) and RMS error (b) of the wind speed/pressure relationship approximations examined here. Total number of sample points is in Table 2. Both bias estimates and RMS for the GWE are from three year jack-knifing.

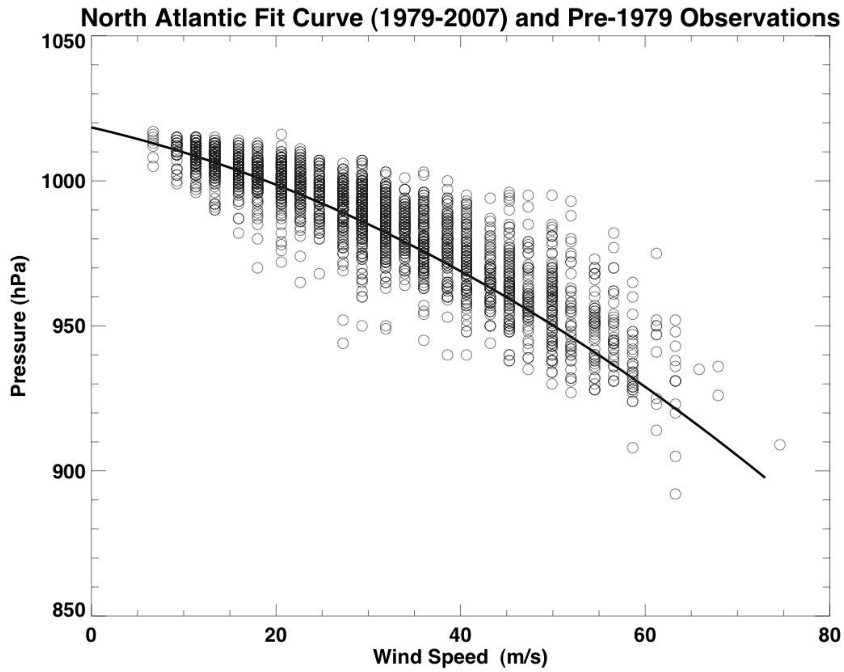

FIG. 4. Estimated Gradient Wind Equation (GWE) curve for the North Atlantic based on parameters determined using 10 595 IBTrACS data points from 1979-2007. Open circles show all the available IBTrACS simultaneous estimates of wind speed and central pressure before 1979.

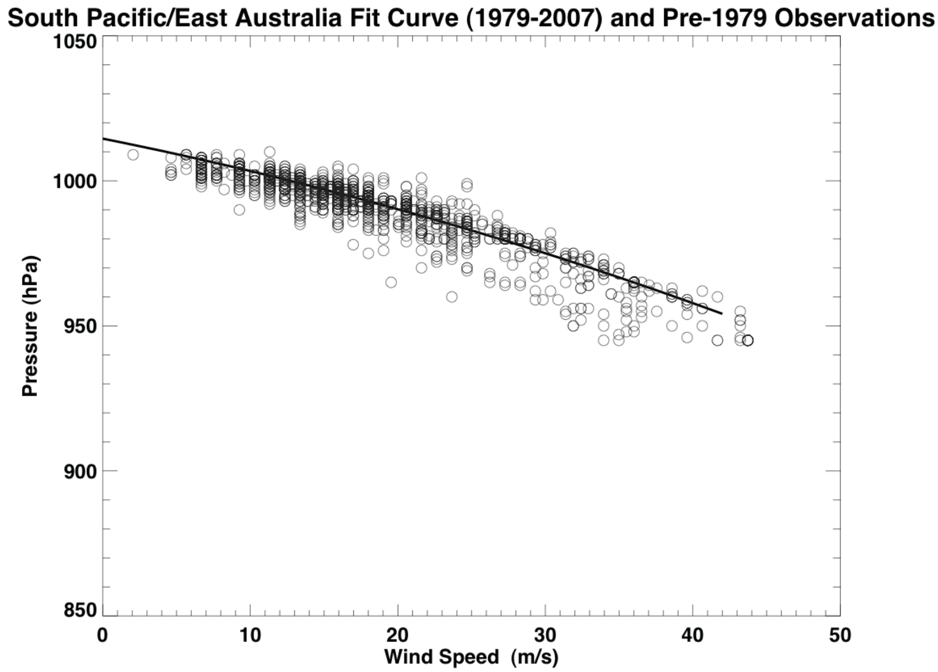

FIG. 5. As in Fig. 4 but for the South Pacific/East Australia sub-basin. The parameters to obtain the GWE curve are based on 2850 points.

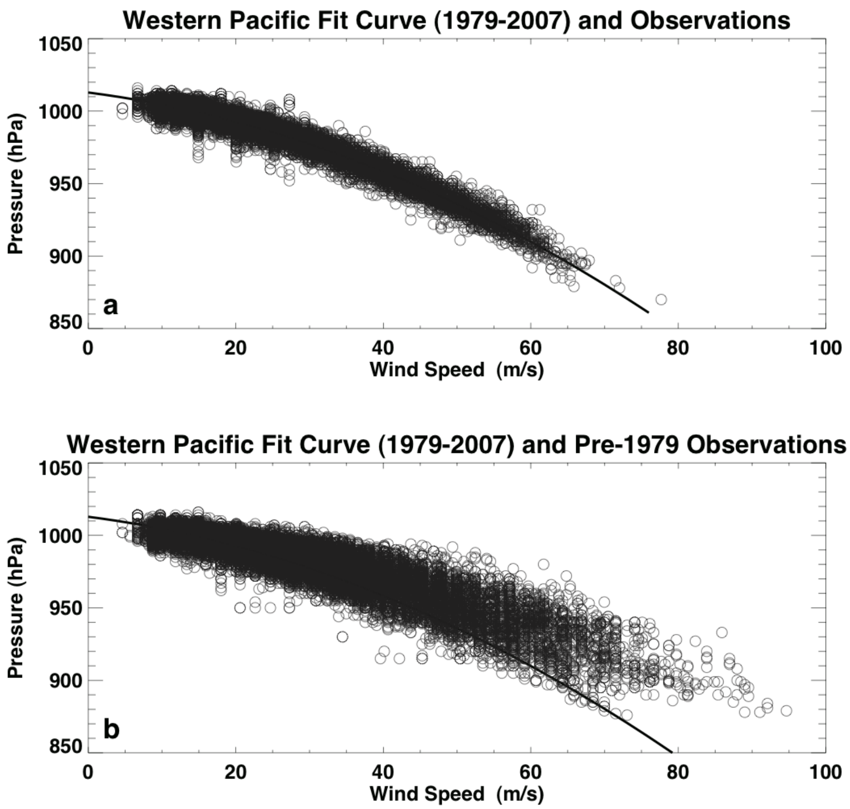

FIG. 6. (a) Estimated Gradient Wind Equation (GWE) curve for the Western Pacific based on parameters determined using 27 957 IBTrACS data points from 1979-2007, shown as open circles. (b) The GWE curve is reproduced, with open circles showing all the available IBTrACS simultaneous estimates of wind speed and central pressure before 1979.

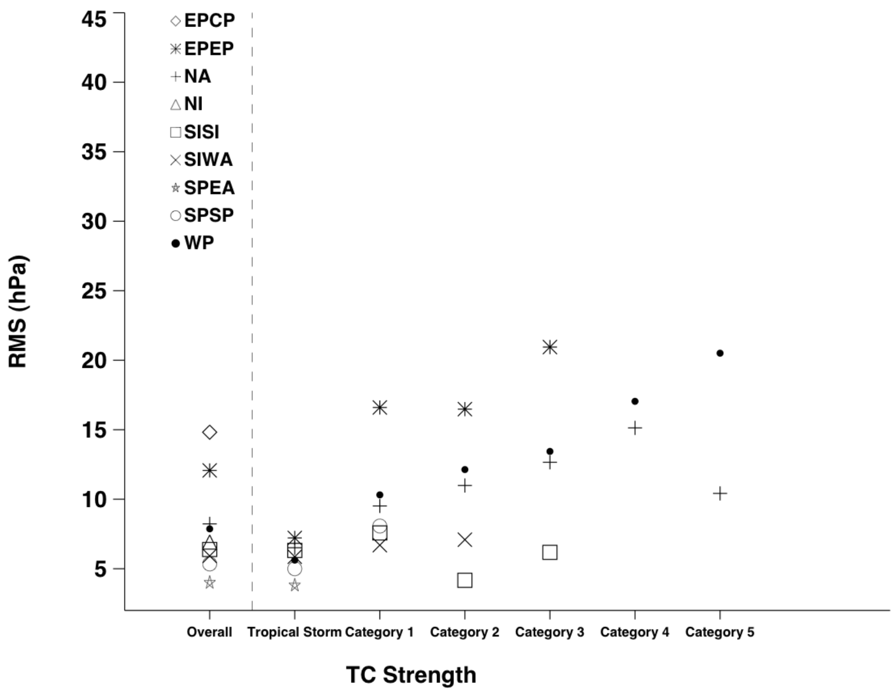

FIG. 7. RMS difference of the GWE-derived central pressure compared to IBTrACS central pressure estimates from the period 1958 to 1978, shown as a function of TC intensity, for the nine sub-basins defined in Fig. 1. GWE parameters were calculated separately for each sub-basin using IBTrACS estimates of wind speed and pressure from the period 1979-2007. RMS values computed from fewer than 40 values are omitted.

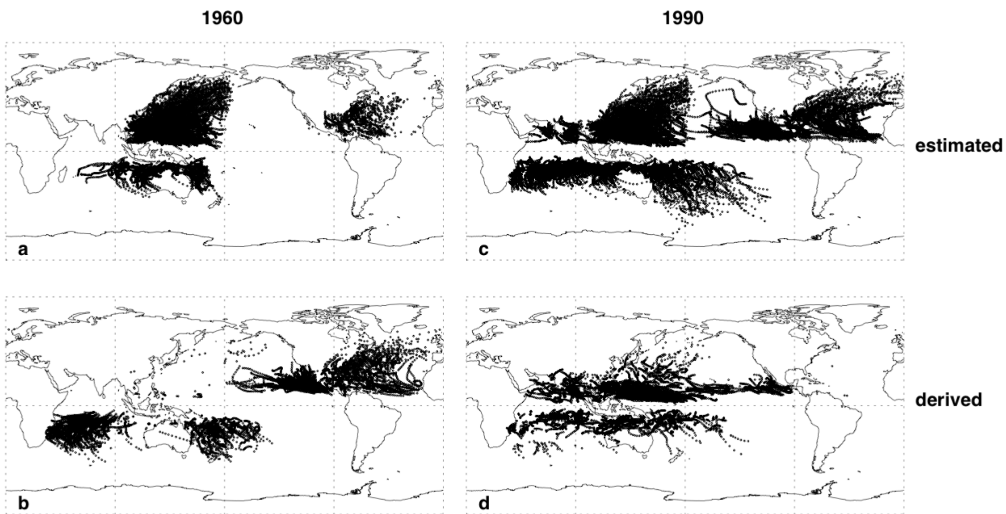

FIG. 8. (a,c) Spatial distribution of estimated and (b,d) derived TC central pressures during the 1960s (left) and 1990s (right).