

## A Pronounced Bias in Tropical Cyclone Minimum Sea Level Pressure Estimation Based on the Dvorak Technique

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### ABSTRACT

A pronounced and highly significant bias is uncovered in tropical cyclone minimum sea level pressure (MSLP) estimates calculated using the Dvorak technique. The bias is present in operational estimates from each of the primary Atlantic tropical analysis centers (TACs). The bias can be approximated as a linear function of latitude and is caused by the dependence of tropopause temperature on latitude. On average, MSLP estimates from each TAC are consistently too high (compared to aircraft reconnaissance measurements) at higher latitudes and too low at lower latitudes. The latitude of zero bias is near 23°N. Because the relationship between tropopause temperature and latitude is fairly robust among the global ocean basins, the latitude-dependent bias that exists in Dvorak technique MSLP estimates of Atlantic basin tropical cyclones should extend to Dvorak technique estimates in all ocean basins.

A simple linear fit is constructed between the Dvorak technique MSLP estimate errors and latitude, and this is applied as a latitude-dependent bias correction to the MSLP estimates. The correction has a significant effect on the error statistics of the samples from each TAC. Root-mean-square error is reduced by roughly 11%, 9%, and 10%, respectively, in the Tropical Analysis and Forecast Branch (TAFB), Satellite Analysis Branch (SAB), and Air Force Global Weather Center (AFGWC) samples.

Using available wind data, it is shown that a much weaker latitude-dependent bias exists in Dvorak technique estimates of near-surface wind ( $V_{\max}$ ). This is consistent with a recent study that used aircraft-based data from Atlantic tropical cyclones (TCs) to demonstrate that for a given MSLP, the associated measured  $V_{\max}$  tends to be weaker at higher latitudes. The empirical relationship between MSLP and  $V_{\max}$  used in the Dvorak technique has no dependence on latitude, which indirectly introduces a bias in the estimated wind that counteracts the bias in the MSLP estimates. This suggests that historical best-track data formed using Dvorak technique estimates contain a systematic latitude-dependent MSLP bias and a systematic inconsistency in the relationship between MSLP and  $V_{\max}$ . Correction of the MSLP bias in past tropical cyclones that were estimated using the Dvorak technique may have measurable effects on the present tropical cyclone climatology.

### 1. Introduction

For the past 30 years, the Dvorak (1975, 1984) technique has served as the benchmark for tropical cyclone (TC) intensity estimation using satellite data. The method relates TC minimum sea level pressure (MSLP) and maximum near-surface wind ( $V_{\max}$ ) to satellite-measured cloud features. The Dvorak technique has proven reliable over the years, and since most oceanic basins do not benefit from regular in situ measurements from aircraft, it is heavily relied on around the world as the only source of quantitative information on TC intensity that is available in a timely and continuous manner. The Dvorak technique uses geostationary satellite imagery to estimate TC intensity at all stages of its lifetime. The earliest documented versions of the technique (Dvorak

1973, 1975) relied heavily on visible imagery to extract intensity information by subjectively analyzing TC cloud patterns (e.g., eye and eyewall patterns, referred to collectively as “central features,” and “spiral band patterns”). This method of analyzing cloud patterns using visible images is called the Dvorak VIS technique. The Dvorak technique yields intensity estimates in terms of  $T$  numbers (short for tropical numbers). The  $T$  numbers are then related to current intensity (CI) numbers that are then directly related to MSLP and  $V_{\max}$  using a simple table (with greater  $T$  numbers associated with greater intensity).

With improvements in satellite infrared (IR) imagery, the Dvorak technique was modified to include the enhanced IR (EIR) technique, which utilizes this new data source (Dvorak and Wright 1977; Dvorak 1984). The present use of IR data in the Dvorak EIR technique is twofold. First, the IR data can be used as a substitute for visible imagery at night. For example, cloud patterns and related spiral banding structure can be readily seen in IR imagery at any time. Second, the IR data provides

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quantitative digital information about cloud-top temperature and thus serves as a measure of convective vigor. For TCs that have developed an eye, the IR data also gives quantitative information about the eye temperature and thus serves as a measure of eye subsidence. In the Dvorak EIR technique, the cloud-top temperature above the eyewall region and the temperature in the eye region can be related directly to TC intensity using a nomogram (Dvorak 1984, his Fig. 9) in which colder eyewall cloud-top temperatures and warmer eye temperatures are correlated with greater intensity.

How the IR imagery is used by the Dvorak EIR technique depends mostly on the cloud patterns in the satellite scene being analyzed. The patterns seen in either visible or IR imagery are classified within the Dvorak technique as “curved band,” “shear,” “central dense overcast” (CDO), “eye,” or “embedded center” patterns. For curved band and CDO scene types, the IR imagery is used only to discern shapes and sizes of cloud features, respectively. In the case of curved band analyses, the EIR and VIS techniques are the same (Dvorak 1984). For shear scene types, the IR imagery is used to measure distance between the TC center and the horizontally displaced cold cloud tops. For eye and embedded center patterns (referred to hereafter as E/EMB scenes), digital IR temperature measurements are of primary importance in the Dvorak EIR technique.

In this paper, we demonstrate a robust, highly significant, and pronounced bias that exists in MSLP estimates from the Dvorak EIR technique when applied to Atlantic basin tropical cyclones exhibiting E/EMB scenes (section 3a). Removal of this bias from the MSLP estimates has a significant effect on error distributions and statistics—reducing root-mean-square error (rmse) by 10% on average (section 3b)—and thus offers a significant improvement over the present operational Dvorak technique<sup>1</sup> performance. The bias is an approximately linear function of latitude and is caused by the dependence of cloud-top temperature on latitude that results from the relationship between tropopause temperature and latitude (section 4). We find that given two TCs with the same MSLP, the TC at higher latitudes will generally have warmer cloud-top temperatures than the TC at lower latitudes, and thus the Dvorak technique will, on average, yield an erroneously lesser (greater) MSLP for the TC at lower (higher) latitudes. We also find that with the exception of the northern Indian Ocean, the relationship between tropopause temperature and latitude is fairly consistent between the various global ocean basins (section 4), and thus we expect that the latitude-dependent bias uncovered in the Atlantic basin can be extended to apply globally to Dvorak technique estimates of TC MSLP.

<sup>1</sup> Hereafter, “Dvorak technique” refers to the Dvorak EIR technique applied to E/EMB scenes.

## 2. Data and method

The datasets used in this study are the following:

- 1) 1419 aircraft reconnaissance fixes in 26 TCs that occurred in the Atlantic basin during the period 1995–2002. Each aircraft fix contains the maximum tangential wind encountered along the flight-level radial leg (toward or away from the TC center, typically along the 700-mb pressure level) and the minimum pressure at the TC center, extrapolated from flight level to the sea surface (MSLP).
- 2) 1688 Geostationary Operational Environmental Satellite (GOES) IR images captured within 1 h of each aircraft fix.
- 3) 1075 operational TC intensity estimates calculated using the Dvorak technique applied to GOES imagery captured within 1 h of an aircraft fix. The intensities were estimated at the three primary Atlantic tropical analysis centers (TACs)—the Tropical Analysis and Forecast Branch (TAFB) located at the National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction (NOAA/NCEP) Tropical Prediction Center, the NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) Satellite Analysis Branch (SAB), and the U.S. Air Force Global Weather Center (AFGWC). We have 408, 394, and 273 Dvorak technique estimates of MSLP from TAFB, SAB, and AFGWC, respectively. An inventory of the Dvorak technique intensity estimates used in this study is shown in Table 1.

The seminal construction of the Dvorak technique is based on correlations between MSLP and satellite-measured cloud features (V. Dvorak 2003, personal communication). However,  $V_{\max}$  is a more useful metric for TC intensity because it is the wind surrounding the TC, and not the MSLP, that poses the direct threat to life and property. Dvorak (1975) related  $T$  numbers to MSLP, but the associated CI numbers were ultimately related to  $V_{\max}$  using an empirical relationship between MSLP and  $V_{\max}$ . Our flight-level data contain information regarding maximum flight-level wind and MSLP, but the maximum flight-level wind can be strongly dependent on TC azimuth (measured around the TC center) and thus can be highly variable between consecutive flight-level radial legs. This results in apparent transient variations that are typically not well correlated with the more slowly evolving intensity of the storm. In comparison, MSLP has no spatial dependence and only varies in time and thus is a smoother and more consistent measure of intensity evolution. Furthermore, the empirically based methods used to extrapolate flight-level wind to near-surface wind ( $V_{\max}$ ) have varied over time (Franklin et al. 2003), and thus archival near-surface wind data presently contain systematic inconsistencies. The method used to extrapolate MSLP from flight level is more physically fundamental—it is based on a simple

TABLE 1. Number of operational Dvorak EIR technique tropical cyclone intensity estimates calculated at each of the three primary Atlantic basin tropical analysis centers, in each of the 26 storms in the dataset.

Storm	TAFB	SAB	AFGWC
Bertha (1996)	16	12	9
Bonnie (1998)	23	22	22
Bret (1999)	7	7	8
Danielle (1998)	20	20	16
Danny (1997)	6	8	5
Dennis (1999)	16	16	18
Edouard (1996)	24	23	13
Erika (1997)	13	13	7
Felix (1995)	15	14	8
Floyd (1999)	29	29	21
Fran (1996)	33	34	6
Georges (1998)	20	19	17
Gert (1999)	10	10	6
Hortense (1996)	17	18	8
Irene (1996)	4	4	7
Iris (1995)	8	6	2
Iris (2001)	10	10	6
Keith (2000)	15	14	12
Lenny (1999)	22	20	21
Lili (2002)	13	13	20
Luis (1995)	14	14	2
Marilyn (1995)	19	18	4
Michelle (2001)	12	11	10
Mitch (1998)	15	13	10
Opal (1995)	9	9	6
Roxanne (1995)	18	17	9
Total:	408	394	273

hydrostatic integration—and is thus more consistent in archival data.

Another data source that provides wind information is the best-track archive maintained by the Tropical Prediction Center in Miami, Florida (Jarvinen et al. 1984). When reconnaissance data is available, the postseason construction of the best-track data reflects a spatial average of near-surface wind extrapolated from the available flight-level wind. This wind information is then smoothed to 6-h temporal resolution. As noted above, flight-level (and near-surface) wind is strongly dependent on azimuth measured around the TC center, and the rarefied spatial sampling of flight-level wind may not be adequate to represent the overall intensity of the TC being measured. Thus there are a number of significant challenges to the accurate interpretation of available in situ TC wind data, and our main results in section 3 are limited to consideration of MSLP. We will comment again on best-track wind data in section 5.

As noted in section 1, our analyses should be limited to MSLP estimations for E/EMB scenes. This is because in the three remaining scene types, the digital temperature information in the IR data is used only informally and subjectively as an aid for determining patterns, sizes, or distances. Unfortunately, information regarding what scene type was operationally applied by the forecaster is not typically included in the existing archives of Dvorak technique estimates. In order to best stratify

the data to exclude scene types other than E/EMB, we used the fact that estimates of E/EMB scene types always result in a  $T$  number of at least 3.5 (MSLP  $\sim$  994 mb), while curved band and shear scene types never result in a  $T$  number greater than 3.5. We then stratified the operational Dvorak technique estimates by excluding all estimates with a  $T$  number less than 3.5. Our dataset thus consists of intensity estimates based on E/EMB scene types with some contamination of the stratified data by the presence of some CDO scene types. To estimate the amount of contamination in our dataset, an analysis was performed at SAB using available operational Dvorak technique estimates from the current 2003 season. These estimates still contain information regarding scene type. Of the 1150 estimates in the sample, the CDO pattern was applied 21 times and E/EMB patterns were applied 244 times. Within the subset of 21 CDO patterns, only 8 resulted in  $T$  numbers greater than or equal to 3.5. Thus, based on this sample, for  $T$  numbers greater than or equal to 3.5, we would expect 97% of the scene types to be E/EMB patterns.

### 3. Results

#### *a. A latitude-dependent bias in tropical cyclone MSLP estimated using the Dvorak technique*

Scatterplots of Dvorak technique error versus latitude for each of the three Atlantic TACs are shown in Fig. 1. Error is defined here as the MSLP estimated by the Dvorak technique (using the Dvorak CI number) minus the aircraft-measured MSLP. Thus, negative (positive) errors are indicative of overestimation (underestimation) of MSLP-measured intensity by the Dvorak technique. Latitude represents the latitude of the TC center estimated by the forecaster for use in the Dvorak technique. Each scatterplot in Fig. 1 is annotated with the line of regression of error onto latitude and the statistics and formula of the regression line. The regressions (all significant at greater than 99.9%) explain 15% to 20% of the variance of error in the three samples, and represent a pronounced latitude-dependent bias in the Dvorak technique. It should be noted that comparisons of the errors between the three scatterplots in Fig. 1 should be avoided because the three samples are not homogeneous with respect to each other. The feature of importance here is the robust latitude-dependent bias that is seen in the MSLP estimates from each TAC.

There is some variation in the slopes and intercepts among the regression lines in Fig. 1, and consequently there is some variation in the latitude of zero bias that ranges from 21.7° to 25.0°N, but the general results are all very similar. Figure 2 shows the combined samples from the three TACs and provides a general description of the latitude-dependent bias that exists in the operational TC MSLP estimates obtained using the Dvorak technique in the Atlantic basin. Within the range of latitudes 10°–40°N, the bias in the combined sample

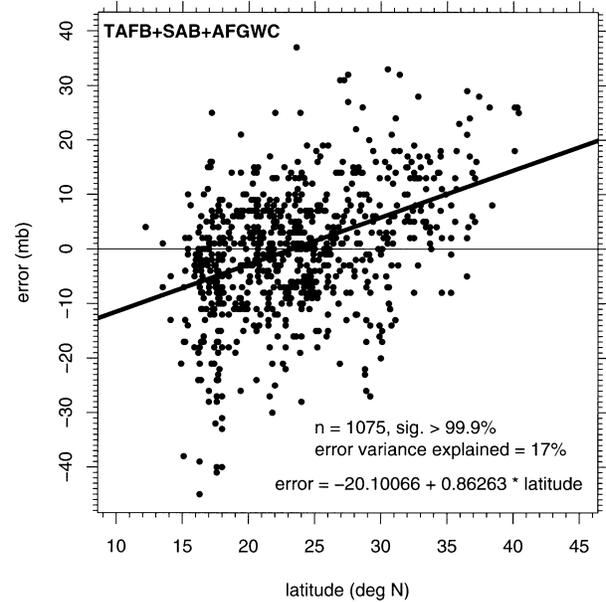
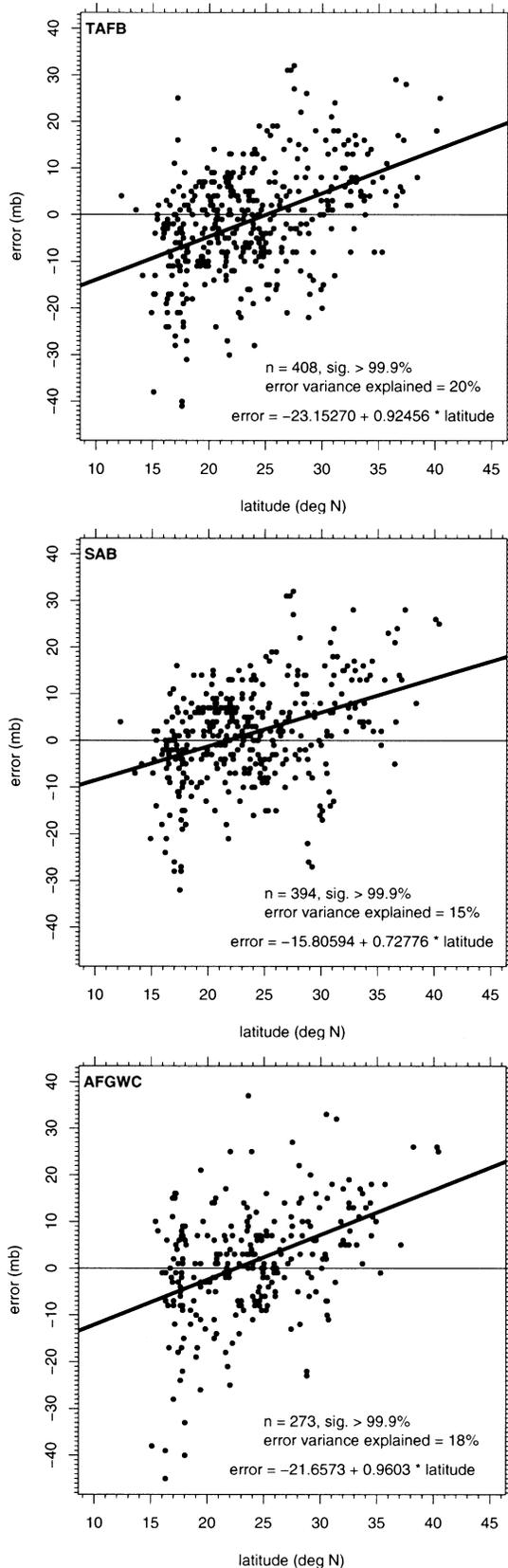


FIG. 2. Same as Fig. 1, but for the combined sample (all three TACs). The line of regression gives a general description of the latitude-dependent bias that exists in Atlantic TC MSLP estimates calculated operationally using the Dvorak technique.

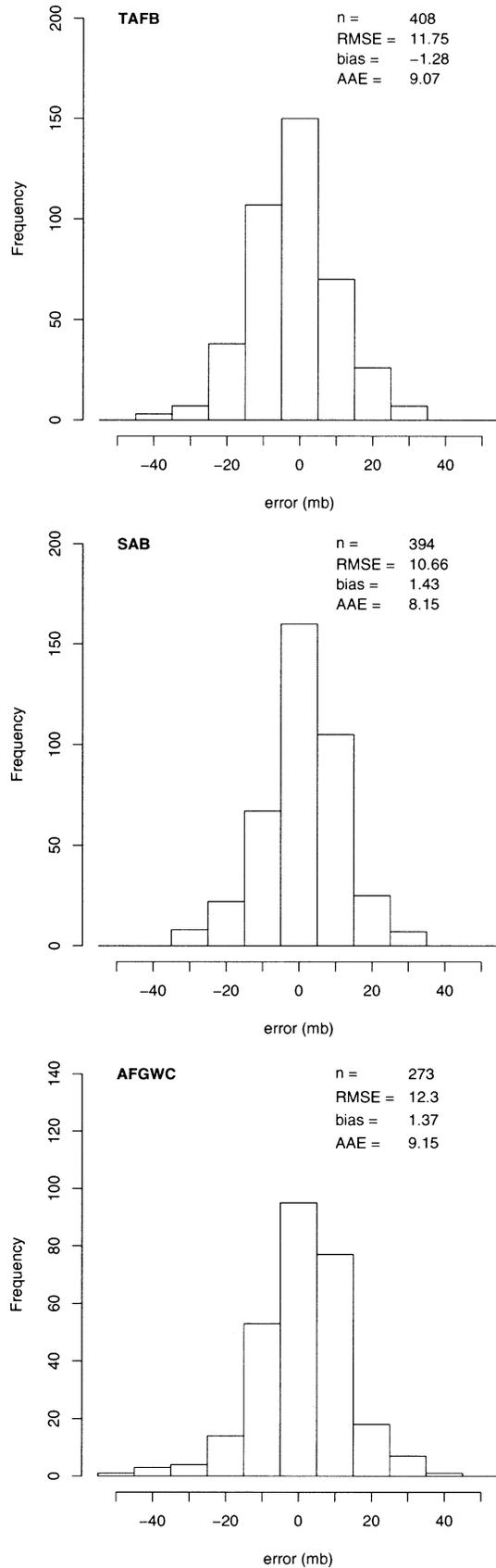
ranges from  $-11$  to  $+14$  mb. The latitude of zero bias for the combined sample is  $23.3^{\circ}\text{N}$ .

*b. Removal of the latitude-dependent bias and its effect on error distributions and statistics*

Histograms showing the error distribution for the Dvorak technique estimates from the three TACs are shown in Fig. 3. Note that the bias from each TAC is always between  $\pm 1.5$  mb and thus by itself does not suggest a serious systematic problem with the Dvorak technique. But as shown in section 3a, the bias at a particular latitude can range between  $-11$  and  $+14$  mb. Figure 4 shows the error distributions after subtracting the latitude-dependent biases (shown by the regression lines in Fig. 1) from the MSLP estimates. In each case, applying the bias correction to the sample reduces the error of the outliers and reduces rmse roughly 11%, 9%, and 10%, respectively, for the TAFB, SAB, and AFGWC samples. Although an average improvement of 10% may seem small, it is very significant when applied to a method that has been in worldwide use for 30 years and has remained essentially unchanged for 20 years.

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FIG. 1. Dvorak technique MSLP-based intensity estimate error as a function of latitude for each TAC. For each TAC, the line of regression, its statistics, and its formula are shown. Negative (positive) errors indicate that the Dvorak technique overestimated (underestimated) intensity. The regression lines indicate a pronounced latitude-dependent bias in the MSLP estimates.



It is clear from Fig. 1 that the removal of the latitude-dependent bias will adjust different estimates in different ways; that is, while the bias correction reduces error when considering the overall samples from each TAC, it will certainly degrade a subset of intensity estimates. To quantify this, we looked at the effect that the bias removal has on the rmse of each of the 26 individual TCs in the sample. We found that for the TAFB estimates, the bias correction reduces (increases) rmse in 14 (8) of the TCs, with the rmse for 4 TCs remaining roughly unchanged (rmse change between  $\pm 0.2$  mb). The average rmse change for the improved cases was  $-2.4$  mb and the average change for the degraded cases was  $+1.2$  mb. For the SAB estimates, rmse in 15 (7) TCs was improved (degraded) and 4 TCs were unchanged. The average rmse improvement (degradation) was  $-1.8$  ( $+1.7$ ) mb. For the AFGWC estimates, rmse in 17 (8) TCs was improved (degraded) and 1 TC was unchanged. The average rmse improvement (degradation) was  $-2.6$  ( $+2.0$ ) mb. Thus, for the combined sample the bias correction reduces rmse in about twice as many TCs as it increases rmse, and the magnitude of rmse change is typically around 40% greater for the improved cases than the degraded cases.

We have thus far documented a robust latitude-dependent bias that exists in archival data samples of Dvorak technique TC MSLP estimates and have demonstrated the effect that removal of the bias has on the error statistics of the samples. From an operational point of view, however, a natural question is how much improvement can be expected when the bias correction is applied in a real-time setting. To address this question more rigorously, we repeated our analyses for each TAC using a jackknife approach in which each TC in the 26 TC sample was individually removed from the sample and the regression line describing the bias was derived using the remaining 25 TCs. The resulting latitude-dependent bias was then subtracted from the MSLP estimates for the omitted TC. These steps were repeated for each TC and the accumulated errors were tallied. As expected, this method reduced the improvement of rmse, but the reduction was small ( $\sim 2\%$ ) for each of the three TACs. Thus a reasonable expectation in an operational setting would be that application of the latitude-dependent bias correction will result, on average, in a roughly 8% reduction of rmse.

**4. Physical explanation**

In section 1, it was noted that Dvorak EIR technique intensity estimates applied to E/EMB scene types rely largely on IR-measured cloud-top temperatures in the

FIG. 3. Dvorak technique MSLP error distributions for each TAC. The number of estimates ( $n$ ), rmse, average error (bias), and absolute average error (AAE) are shown on each plot.

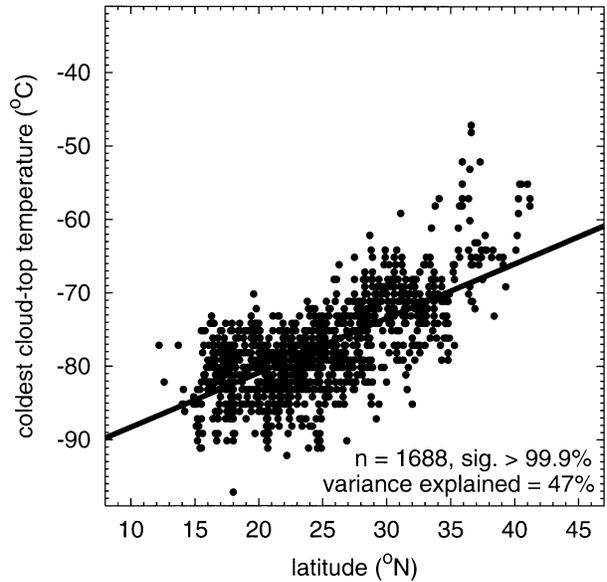
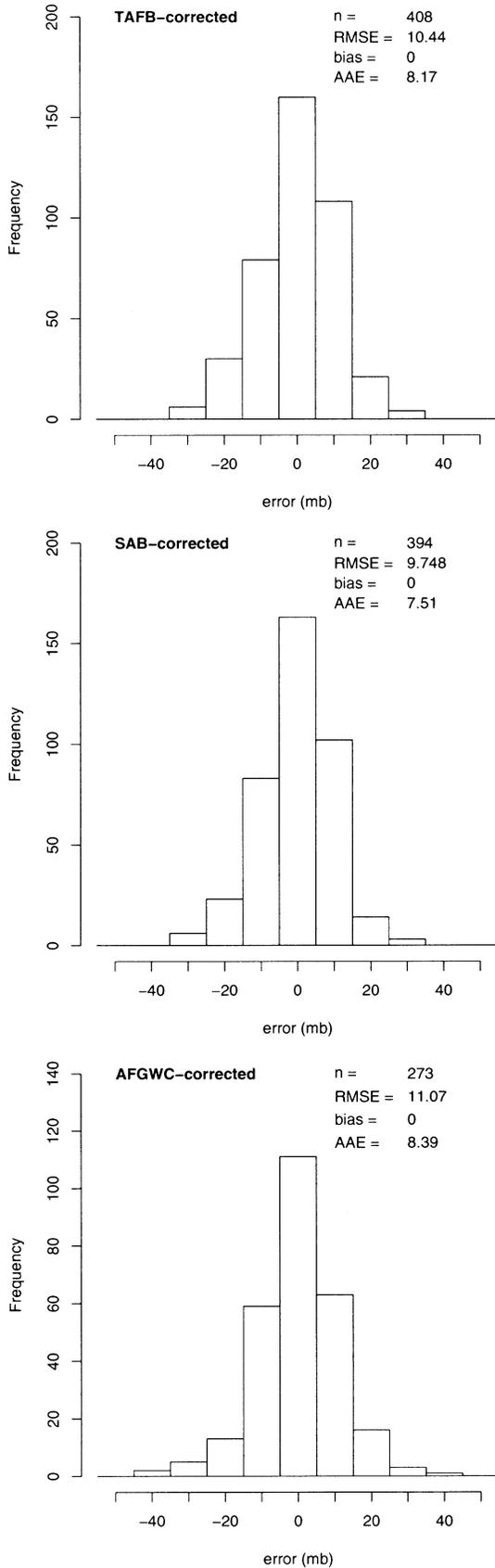


FIG. 5. Relationship between latitude and coldest IR-measured cloud-top temperature within 150 km of the TC center. The line of regression explains 47% of the variance of cloud-top temperature.

eyewall region. Here we will demonstrate that the latitude-dependent bias of Dvorak technique estimates of MSLP is a result of the relationship between IR-measured cloud-top temperature and latitude. This relationship is shown in Fig. 5 and results from the relationship between tropopause temperature and latitude in the Atlantic basin (shown by the thin solid line in Fig. 6—the other lines will be discussed later). The height of the tropopause typically lowers, and the tropopause temperature consequently increases, with increasing latitude. Since the tropopause acts as a lid on TC eyewall convection, the minimum achievable cloud-top temperature above the eyewall region increases with increasing latitude. However, this latitude-dependent limitation on the minimum achievable eyewall cloud-top temperatures apparently does not represent a strong enough limitation on MSLP-measured intensity to negate the bias. In other words, imposing a lower lid on eyewall convection does not impede the intensity in a way that is commensurate with the amount that the Dvorak technique lowers its intensity estimate based on the warmer cloud-top temperatures. Thus, for example, a TC with some fixed mean eyewall cloud-top temperature will have lower MSLP at higher latitudes, all other parameters being equal.

Another way to elucidate the role that latitude plays in the relationship between MSLP and cloud-top temperature is by regressing aircraft-measured MSLP onto

FIG. 4. Dvorak technique MSLP error distributions for each TAC after removing the latitude-dependent biases given by the regression lines in Fig. 1.

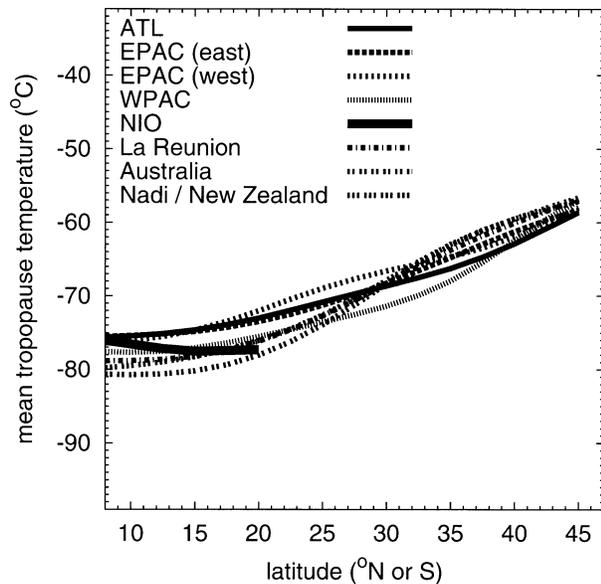


FIG. 6. Variation of mean tropopause temperature with latitude in each global ocean basin during the period 1948–2002. For Northern (Southern) Hemisphere basins, averages span Aug, Sep, Oct (Feb, Mar, Apr). For Northern Hemisphere basins, longitudinal averages span 260°–340°E for the Atlantic (ATL), 220°–250°E and 180°–220°E for the east Pacific (EPAC), 120°E–180° for the west Pacific (WPAC), and 50°–100°E for the northern Indian Ocean (NIO). For the Southern Hemisphere, longitudinal averages span 40°–90°E for the La Reunion Island region of the southern Indian Ocean, 90°–160°E for the Australian region, and 160°–240°E for the Nadi/New Zealand region. The data are from the NCEP reanalysis data archive.

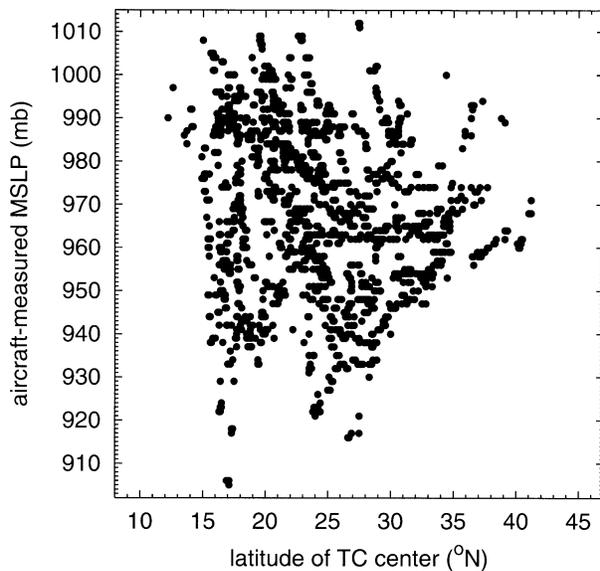


FIG. 7. Relationship between aircraft-measured MSLP (in the Atlantic basin) and latitude of the TC center. There is no meaningful functional relationship in the data.

mean eyewall cloud-top temperature and latitude (Kossin et al. 2003). The results of this multiple regression show that the correlation coefficient between MSLP and mean eyewall cloud-top temperature is highly significant and positive (i.e., colder cloud-top temperatures correlate to lower MSLP) as expected, but the coefficient on latitude is negative. This does not indicate that TCs at higher latitudes are systematically deeper (i.e., have lower MSLP) than TCs at lower latitudes—in fact, there is no significant functional relationship between aircraft-measured MSLP and TC latitude in our dataset. This can be seen in Fig. 7, which shows the relationship between aircraft-measured MSLP and TC latitude and demonstrates that, on average, the most intense TCs in our Atlantic sample are generally found between 15° and 30°N, while weaker TCs are found at all latitudes. The same general relationship was found in western Pacific basin TCs (Weatherford and Gray 1988, their Fig. 7). While there is no systematic functional relationship between MSLP and latitude, the latitude does act to modulate the relationship between the cloud-top temperature and MSLP in such a way that it “intensifies” (deepens) TCs at higher latitudes and “weakens” (fills) TCs at lower latitudes. The highly significant regression of MSLP onto eyewall cloud-top temperature explains 17% of the variance of MSLP. The multiple regression of MSLP onto eyewall cloud-top temperature

and latitude explains around two-thirds more (28%) of the variance of MSLP because the latitude *modulates* the direct relationship between cloud-top temperature and MSLP.

Figure 8 shows the global distribution of tropopause temperature, based on long-term monthly means from the period 1948–2002. The Northern Hemisphere temperatures (Fig. 8a) were averaged over the peak TC season August–October and the Southern Hemisphere temperatures (Fig. 8b) were averaged over February–April. Mean tropopause temperature profiles based on longitudinal averages across each oceanic basin—defined by the regions of responsibility of each World Meteorological Organization (WMO) tropical cyclone Regional Specialized Meteorological Centre (RSMC)—are shown in Fig. 6 and represent the average conditions during active TC periods in each hemisphere. Note that with the exception of the northern Indian Ocean, the mean tropopause temperature profiles in all the basins are similar to the profile in the Atlantic basin. The Southern Hemisphere profiles tend to have steeper meridional gradients from ~20°–40°S, and we may then expect the latitude-dependent bias in the Dvorak technique to be more pronounced there. The west Pacific basin is generally colder than the Atlantic,<sup>2</sup> but the gradients are about the same in the two basins, and thus the bias correction for the Atlantic is likely to be appropriate for west Pacific TC MSLP estimation.

The northern Indian Ocean extends only to around 20°N, and the gradient of the tropopause temperature

<sup>2</sup> The relationship between Dvorak technique CI number and MSLP is adjusted in the west Pacific to account for the colder tropopause (Dvorak 1975, 1984; Shewchuk and Weir 1980).

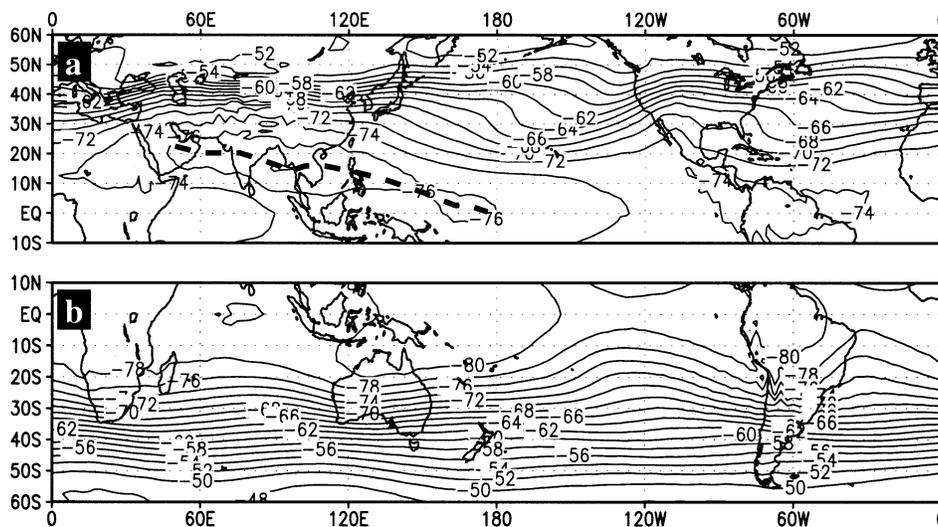


FIG. 8. Global distribution (from NCEP reanalysis) of long-term (1948–2002) mean tropopause temperature ( $^{\circ}\text{C}$ ) in (a) the Northern Hemisphere during Aug–Oct and (b) the Southern Hemisphere during Feb–Apr. The thick dashed line in (a) denotes the axis of the cold tongue spanning the longitudes from  $60^{\circ}\text{E}$  to  $180^{\circ}$ .

profile has opposite sign compared with all other basins. The causal feature for this gradient reversal is seen in Fig. 8 as a cold tongue extending northwest to southeast across the Arabian Sea, Bay of Bengal, South China Sea, and part of the western Pacific Ocean. This feature has been described as a component of a “stratospheric fountain” (Newell and Gould-Stewart 1981) where tro-

pospheric air enters the stratosphere. In regions south of the cold tongue axis (shown by the thick dashed line in Fig. 8a), tropopause temperatures decrease with increasing latitude, and application of the latitude-dependent bias correction is not expected to be appropriate.

## 5. Discussion

The Dvorak technique has been in use globally for roughly 30 years, and for the past 20 years the Dvorak EIR technique has relied on IR data to estimate TC intensity. Also in the past 20 years, the Atlantic basin is the only region that has maintained regular aircraft reconnaissance into TCs. Even when aircraft measurements are available, the Dvorak technique still provides routine intensity estimates. Thus most of the TCs that occur around the world are estimated at least partly, and in some cases entirely, by the Dvorak technique. This study has documented a pronounced latitude-dependent bias that exists in Dvorak technique MSLP estimates of Atlantic basin TCs. The bias explains about 17% of the operational MSLP estimate error variance from the three primary Atlantic TACs, and removal of the bias reduces the MSLP rmse by around 10%. The latitude-dependent bias is a product of the relationship between tropopause temperature and latitude, and since this relationship is fairly consistent in all other ocean basins (except the northern Indian Ocean), it is likely that a very similar bias exists in TC MSLP estimates from the east, west, and South Pacific Ocean, and the southern Indian Ocean. In addition, methods such as the Objective Dvorak Technique (ODT; Velden et al. 1998) that imitate the IR-measured temperature relationships of the Dvorak technique should also benefit from a similar bias correction.

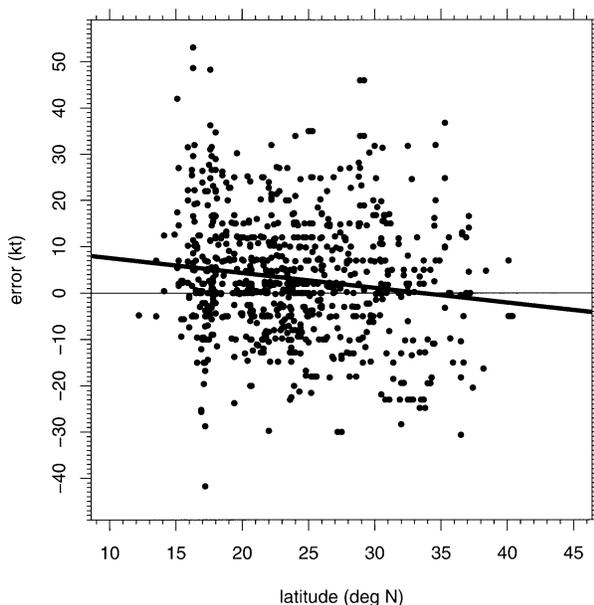


FIG. 9. Dvorak technique–estimated  $V_{\max}$  error (kt) as a function of latitude for the combined sample (all three TACs). Error is defined as Dvorak technique wind estimates minus best-track wind. The best-track winds reflect a smoothed postanalysis of the available aircraft flight-level data. The line of regression explains less than 2% of the variance of error.

The latitude-dependent bias in the Dvorak technique MSLP estimates can be simply corrected using the regression equations provided in Figs. 1 and 2. The aircraft reconnaissance and TAC data samples will expand over time, and these regression equations can be easily updated at the end of each hurricane season. Another, perhaps more elegant way to remove the latitude-dependent bias from the MSLP estimates is to recast the Dvorak technique nomogram (discussed in section 1) to include an additional dimension that takes latitude into account.

A recent study by Landsea et al. (2003) provides insight into the relationship between latitude and Dvorak technique wind estimates. By regressing Atlantic best-track MSLP onto the concurrent best-track  $V_{\max}$  (in cases when aircraft data were available), they found that the empirical relationship between MSLP and  $V_{\max}$  employed by the Dvorak technique (which has no latitudinal dependence) generally provides wind that is too strong for a given pressure. More relevant to our results, they found that the overestimation of  $V_{\max}$  worsened with increasing latitude. This latitude dependence would counteract the bias we found in the MSLP estimates, and thus the Dvorak technique estimates of  $V_{\max}$  should be expected to exhibit a weaker latitude-dependent bias than MSLP, if a bias exists at all.

Keeping in mind the caveats of the best-track wind data addressed in section 2, we extracted the best-track  $V_{\max}$  values associated with our datasets by linearly interpolating the  $V_{\max}$  values to the times of our operational Dvorak technique estimates with  $T$  number  $\geq 3.5$ . The error in the Dvorak technique  $V_{\max}$  estimates relative to best-track wind is plotted against latitude in Fig. 9. Consistent with expectations, the latitude-dependent bias of  $V_{\max}$  is much less pronounced than the bias found in MSLP. The regression of latitude onto  $V_{\max}$  error is significant (greater than 99.9%) but explains very little (less than 2%) of the error variance. Our conclusion is that the latitude-dependent bias in the relationship between MSLP and  $V_{\max}$  specified by the Dvorak technique appears to almost entirely counteract the latitude-dependent bias noted in the MSLP estimates. This suggests that while archival values of Dvorak technique-estimated MSLP contain a bias, the corresponding values of  $V_{\max}$  may not contain a similar bias. This is an important result that will need to be taken into account when considering pressure-wind relationships using these archival data. When aircraft data are not available, Dvorak technique MSLP and  $V_{\max}$  estimates are used in the development of the postseason best-track datasets, and thus the existing archival datasets that define TC climatology contain a systematic bias in MSLP and systematic inconsistencies in the relationship between MSLP and  $V_{\max}$ . Fortunately, the reanalysis of existing best-track datasets could be accomplished fairly easily,

but the effect that such a reanalysis will have on present TC statistics is not yet clear.

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