An Evaluation of Dvorak Technique–Based Tropical Cyclone Intensity Estimates

JOHN A. KNAFF

NOAA/NESDIS/Regional and Mesoscale Meteorology Branch, Fort Collins, Colorado

DANIEL P. BROWN

NOAA/NWS/National Hurricane Center, Miami, Florida

JOE COURTNEY

Bureau of Meteorology, Perth, Western Australia, Australia

GREGORY M. GALLINA

NOAA/NESDIS/Satellite Analysis Branch, Camp Springs, Maryland

JOHN L. BEVEN II

NOAA/NWS/National Hurricane Center, Miami, Florida

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ABSTRACT

The satellite-based Dvorak technique (DVKT) is the most widely available and readily used tool for operationally estimating the maximum wind speeds associated with tropical cyclones. The DVKT itself produces internally consistent results, is reproducible, and has shown practical accuracy given the high cost of in situ or airborne observations. For these reasons, the DVKT has been used in a reasonably uniform manner globally for approximately 20 years. Despite the nearly universal use of this technique, relatively few systematic verifications of the DVKT have been conducted. This study, which makes use of 20 yr of subjectively determined DVKT-based intensity estimates and best-track intensity estimates influenced by aircraft observations (i.e., ± 2 h) in the Atlantic basin, seeks to 1) identify the factors (intensity, intensity trends, radius of outer closed isobar, storm speed, and latitude) that bias the DVKT-based intensity estimates, 2) quantify those biases as well as the general error characteristics associated with this technique, and 3) provide guidance for better use of the operational DVKT intensity estimates. Results show that the biases associated with the DVKT-based intensity estimates are a function of intensity (i.e., maximum sustained wind speed), 12-h intensity trend, latitude, and translation speed and size measured by the radius of the outer closed isobar. Root-mean-square errors (RMSE), however, are shown to be primarily a function of intensity, with the best signal-to-noise (intensity to RMSE) ratio occurring in an intensity range of 90–125 kt (46–64 m s^{-1}). The knowledge of how these factors affect intensity estimates, which is quantified in this paper, can be used to better calibrate Dvorak intensity estimates for tropical cyclone forecast operations, postseason best-track analysis, and climatological reanalysis efforts. As a demonstration of this capability, the bias corrections developed in the Atlantic basin are also tested using a limited east Pacific basin sample, showing that biases and errors can be significantly reduced.

1. Introduction

The Dvorak technique (DVKT), which estimates the intensity of tropical cyclones (TCs) by analyzing satellite image patterns (Dvorak 1972, 1975, 1984) and infrared cloud-top temperatures (Dvorak 1984, 1995), has become an important operational tool over the last 30 years (Velden et al. 2006a). The DVKT assigns an intensity estimate in terms of intensity units or "T numbers," which range from 1 to 8 in increments of 0.5 where a unit T number was designed to correspond to the climatological rate of tropical cyclone intensification.

Corresponding author address: John Knaff, NOAA/NESDIS/RAMMB, Colorado State University, CIRA, Foothills Campus Delivery 1375, Fort Collins, CO 80523-1375.
E-mail: john.knaff@noaa.gov

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Without going into great detail, the method involves locating the storm center, assigning a pattern (e.g., eye, shear, banded, central dense overcast, etc.), making measurements from satellite imagery (visible or enhanced infrared), assigning a T number, and estimating the current intensity (CI) by following the rules or constraints specified by the technique. The visible and enhanced IR (EIR) techniques also provide similar results [i.e., 95% were within a half T number; Gaby et al. (1980)]. The CI then corresponds to a maximum wind speed, as show in Table 1, which comes from Dvorak (1984). Other CI versus maximum wind speed/minimum sea level pressure (MSLP) tables have also been developed for use at other World Meteorological Organization (WMO) Regional Specialized Meteorological Centres (RSMCs) and Australian Tropical Cyclone Warning Centres (TCWCs) to account for different wind-averaging periods and wind–pressure relationships. For more information on wind–pressure relationships, see Koba et al. (1990, 1991), Knaff and Zehr (2007, 2008), Courtney and Knaff (2009), Holland (2008), and Harper (2002). It should also be noted that users of the DVKT in other basins have also applied regional variations and modifications (Velden et al. 2006b) to the DVKT as described in Dvorak (1984).

Throughout the late 1980s and 1990s, there was a concerted WMO training effort to educate forecasters in the use of proven/standard techniques for tropical cyclone forecasting, including the Dvorak technique (WMO 2000). As a result of this effort, most WMO RSMCs and TCWCs were using the Dvorak technique in operations by the late 1980s (Harper et al. 2008; Velden et al. 2006a). The DVKT has been shown to be relatively stable with respect to satellite sensor resolution (Zehr et al. 2010). The DVKT has also been shown to be reproducible and internally consistent [i.e., different analysts using the same imagery produce roughly the same results; Guard (1988); Mayfield et al. (1988)]. Guard (1988) found that 54% and 82% of 87 of the more difficult 1986 western North Pacific cases were within ± 0.5 and ± 1.0, respectively, T numbers when analysts were shielded from operational information. Mayfield et al. (1988) examined the reliability of DVKT estimates by using as many as 14 analysts in a controlled study of eastern Pacific tropical cyclones to produce dispersion statistics associated with the DVKT; finding standard deviations from the consensus average of 4.3, 9.0, 10.7, and 12.0 kt for tropical depressions, tropical storms, hurricanes with intensities of 65–95 kt (33–49 m s^{-1}; 1 kt = 0.514 m s^{-1}), and hurricanes with intensities greater than 95 kt, respectively. Historical records of DVKT-based intensity estimates also exist, which represents a quality global climate record of tropical cyclone intensity (e.g., Sampson and Schrader 2000; Nakazawa and Hoshino 2009). However, few systematic, multiyear validations of these estimates versus aircraft reconnaissance estimated/influenced maximum surface winds estimates (i.e., via best track when aircraft reconnaissance is available) have been performed. One such study (Sheets and McAdie 1988) examined the error distribution based on best-track intensities with aircraft reconnaissance within 6 h of the DVKT estimate in the Atlantic basin. Sheets and McAdie (1988) found biases of 2.1, −3.5, and −3.2 kt and RMS errors of 5.7, 8.0, and 13.2 kt for the tropical depression, tropical storm, and hurricane cases, respectively. This paper will conduct a similar, yet more comprehensive, study.

TABLE 1. The lookup table for Dvorak CI vs tropical cyclone maximum wind speed from Dvorak (1984). Wind speeds are valid for 1-min maximum sustained winds at a 10-m elevation and a marine exposure and are given in knots (kt).

Dvorak CI	Max wind speed (kt)
1.0	25
1.5	25
2.0	30
2.5	35
3.0	45
3.5	55
4.0	65
4.5	77
5.0	90
5.5	102
6.0	115
6.5	127
7.0	140
7.5	155
8.0	170

The purpose of this verification is to document error characteristics and possible systematic biases associated with the use of the DVKT. Specifically we seek to answer the following questions: How accurate is the DVKT? Does the DVKT have systematic biases? Are there systematic differences between estimates made at different agencies? Can the DVKT be better calibrated by using conditional information available in the operational setting?

Previous studies have documented DVKT biases and errors as functions of intensity (Sheets and McAdie 1988), latitude (Kossin and Velden 2004), and intensification trend (Koba et al. 1990, 1991; Brown and Franklin 2002, 2004). Several authors have also mentioned that the DVKT assumes a climatological translation speed (e.g., Velden et al. 2006a; Courtney and Knaff 2009; Harper 2002; Harper et al. 2008). In addition to latitude and intensification trends, biases and errors will be quantified as a function of intensity, size in terms of the radius of the outer closed isobar (ROCI), and storm translation speed.

Those results will then be used to create a conditional calibration of DVKT intensity estimates that may be useful in operations as well as for climatological reanalyzes. The following sections describe the datasets used in this study, details about how the verification was conducted, results of the verification, and a description of the resulting calibration method. The final section will summarize the important results and discuss their implications for climatological tropical cyclone reanalysis and operational tropical cyclone forecasting.

2. Datasets

All of the datasets used in this study come from the databases of the Automated Tropical Cyclone Forecast (ATCF; Sampson and Schrader 2000) system. This study makes use of all tropical cyclones occurring from 0° to 140°W longitude during the years 1989–2008. The Atlantic basin sample is used as a dependent sample and the east Pacific is used as an independent sample. Specifically, the intensity estimates used for verification come from the best tracks (i.e., B decks). The Dvorak intensity estimates, from the National Environmental Satellite, Data, and Information Service's (NESDIS) Satellite Analysis Branch (SAB) and the Tropical Analysis and Forecast Branch (TAFB), which is part of the Tropical Prediction Center/National Hurricane Center, and aircraft reconnaissance fixes come from the fix file (i.e., F deck). Since it was also desirable to examine the effects of TC size, the radius of the outer closed isobar (ROCI) was provided in the objective aid file (A deck). The ROCI values are not available in the best track, prior to 2004, so ROCI estimates are taken from the A deck, which is the same procedure used in the "extended best track" (Kimball and Mulekar 2004; Demuth et al. 2006). ROCI is not reevaluated following the season as is the track and intensity and, thus, is likely of lower quality. Since the native units for intensity are knots, or nautical miles per hour, and for ROCI are nautical miles (n mi, where 1 n mi = 1.85 km), these units will be used throughout the remainder of the manuscript.

There are also a few modifications to the fix files that were necessary to properly complete this study. The fix files were modified in the following ways for use with the software developed for this study: 1) intensities for the Dvorak fixes were added to the files in 2002 using the CI to intensity table (CI was in the fix files); 2) if the aircraft fixes reported a minimum sea level pressure and a maximum wind estimate, an "I" (i.e., as an intensity fix) was added to the fix identifier in 2002; 3) all references to the site KSAB were changed to SAB in 1989; and 4) all the fixes from the National Hurricane Center in Miami, Florida [i.e., those from the Tropical Satellite Analysis Center (TSAC), Tropical Satellite Analysis and Forecast (TSAF) unit, and TAFB] are treated as coming from TAFB, and references to TSAC and TSAF were changed to TAFB. None of these changes introduced intensity information not already included in the individual fixes, but allowed for a longer homogeneous record by correcting inconsistencies in the file format and errors introduced by different operational procedures and software.

Since the rules or "constraints" of the DVKT limit the rate of change of the DVKT intensity estimates, the timing of the first DVKT intensity classification can be important in determining the final DVKT intensity estimate or CI. For this reason, this study will also examine the timing of the initial fix times for each of the two agencies. This was accomplished by examining all of the DVKT-based intensity fixes from SAB and TAFB, with and without aircraft reconnaissance, in the same 0°–140°W domain and years.

One could also argue that once an aircraft intensity estimate has been obtained, the estimate influences subsequent DVKT- based intensity estimates. To examine the possible influence of aircraft-based fixes on subsequent DVKT intensity estimates, this study will also examine biases with respect to intensity associated with DVKT intensity fixes that coincide or proceeded the time of the first aircraft MSLP estimate/fix on a tropical cyclone.

Infrared imagery archives maintained at the Cooperative Institute for Research in the Atmosphere (CIRA; Zehr and Knaff 2007) and the NHC are also examined to interpret the DVKT validation results. It should be mentioned that both of these datasets have reduced precision when compared to the raw Geostationary Operational Environmental Satellite (GOES) data. The CIRA archive has 8-bit resolution (256 counts) and the NHC archive has 7-bit resolution (128 counts). Despite these differences, the calibration at colder temperatures is the same for the CIRA and NHC archives. GOES imagery has 10-bit precision (1024 counts). The use of 7-bit data in operations, however, results in a random (rather than a systematic) cloud-top enhancement differences. This reduction in precision will occasionally change the interpretation of individual cases if 10- or 8-bit GOES data are enhanced and the EIR technique applied.

3. Methodology

A homogeneous verification of the DVKT-based intensity estimates is constructed using a time window of ±2 h of a best-track time. The verification was based upon periods that the best-track intensity was influenced by a reconnaissance fix (i.e., within ±2 h) and the DVKT fixes were also within the same time window. For

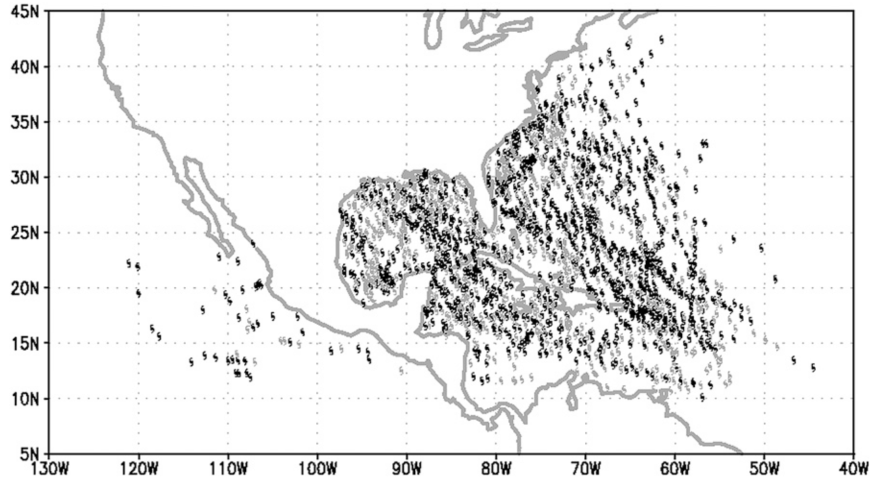


FIG. 1. A map showing the locations of the homogeneous verification points whose best-track intensities were influenced (within ±2 h) by aircraft reconnaissance used in this study. The black and gray hurricane symbols indicate that the best-track intensity was greater than or equal to the hurricane strength and less than the hurricane strength, respectively, for that verification point. Points in the Atlantic basin are used to examine biases and errors associated with the DVKT and points in the east Pacific are used as an independent dataset to test the results found in the Atlantic sample.

each DVKT-based intensity fix, the best-track intensity is interpolated to the time of that individual fix observation. From these individual verification points the biases and errors associated with the fixes are calculated. The verifications are further stratified by intensity and latitude, storm speed, intensity trend, and ROCI in combination with intensity. Statistics associated with the errors and biases, as well as the stratification factors, are compiled for each verification subset. Figure 1 shows the best-track locations of the homogeneous fixes used in this study. The reader should notice the reliance on aircraft results in relatively few fixes west (east) of 110°W (60°W) and equatorward (poleward) of 12°N (40°N). For this study we will initially concentrate on intensity estimates made in the Atlantic basin and then apply the Atlantic results to a much smaller sample of east Pacific cases. This stratification in the Atlantic resulted in a sample of 2003 cases, of which 6.0%, 43.7%, 31.1%, and 19.2% were tropical depressions, tropical storms, minor hurricanes, and major hurricanes, respectively. Similarly, there were 49 cases in the east Pacific, of which 0.0%, 30.6%, 38.7%, and 30.6% were tropical depressions, tropical storms, minor hurricanes, and major hurricanes, respectively. The fact that these distributions vary from climatology will be addressed by binning classifications to equalize their influences on subsequently presented statistics.

Since the timing of the first DVTK intensity estimate is potentially important in the determination of the DVKT intensity estimation or CI because the constraints limit the rate of intensification to 2.5 T numbers per day, statistics concerning the time differences between the first fix made by each agency were also compiled based on the combination of all fixes in both basins. These statistics are then used to examine the possible effects of first classification timing differences on interagency intensity estimation differences.

To examine the potential impacts of aircraft-based intensity estimates on subsequent DVKT intensity estimates, best-track times were identified that were influenced by aircraft fixes, but the DVKT intensity estimates near those best-track times were created coincidently or after the first aircraft estimate of MSLP was observed. For this limited analysis the DVKT intensity estimates from both agencies had to be made coincidently or before, but within 2 h of when the first aircraft-based intensity estimate was available. Presumably, the DVKT fixes from these cases will not benefit from knowing the observed intensity of the storm at any prior time and thus are more independent.

4. Results

a. *Interannual statistics*

The interannual variations of the DVKT intensity estimates are first examined to see if known changes in technology have affected the bias and error characteristics of the DVKT-based intensity estimates. Examples of such changes include satellite coverage and resolution[1] changes in the analysis domain and viewing angles with the introduction of *GOES-8* in 1995 and *GOES-9* in 1997, which replaced *GOES-7*, which was located in a central location (105°W). Other factors include the impacts of changes in flight-level to surface wind reductions based on GPS dropwindsonde analyses that started in approximately 2000 [and that are documented in Franklin et al. (2003)] might have had on operational and best-track intensity estimates. There were also potential procedural differences that occurred during this time period, such as the treatment of weakening systems (i.e., Brown and Franklin 2004)[2] and the Dvorak (1995) notes on the shear pattern.

Figure 2 shows the interannual variations of biases, mean absolute error (MAE), and root-mean-square error (RMSE) of the 2003 Atlantic DVKT cases. There is a tendency for TAFB's estimates to be slightly higher than SAB's estimates. These differences have diminished since 2002. One would expect technological (e.g., satellite resolution and viewing angles, dropwindsondes) and procedural changes (e.g., flight-level to surface reduction) to effect the performance of both agencies. However, there do not seem to be any visually detectable change points associated with known changes in operational procedures or technology. There is however a slight upward trend in errors in the TAFB fixes that explains about 13% of the variance, which does not seem to be associated with any of the changes in technology and may reflect other internal changes. No statistically significant trends were found in the MAE or RMSE statistics. There is also a fair amount of interannual variance in the biases and errors, but the statistics from the two agencies seem to have a reasonable covariance. *The DVKT is also shown to be much more reproducible than in the Guard (1988) study, with 95% and 55% of the SAB and TAFB fixes being within ±0.5 T number and equal, respectively, for the 2003-case Atlantic sample. Average MAEs and RMSEs are also remarkably stable during 1989–2008, with mean values of approximately 8 and 11 kt, respectively.* Note here that the Guard (1988) study purposely examined the 87 most difficult cases and was likely more shielded from the intensity information coming from aircraft. The lack of coincident change points,[3] particularly in

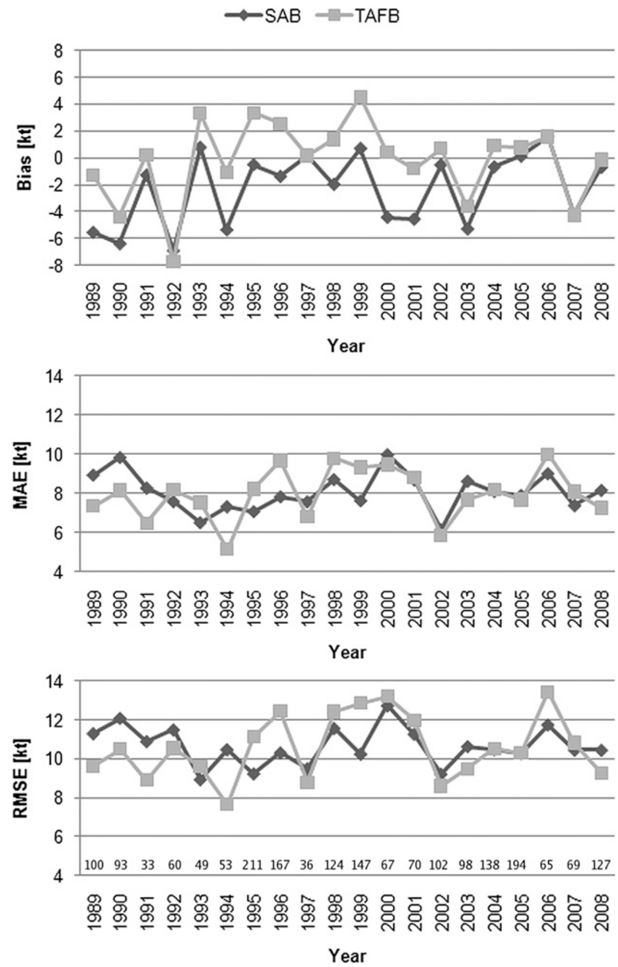


FIG. 2. Time series of the (top) interannual variability of biases, (middle) MAEs, and (bottom) RMSEs associated with the Dvorak tropical cyclone intensity estimation technique. Statistics are based on a homogeneous comparison between fixes made at SAB and TAFB that were made within ±2 h of an aircraft reconnaissance fix and have units of knots. The verification is based on best-track intensity estimates at those times, and the analysis domain was the Atlantic basin. The number of cases is provided in the bottom panel.

the MAE and RMSE, provides confidence that the entire 1989–2008 time period can be treated as quasi-stationary and can be examined in a homogeneous manner. This assumption is further supported by the interagency correlation coefficients of 0.81, 0.48, and 0.48 for biases, MAEs and RMSEs, respectively, and the detrending of these datasets did not change these correlations. These calculations suggest that there are likely systematic, rather than random, causes for the interannual variations that affect the DVKT performance at both agencies that have remained consistent throughout the time of analysis. The assumption of quasi-stationary also allows for the more thorough examination of potential conditional biases

[1] The spatial resolutions of the visible and IR imagery are approximately 2 and 8 km for *GOES-7* and 1 and 4 km for *GOES-8* and *GOES-9*.

[2] While Brown and Franklin (2004) made recommendations on how to improve the treatment of weakening systems, these recommendations were never formally adopted at SAB or TAFB.

[3] A rank-order change-point test was inconclusive; see Peterson et al. (1998) for test details.

associated with the DVKT. To provide the reader with additional information, many of the analyses that are discussed in the following sections were performed on the full 1989–2008 period and on the much shorter 2002–08 period; comments about the differences found are provided.

b. Biases and errors as a function of intensity

The results of the homogeneous verification are compiled in overlapping bins that have endpoints that correspond to the CI versus intensity table shown in Table 1. For instance, the first and second bins have best-track intensity ranges of 20–35 and 25–45 kt, respectively. Figure 3 shows the biases, MAEs, and RMSEs associated with the DVKT-based intensity estimates. Also shown in Fig. 3 is the number of cases in each bin. The last bin extends from 127 to 170 kt because there are limited numbers of cases with best-track intensities greater than 140 kt. The biases, MAEs, and RMSEs shown in Fig. 3 appear to be a function of intensity. *The biases show that the DVKT has a tendency to underestimate intensities when TCs have intensities between 35 and 55 kt and greater than 125 kt. On the other hand, overestimation of intensities occurs for intensities between 75 and 105 kt.* These results are mirrored in the shorter 2002–08 results (not shown), though the differences between SAB and TAFB are nearly zero above 80 kt; the implications of which will be discussed in section 4e. The low biases between 35 and 55 kt (CIs between 2.5 and 3.5) are consistent with those found by Sheets and McAdie (1988), Koba et al. (1990, 1991), and Brown and Franklin (2002). This issue likely resulted in Koba et al. (1990, 1991) adjusting the CI versus intensity table used at RSMC Tokyo, effectively increasing the intensities for CI < 4.5. Independently, Brown and Franklin (2002) suggested that DVKT rules limiting the rate of strengthening of these weaker systems may be too restrictive. The high biases between 75 and 100 kt were attributed to rules concerning a sometimes unrealistic persistence of peak intensities in Brown and Franklin (2002) and led Koba et al. (1990, 1991) earlier to decrease their intensities for CI > 5.0. Intensity estimates in this range can also be obtained by using the embedded center pattern, which is difficult to apply without accurate center positions. Noteworthy for this discussion is that the embedded eye pattern appears to give higher than warranted intensity estimates when the embedded center pattern is used after employing some other pattern (Burton 2005). The low biases above approximately 125 kt were not apparent in the Brown and Franklin (2002, 2004) or Koba studies, but in this study they were primarily associated with several long-lived major hurricanes (Ivan in 2004; Dennis, Emily, and Wilma in 2005; and Dean in 2007) that occurred since that time. These results roughly agree with Sheets and McAdie (1988), who found underestimation occurred for a relatively large sample of hurricanes within ±6 h of reconnaissance.

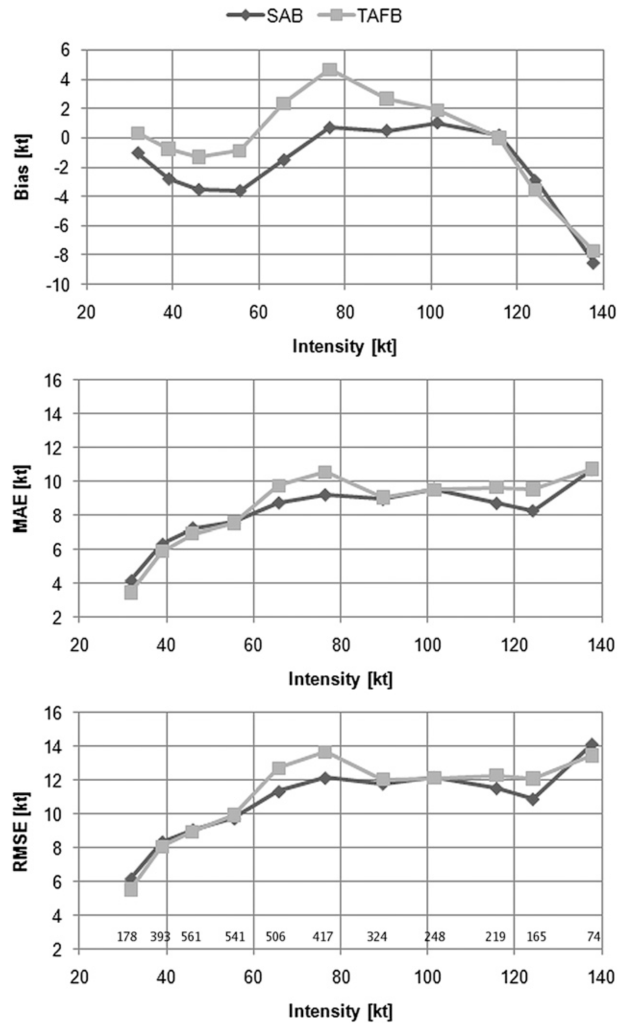


FIG. 3. (top) Biases, (middle) MAEs, and (bottom) RMSEs associated with Dvorak tropical cyclone intensity estimates (kt) from SAB and TAFB that were made with ±2 h of an aircraft reconnaissance fix. The verification is based on the best-track intensities at those times, and the analysis domain was the Atlantic basin. The number of cases is provided in the bottom panel.

MAEs and RMSE, also shown in Fig. 3, are lowest for weak storms and largest for the higher intensities. The errors associated with hurricanes and tropical storms in this study, in general, are slightly smaller (~1 kt) than those reported by Sheets and McAdie (1988). A possibly better measure of the DVKT ability is the signal (intensity) to noise (RMSE error) ratio. Using this metric, the intensity estimate is most skillful–least in error in an intensity range from approximately 90 to 125 kt (i.e., CIs of from 5.0 to 6.5), where signal to noise ratios are greater than 7. This is likely due to the existence of the relatively stable ''eye'' pattern that exists in these intensity ranges; therefore, the technique is more objective in this range. It also appears that the method has more difficulty in estimating the intensities of weaker tropical cyclones, where the signal-to-noise ratio has a value between 5 and 6. At these lower intensities, there can be multiple DVKT patterns associated with a given intensity estimate and the centers of these systems are often more difficult to locate. Somewhat surprising are the errors that result from large negative biases at the highest intensity ranges that suggest that above ~125 kt there is less skill in discriminating the stronger category 4 (114–135 kt) from category 5 (>135 kt) storms. Possible reasons for these findings include the following. 1) Because the climatological tropopause temperature in the Atlantic is about −76°C, it is more difficult for convection to produce a complete ring of cloud tops −76°C or colder with a minimum width requirement of 55 km. This type of pattern is generally required for intensity estimates of 6.5 T numbers or greater using the EIR method. 2) Smaller very intense storms are likely underestimated due to not having a cold ring of convection surrounding the eye that meets the minimum width requirement in the EIR technique. 3) There is an inability in some cases to resolve the warm eye temperatures that occur with very small eyes or ''pinhole eyes'' or at steep satellite viewing angles. 4) Dvorak constraints can be too restrictive for rapidly intensifying storms. 5) There is no explicit treatment of concentric multiple eyewalls and there are no explicit rules that apply to eyewall replacement cycles. These potential shortcomings will be discussed further in section 4e. The results discussed above are not significantly different from the results obtained using the 2002–08 time period, though the differences corresponding to near-hurricane intensity between the SAB and TAFB errors are reduced (not shown).

Since the precision of the DVKT CI versus intensity table (i.e., Table 1) is itself a function of intensity, it is worth calculating the RMSEs in terms of DVKT T numbers as a function of CI. This comparison is shown in Fig. 4. It appears that the DVKT was designed to have RMSEs of roughly 0.5 T number. This transformation does not change the results shown in Fig. 3 and still shows that the relative errors are larger for weak and very strong storms with a relative ''sweet spot'' for intensity estimation for CI ranging from 5.0 to 6.5. However, it also suggests that the signal-to-noise ratio in terms of T numbers is roughly increasing linearly from a low of ~4 at CI = 2.0 to a high near ~14 at CI = 7.0. This transformation also highlights the larger TAFB errors for CIs of 4.0 and 4.5, which are largely attributed to overestimation or high bias in this intensity range.

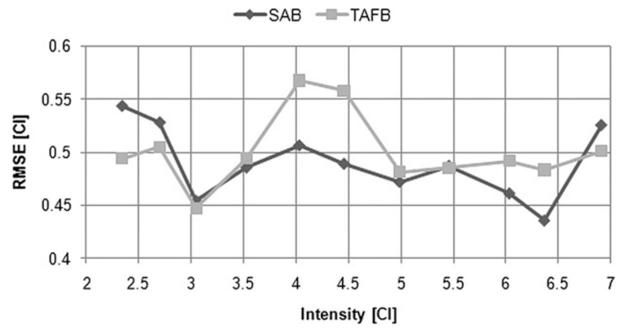


FIG. 4. The RMSE results in Fig. 3 are transformed so that both intensity and RMSE are in terms of DVKT CI numbers.

c. *Influences of aircraft reconnaissance*

Following the initial DVKT-based intensity estimate, subsequent DVKT intensity estimates are influenced by an expectation based on previous intensity estimates. There is also the possibility of aircraft intensity information potentially influencing DVKT-based intensity estimates, if the analyst were privy to that information. One could argue that once aircraft intensity information influences the DVKT, it is difficult to claim the DVKT intensity estimates are truly independent. This debate has been going on essentially since Dvorak first proposed the method. Other studies (e.g., Guard 1988) shielded analysts from aircraft reconnaissance information. Here, we will simply examine the first DVKT-based intensity estimates from both SAB and TAFB that occurred coincident to or prior to the first aircraft reconnaissance center fix (i.e., vortex message containing MSLP estimates). This should create an assessment of DVKT intensity biases and errors that is more independent of aircraft reconnaissance.

In the Atlantic there were 180 cases when DVKT intensity estimates were made by both SAB and TAFB at or before the first aircraft center fix and within 2 h of that center fix. The average intensity, latitude, speed, size, and 12-h intensity trend of the sample are 49.5 kt, 21.9°N, 9.4 kt, 166 n mi, and 6.0 kt respectively. The sample biases, MAEs, and RMSEs are −3.9, 6.4, and 8.6 kt, respectively, for SAB fixes and are −1.5, 6.2, and 8.2 kt, respectively, for TAFB fixes. Figure 5 shows these bias and error distributions for these cases for comparison with Fig. 3. In general, this first fix sample has lower errors than the whole sample, which seems a bit counterintuitive given the lack of previous aircraft-based intensity information. This first fix sample is dominated by storms with intensities less than 80 kt, so not much can be said about the biases above 80 kt, but the

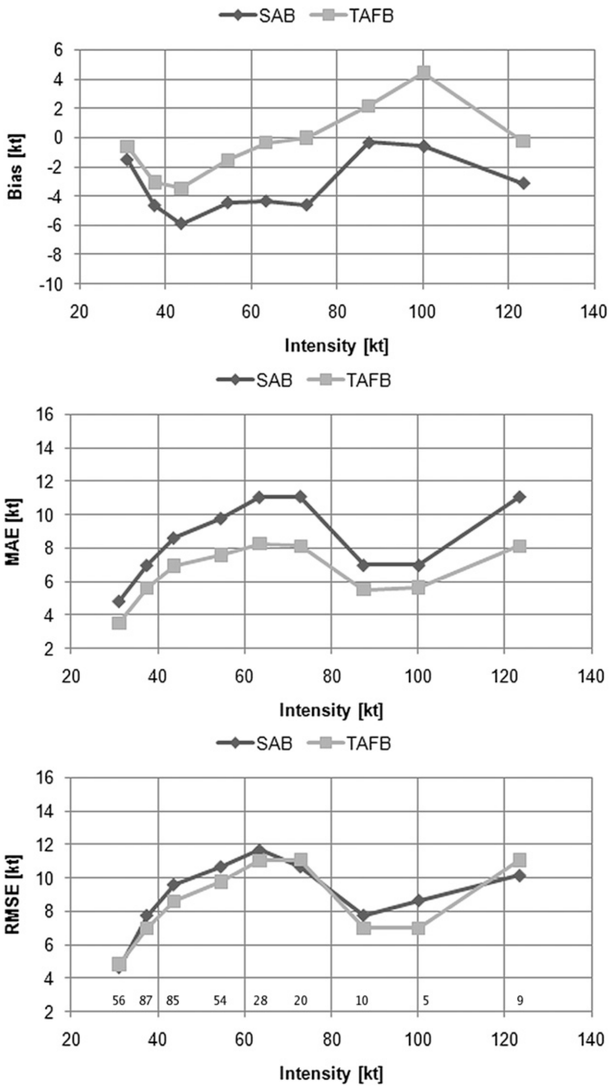


FIG. 5. As in Fig. 3, but for the cases of the first DVKT intensity estimate occurring coincidently or within 2 h before the aircraft-based center fix including an MSLP estimate.

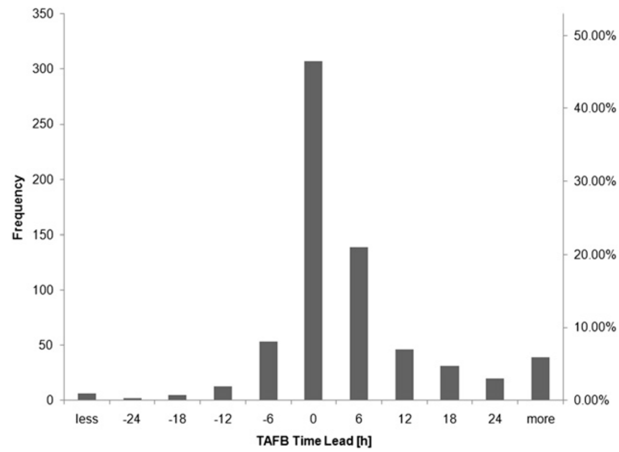


FIG. 6. The frequency distribution of the time differences between the first Dvorak intensity estimates from SAB and TAFB. The time differences are shown in terms of TAFB leading SAB. The analysis is based on all Dvorak tropical cyclone intensity fixes during 1989–2008 in the 0°–140°W domain. The average of the distribution is 5.75 h.

shape of the biases at lower intensity is similar to the larger Atlantic sample. These first-fix cases are also dominated by intensifying systems and systems located in the tropics. These sample specific factors are also important in determining biases, which are discussed in section 4e.

d. *Fix timing and its consequences*

Figures 2 and 3 show the tendency for biases of TAFB to be more positive when compared to SAB, which is even true, below 80 kt, in the 2002–08 period (not shown). Upon closer examination, the first TAFB fix (i.e., CI $\geq$ 1.0) also has a tendency to lead the SAB fixes, on average, by about 6 h. Using all of the initial fixes during 1989–2008, these time differences (Fig. 6) seem to offer a partial explanation for the mean differences between the two agencies. When the intensity differences at the first homogeneous fix are examined, the intensity difference is on the order of 1.4 kt for time differences between 3 and 6 h (Fig. 7). This difference is roughly 25% of a T number. If a climatological rate of intensification occurs, this initial difference would affect subsequent intensity estimates. For instance if at a later time the CI = 4.0 or 65 kt (Table 1), these same 25% differences are on the order of 5 kt. Our results show that the intensity differences between the two agencies are about 1–4 kt for the intensities between 25 and 100 kt. So it appears that the mean intensity differences between TAFB and SAB could be partially explained by TAFB beginning their initial DVKT analysis on average about 6 h prior to SAB. Further evidence of the effects of timing differences can be seen in Fig. 2, where the biases at SAB and TAFB are nearly identical to those from 2002–08, as mentioned in section 4a. This later period also corresponds to the time when the first DVKT fix time differences are the least.

This improved first intensity estimate timing is thought to be partially due to better coordination between SAB and TAFB. Around 2002, TAFB and SAB increased their coordination by instituting notification of initial classifications being initiated via telephone to SAB (and vice versa) for suspect areas warranting position fixes and/or Dvorak classifications; note that the actual center fixing process and Dvorak intensity estimation remained independent. It is also noteworthy that in 2000–02 other

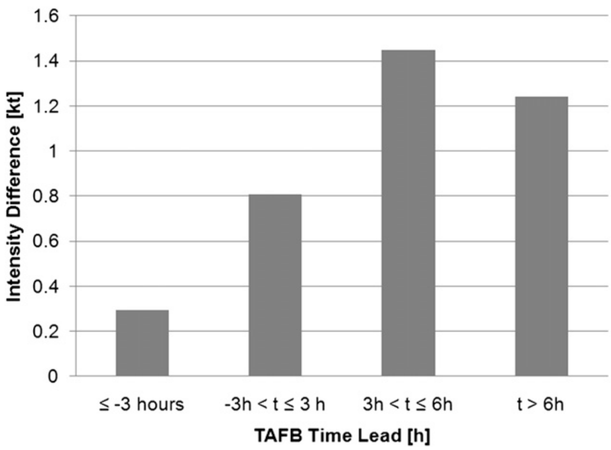


FIG. 7. The mean intensity difference between the first homogeneous pair of fixes from SAB and TAFB, plotted as a function of the binned time difference between the first fix produced by each agency. Note that the bins are large and the vast majority (+99%) of the fixes are separated by increments of 6 h ± 15 min.

TABLE 2. Description of the ranges of values used for the composites of the DVKT intensity biases as a function of 12-h intensity trend, latitude, translation speed, and ROCI.

	12-h intensity trend (kt)	
Weakening	Steady/intensifying	Rapid
<−2.5	≥−2.5 and <7.5	≥7.5
	Latitude (°N)	
<20	≥20 and <30	≥30
	Translation speed (kt)	
Slow	Avg	Fast
<6.0	≥6.0 and <14.0	≥14.0
	ROCI (n mi)	
Small	Avg	Large
<165	≥165 and <270	≥270

significant operational changes were also taking place.[4] The relative independence of the intensity estimates is inferred by a systematic difference (TAFB higher than SAB) between the two agencies that persists throughout the whole 1989–2008 period, centered on T number of 4.0 or 65 kt (not shown); the cause of this difference is likely procedural and abates at higher intensity when the DVKT becomes more objective (i.e., eye-pattern dominated). For purely practical purposes, it is worth noting that the biases and errors for the whole sample decrease when a simple equally weighted consensus is applied to the two independent fixes. Individually, SAB (TAFB) had biases of −1.93 kt (0.42 kt) and RMSEs of 10.59 kt (10.94 kt). The simple consensus results in biases of −0.66 kt and an RMSE of 10.01 kt for the same sample—a 5% reduction of the SAB RMSE. *These results indicate that having multiple agencies or analysts make independent DVKT intensity estimations is beneficial to operations* and that a more comprehensive study of the use of consensus DVKT-based and satellite-based estimates is warranted.

e. *The effects of intensification, latitude, translation, and size*

The same intensity binning methodology that is used in section 4a is used here to further stratify the verification results by 12-h intensification trends, latitude, translation speed, and size or ROCI for the 1989–2008 Atlantic samples. Each of the intensity bins is further subdivided into three composites of each of these factors using the ranges shown in Table 2. The data distributions determined these ranges, which are approximately ±1 standard deviation from the mean, except in the case of ROCI, where the work of Kimball and Mulekar (2004) was used as guidance. Results are shown in Fig. 8 and the corresponding number of cases is listed in Table 3 for both agencies used in this study (TAFB and SAB). These results show that the Dvorak intensity estimations in general produce high and low biases for weakening and strengthening, respectively. Upon closer examination, this finding is primarily the result of biases associated with DVKT intensity estimates for storms experiencing the most rapid intensity changes, where weakening (strengthening) cases, produce pronounced large high (low) biases. *This finding suggests that the DVKT intensification/weakening constraints [i.e., DVKT rules 8 (final T-number constraints) and 9 (CI number rules)] may be too strict.* The effects of translation speed also show that fast- (slow-) moving storms have low (high) biases associated with their intensity estimates. These results support the discussions in Brown and Franklin (2002, 2004), Holland (2008), Velden et al. (2006a), and Courtney and Knaff (2009). *These results suggest the DVKT CI versus intensity table (Table 1) includes an implicit climatological translation speed, which was not documented in Dvorak (1972, 1975, 1984, or 1995).*

The effects of variations of latitude seem primarily confined to those storms poleward of 30° latitude and with intensities greater than 80 kt. The probable cause of these results is that the cloud-top temperatures used with the EIR technique (Dvorak 1984) are warmer at high latitudes. These warmer IR temperatures affect the

[4] NHC changed its image analysis software from McIDAS to NMAP, and the ATCF was updated to a UNIX version during 2000–02.

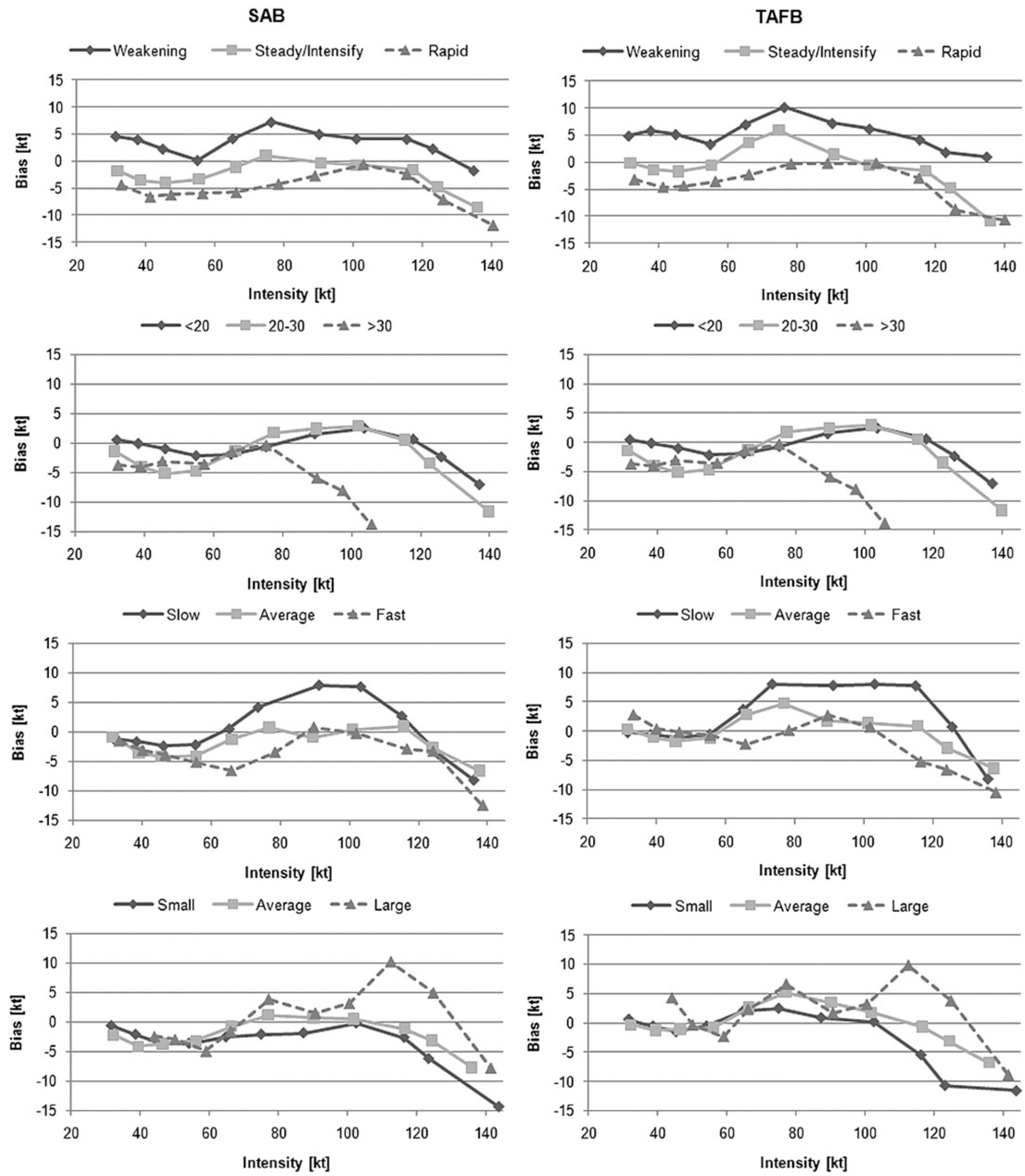


FIG. 8. Average biases in the Atlantic basin associated with the Dvorak technique coming from two agencies: (left) SAB and (right) TAFB. The comparisons are homogeneous. The composites were constructed using (first row) 12-h intensity trends, (second row) latitude, (third row) translation speed, and (fourth row) ROCI. Stratifications are explained in Table 2.

eye-to-cold-ring temperature gradient and the interpretation of banding features, resulting in erroneously low intensity estimates for stronger tropical cyclones, particularly those that have eyes in IR imagery. Relatively warm cloud tops are also observed in subtropical cyclones that transition to hurricanes, which also most commonly occur at higher latitudes. This analysis also includes tropical cyclones that were becoming extratropical—a situation when the DVKT is known to perform poorly. The resulting intensity biases as a function of latitude also physically agree with the results of Kossin and Velden (2004), which showed that the DVKT had a high (low) bias at higher (lower) latitudes when they verified aircraft-based MSLPs, but not in maximum wind speed estimates. However, the use of MSLP as an intensity metric requires the use of pressure–wind relationships that account for the latitude explicitly (e.g., Knaff and Zehr 2007; Holland 2008; Courtney and Knaff 2009), and the DVKT provides a single pressure–wind relationship for the Atlantic basin. As a consequence, it is difficult to determine the extent of

TABLE 3. The number of individual fixes associated with the composite averages shown in Fig. 7.

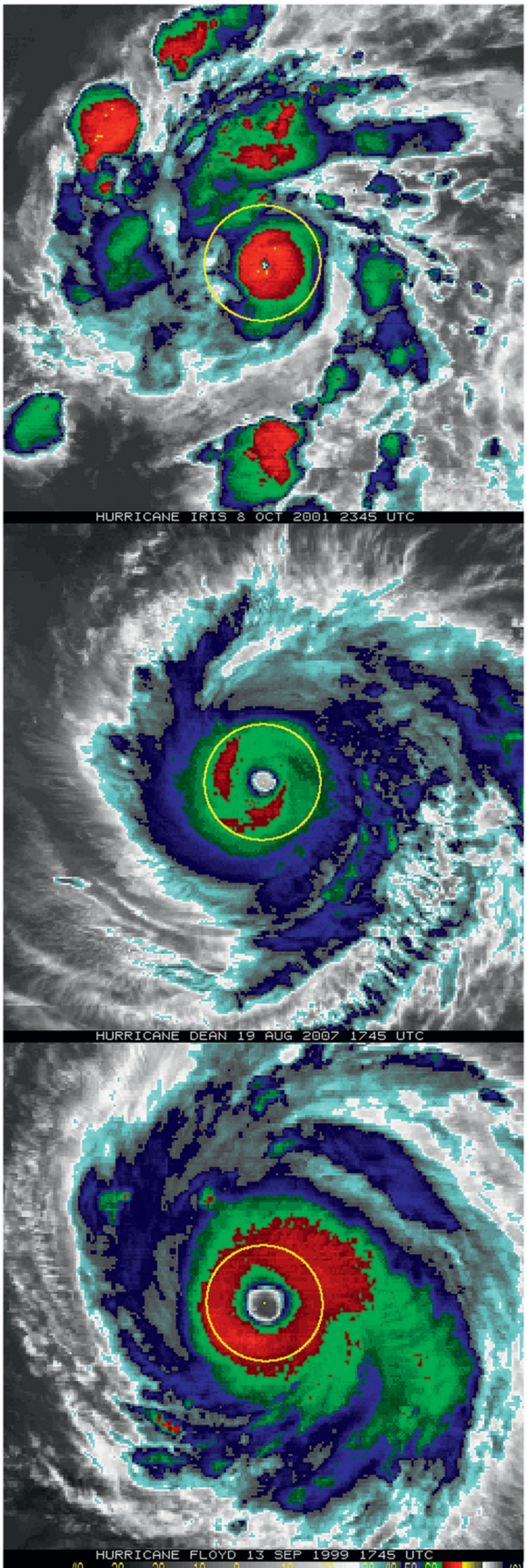
Stratification	25–35 kt	30–45 kt	35–55 kt	45–65 kt	55–77 kt	65–90 kt	77–102 kt	90–115 kt	102–127 kt	115–140 kt	>127 kt
Weakening	32	79	108	111	119	112	106	87	79	61	19
Steady	121	216	271	234	211	146	92	76	66	53	17
Rapid	25	98	182	196	176	159	126	85	73	50	38
$\varphi < 20°N$	59	123	173	177	152	103	58	48	72	81	50
$20°N \le \varphi < 30°N$	99	211	296	241	216	218	196	159	141	84	24
$\varphi \ge 30°N$	20	59	92	123	138	96	70	41	6	0	0
Slow	76	138	180	167	146	87	34	25	17	11	5
Avg	86	208	305	292	287	254	210	165	151	112	46
Fast	16	47	74	80	72	74	77	56	51	42	23
Small	135	260	331	251	177	115	52	30	33	21	9
Avg	43	127	202	224	251	239	208	162	157	132	52
Large	0	6	28	66	78	63	64	56	29	12	13

the wind speed biases, if any, from the Kossin and Velden (2004) study alone. The wind speed biases presented here help clarify at what latitudes and intensities the intensity biases are most pronounced in terms of wind speed. *The impacts of warmer cloud-top temperatures at higher latitude result in DVKT intensity estimates that are too low, as the most pronounced impacts on intensity estimation are at latitudes greater than 30° and for storms with intensities greater than 80 kt.* We feel confident that this cloud-top temperature effect is dominant, though it is worth noting that latitude is correlated with 12-h intensity trends ($r = -0.27$) and ROCI ($r = 0.16$), suggesting simply that higher-latitude storms tend to be both larger and weakening. These issues will be revisited in section 5.

The effects of tropical cyclone size on the DVKT intensity estimates are also mostly confined to the higher-intensity storms (those with intensities greater than 100 kt). Large storms are systematically overestimated for intensities 100–125 kt and average and small storms tend to be underestimated. This finding is believed to be related to a combination of the application of the EIR technique, scaling differences, and varying intensification rates. In stronger TCs the extent of the coldest cloud is related to tropical cyclone size and wind radii (Zehr and Knaff 2007), suggesting a general proportionality among the various TCs' sizes. The relationship between the radial profiles of the IR brightness temperature and the resulting TC wind field (i.e., proportionality) was further demonstrated by the objective techniques developed by Mueller et al. (2006) and Kossin et al. (2007), which showed that the radial extent of the coldest cloud tops was related to the radial extent of the winds and the radius of maximum winds. IR imagery of small, average, and large 125-kt cases with ROCI estimated at 100, 200, and 300 n mi, respectively, visually shows this general proportionality (Fig. 9). The EIR technique, which is most commonly used because of its ability to make fixes at all times, uses a specific one-size-fits-all width criteria for the cold cloud ring that surround the eyewall (55 km for 6.0 and 6.5 T numbers); ignoring the relative proportionality among very strong storms. As a result, some very small storms do not meet the minimum ring width requirement necessary to reach the highest intensity (i.e., CI) estimates. This was certainly the case for some of the smallest storms examined in this study[5] (e.g., Bret, 1145 UTC 22 August 1999; Felix, 1745 UTC 2 September 2007). However, it is more often the case that the scaling shown in Fig. 9 effects both the measurement of the eye temperature (too cold/not resolved) and the ring width, as was the case with Hurricane Charley (1745 UTC 13 August 2004).

The high bias associated with large tropical cyclones in the intensity range 100–125 kt appears to be primarily associated with the weakening phase of several cases. The DVKT appears to not weaken several of these storms fast enough and this is responsible for the high bias in Fig. 8. Specific cases include Hurricane Floyd (1999) during the period 1745 UTC 13 September–1745 UTC 14 September, Hurricane Katrina (2005) at 0615 and 1145 UTC 29 August, and Hurricane Rita (2005) during the period 1745 UTC 22 September–2345 UTC 23 September. This directly relates to DVKT rule 9 (CI rules), discussed in Dvorak (1995) and in Velden et al. (1998), which limits weakening, holding the T number constant from the peak intensity during the first 12 h of weakening and then holding the CI 0.5 to 1 T number higher as the storm weakens. This result suggests that larger storms may generally present cloud patterns that are suggestive of a slower weakening and, when combined with the CI rules, may result in an overestimation of this sample. However, the sample is relatively small and this result is thus tentative. It is also noteworthy that the large TC with

[5] The SAB's Dvorak IR enhancement was used to enhance 8-byte imagery in these cases.



the largest high bias, mentioned above, also had eyewall replacement cycles near peak intensity. *The effects of tropical cyclone size on DVKT intensity estimates, which are seen at intensities greater than 100 kt, seem to be primarily caused by changes in tropical cyclone scale with the requirements for the largest DVKT intensities generally being more difficult to obtain for the smaller storms.* The results of the large composite, which are dominated by weakening cyclones in the 115–130-kt range further reiterates the likelihood that the CI rules for weakening are too strict.

It is also noteworthy that, on average, all sizes of tropical cyclones with intensities greater than 140 kt (i.e., CI = 7.0) are underestimated. To obtain a CI of 7.0, the storm must have a cold ring with a 55-km width and a relatively warm eye. Closely examining the cases used in this study, there are several causes for not meeting these criteria. There are some cases when the eye was unresolved by the ~4-km resolution of the geostationary satellite imagery (e.g., Opal, 1145 UTC 4 October 1995; Dennis, 1145 UTC 8 July 2005; Wilma, 2345 UTC 18 October 2005). Notably, Hugo (1989) at 1800 UTC 15 September also falls into this category due to the steep viewing angle from *GOES-7*, but is not considered in our dataset because of a lack of a ROCI estimate. Some storms have eyewall replacement cycles that disrupt the cold cloud tops and result in lower estimates (e.g., Isabel, 0615 UTC 13 September 2003; Ivan, 0645 UTC 13 September 2004). Other cases show that the cold cloud tops are just not cold enough (e.g., Luis, 0645 UTC 4 September 1995; Isabel, 1745 UTC 14 September 2003; Felix, 2345 UTC 2 September 2007), which reiterates the potential effect of the relatively warm Atlantic tropical tropopause temperature compared to the Eastern Hemisphere during the months of November – March (Newell and Gould-Stewart 1981; Seidel et al. 2001). There were also cases that had a combination of too warm of a ring of cold cloud temperatures and too cold eye temperatures in combination. *So it appears that, at least in this Atlantic sample, that there is a propensity for the EIR DVKT to underestimate very strong*

←

FIG. 9. Examples of how tropical cyclones are scaled by size. Shown are (top) Hurricane Iris (2001), (middle) Hurricane Dean (2007), and (bottom) Hurricane Floyd (1999). Each storm has a best-track intensity of 125 kt at the time of the image and ROCIs of 100, 200, and 300 n mi, respectively. Date and time information is provided for each panel, a 110-km circle is shown to provide spatial scale, and the imagery is show on a sinusoidal equal area projection. The temperature scale is provided at the bottom of the image.

tropical cyclones (>140 kt) because of 1) the relatively warm climatological tropopause temperatures in the Atlantic that make it difficult to observe cold rings with temperatures colder than −76°C, 2) the occasional occurrence of erroneous cold eye temperatures resulting from an inability to resolve very small eyes and poor viewing angles, and 3) the occasional disruption of the cold cloud top and eye by eyewall replacement. The latter two points are likely true in all tropical cyclone basins and were also touched upon in Velden et al. (2006a), and the third point suggests that the weakening of storms, in terms of wind speed, during eyewall replacement cycles is less than the DVKT would indicate. This last point is being addressed by adding microwave information to the advanced Dvorak technique (Olander and Velden 2007; C. Velden 2010, personal communication).

Results using the 2002–08 Atlantic sample exhibited similar patterns. However, the numbers of large category 4 and 5 hurricanes are insufficient to address the impacts of size on the biases.

5. Quantification and testing

a. Quantifying the various effects

Using the composites described in the previous section, multiple linear regressions are used to quantify the effects of each of these factors. The first step in this process is to remove the biases that are solely a function of intensity. This is accomplished by averaging the biases from SAB and TAFB as a function of intensity, shown in Fig. 3 (top), and then fitting a quadratic function to the result as a function of best-track intensity ($V_{\max}$). Equation (1) below provides an estimate of the biases as a function of $V_{\max}$. A similar procedure was performed that quantifies the RMSE as a function of intensity and is shown in (2). In application, one would use the estimated $V_{\max}$ to calculate the biases and RMSEs. Both equations are valid for intensities ranging from 30 to 140 kt (or CI of 2.0 to 7.0). Above and below those values, users are advised to employ the estimates calculated at the closest valid range:

$$\mathrm{Bias}(V_{\max}) = 32.174 - 1.990V_{\max} + \left(\frac{V_{\max}}{5.070}\right)^2 - \left(\frac{V_{\max}}{15.076}\right)^3 + \left(\frac{V_{\max}}{34.351}\right)^4, \quad (1)$$

$$\mathrm{RMSE}(V_{\max}) = -10.887 + 0.748V_{\max} - \left(\frac{V_{\max}}{11.196}\right)^2 + \left(\frac{V_{\max}}{33.023}\right)^3. \quad (2)$$

TABLE 4. List of factors associated with Dvorak intensity estimation biases along with their mean and standard deviation values for the Atlantic 1989–2008 sample. Also listed are the normalized regression coefficients associated with each of these factors.

Factors	Mean	Std dev	Normalized regression coefficients
Bias residual	−0.049	3.356	
Sin (latitude)	0.399	0.059	−0.398
Speed factor ($1.5c^{0.63}$)	6.316	1.211	−0.310
ROCI (n mi)	196.753	43.227	0.211
Intensity trend	3.544	6.235	−0.574

To determine the effects of the various operational variables composited in Fig. 8, the biases estimated from (1) are then subtracted from the composites based on intensity trend, latitude, translation speed, and ROCI. In addition, a storm speed factor is introduced to better parameterize for the effects of translation speed on the tropical cyclone wind structure, particularly the maximum winds. The storm speed factor is equal to $1.5c^{0.63}$, where c is the storm speed (in kt) to provide that portion of the asymmetric wind field associated with translation; these values (i.e., 1.5 and 0.63) ‘‘yielded satisfactory results’’ according to the developers Schwerdt et al. (1979). Other applications (e.g., Demuth et al. 2006; Knaff and Zehr 2007; Courtney and Knaff 2009) have also used this formulation successfully for maximum wind applications. The remaining residual biases are standardized (i.e., by subtracting the mean and dividing by the standard deviation) and regressed against the mean standardized values of intensity trend, storm speed factor, sine of latitude (φ), and ROCI that were created during the compositing procedures shown in Fig. 7. The means and standard deviations of each variable along with the normalized regression coefficients are shown in Table 4. The resulting normalized regression coefficients show that each of the factors is relatively important in determining the resulting DVKT biases, with the intensity trend having the greatest effect and the ROCI having the least effect. Table 5 offers an estimate of the impacts that each of these factors and their raw components have on DVKT-based intensity estimation. These results also appear to indirectly justify the use of the Schwerdt et al. (1979) speed factor, which has a $-0.86\ \mathrm{kt}^{-1}$ sensitivity, indirectly suggesting that it is a good approximation (i.e., close to $-1.0\ \mathrm{kt}^{-1}$ sensitivity). The sensitivities shown in Table 5 are relatively small individually, given that intensity is estimated to the nearest 5-kt interval, but in combination they could produce larger biases.

Combining the results of (1) to the regression equation developed to estimate the impacts of the intensity trend ($\Delta V_{\max}$), latitude (φ), speed factor (i.e., $1.5c^{0.63}$), and ROCI leads to a rather complicated equation for the

TABLE 5. Estimates of Dvorak technique-based intensity bias sensitivities examined by this study.

Factors	Predicted bias sensitivity
Latitude (mean = 23.5°N)	≈ -0.38 kt deg^{-1}
Sin latitude (mean = 0.40)	-22.6 kt (sin unit)$^{-1}$
Translation speed (mean = 10.0 kt)	≈ -0.55 kt kt^{-1}
Speed factor (mean = 6.3 kt)	-0.86 kt kt^{-1}
ROCI (mean = 196 n mi)	0.016 kt (n mi)$^{-1}$
Intensity trend (mean = 3.4)	-0.31 kt kt^{-1}

biases associated with the DVKT [see Eq. (3) below], which explains 70% of the composite biases. In application, $\Delta V_{\max}$ would be estimated from the 12-h-old operational intensity estimate and the current DVKT-derived CI. Equation (3), as was the case for (1) and (2), is valid for intensities ranging from 30 to 140 kt (or CI of from 2.0 to 7.0). Above and below those values users are advised to employ the estimates calculated at the closest valid range. Equation (3) also was developed with few cases equatorward of 12° latitude and poleward of 40° latitude (see Fig. 1), suggesting that those latitudes should be used as a minimum and maximum value in application:

$$\begin{aligned}\text{Bias} = 44.559 - 1.990V_{\max} + \left(\frac{V_{\max}}{5.070}\right)^2 - \left(\frac{V_{\max}}{15.076}\right)^3 \\ + \left(\frac{V_{\max}}{34.351}\right)^4 - 22.639\sin|\varphi| - 0.859(1.5c^{0.63}) \\ + 0.016\text{ROCI} - 0.309\Delta V_{\max}. \qquad (3)\end{aligned}$$

A similar procedure was performed for RMSE, but only the intensity trend and latitude factors were statistically significant, and the sensitivity of those factors was found to be approximately two orders of magnitude less than the effects of intensity alone. Thus, it appears that the RMSE associated with the DVKT is primarily a function of intensity, as shown in (2).

b. *Testing bias corrections*

Using the eastern North Pacific cases shown in Fig. 1, the bias correction shown in (3) is tested. This is thought to be a good test of (3) since the eastern Pacific sample contains generally lower-latitude (16.5° versus 23.6°), slower-moving (8.1 versus 10.0 kt), and smaller tropical cyclones (178 versus 197 n mi) when compared the Atlantic basin. The 12-h intensity change of this sample is 2.0 kt versus the 3.5 kt found in the Atlantic sample. From Tables 4 and 5, one might expect that the eastern Pacific biases are high, and that is the case.

During 1989–2008, there were 49 cases when both SAB and TAFB had DVTK intensity estimates within ±2 h of aircraft reconnaissance. The intensities of this sample range from 35 to 140 kt. SAB (TAFB) intensity estimates had average biases of 4.53 kt (6.04 kt), MAEs of 8.48 kt (8.74 kt), and RMSEs of 10.77 kt (11.34 kt) before Eq. (3) is applied. Applying (3) to the individual intensity estimates resulted in sample average SAB (TAFB) biases of 2.12 kt (3.87 kt), MAEs of 7.19 kt (7.80 kt), and RMSEs of 9.32 kt (9.89 kt). Since operational intensity estimates are reported to the nearest 5-kt interval, intensity estimates from (3) were rounded to the nearest 5-kt interval. This resulted in SAB (TAFB) biases of 2.17 kt (4.14 kt), MAEs of 6.98 kt (7.66 kt), and RMSEs of 9.48 kt (10.03 kt). These small changes are nonetheless significant, resulting in 40%, 15%, and 11% reductions, respectively, in the intensity biases, MAEs, and RMSEs of the total 98-case sample.

6. Summary, implications, and applications to tropical cyclone analysis

The DVKT has been an important operational tool for estimating tropical cyclone intensity and is the primary basis for the global tropical cyclone intensity climatology for the last 25 to 30 years. More recently, new satellite techniques have been developed and are used in operations to assess tropical cyclone intensities. However, the DVKT remains the primary tool when aircraft reconnaissance is unavailable for this exercise. The documentation provided here gives the users of the raw DVKT intensity estimates and the historical best tracks, based on the DVKT, quantitative estimates of the biases and errors associated with this method based on a long and large Atlantic sample.

The findings of this study are based on DVTK practices that have been used at SAB and TAFB. The practices at SAB and TAFB closely follow those of Dvorak (1984). Users of the DVKT in other basins have applied regional variations and modifications to the DVKT (Velden et al. 2006b), which may have resulted in DVKT biases in those regions that are different from those found in this study. Given that caveat, this study has shown that the DVKT has a tendency to slightly underestimate intensities of storms receiving CI estimates ranging from 2.5 to 3.5 by an average of 1.5–2.5 kt, overestimate intensities of storms receiving CI estimate ranging from 4.5 to 5.5 by 1.5–2.5 kt, and underestimate intensity estimates of storms receiving CIs ranging from 6.5 to 7.0 by 4–9 kt. The DVKT also has its best intensity estimate (signal) to RMSE (noise) ratio in a range from 90 to 125 kt. Below 90 kt, the technique has its least skill and above 125 kt the errors increase. These situations suggest that the technique has greater limitations when estimating maximum wind speeds below 90 kt and above 125 kt. There is also an indication that the DVKT may have difficulty discriminating between category 4 (114–135 kt) and category 5

(>135 kt) hurricanes in our Atlantic sample. This difficulty appears to be related to cold cloud conditions needed to obtain the highest DVKT intensities. Those conditions are not as common as in the Eastern Hemisphere during the months of November–March where the climatological tropopause temperatures are colder. It is worth noting that this result may not be applicable everywhere because, according to Harper (2002), the original DVKT (i.e., Dvorak 1972, 1975) was developed using a sample dominated by western North Pacific cases, and that this is likely true of Dvorak (1984) as well. This study also examined the first DVKT-based intensity estimate coincident or prior to aircraft reconnaissance. The results found using this limited sample show that the errors and biases are similar to the larger Atlantic basin sample where aircraft-based information could have influenced the application of the DVKT. This should also provide DVKT users some confidence that the influence and availability of aircraft reconnaissance information does not adversely affect the results of this study.

If the biases, which are a function of intensity (maximum wind speed), are accounted for, additional DVKT biases are found to be related to 12-h intensity changes, latitude, translational speed, and the ROCI. These results are generally consistent with past studies. Individually, these factors result in relatively small biases (Table 5), but the combination of these factors and the built-in biases related solely to intensity can be appreciable. Forecasters should be aware of these biases when determining tropical cyclone intensities, be it operationally or during any postevent reanalysis (i.e., "best tracking"). Equation (3) provides a method for estimating the biases of the DVKT based on these factors. Again, caution should be used in applying these results blindly to other TC basins. There are several newly highlighted and remaining shortcomings of the DVKT based on this Atlantic sample. Translation speed, if faster or slower than the sample mean, results in low or high biases, respectively. The translation speed however can be accounted for by using the Schwerdt et al. (1979) equation for wind asymmetry. This speed factor has nearly a 1-to-1 correspondence with the biases related to the translation speed (i.e., Table 5). The average translation speeds found for our sample were 7.5, 8.3, 8.7, 8.9, 9.1, 9.9, 11.0, 11.1, 11.2, 11.2, and 11.0 kt for CI numbers of 2.0, 2.5… 7.0, respectively. This finding highlights the fact that weaker storms often move slower, which is likely similar to the translation speeds that are implicit in Table 1. It is clear that the rules associated with rapid changes in intensity should be revisited and may be abandoned given the frequency (typically half-hourly) of the modern imagery, though this would require more frequent intensity fixes. Currently, the DVKT rules do not allow storms to intensify or weaken as fast as they are observed to do so. The rule of holding storms at peak intensity for 12 h and then keeping the CI from 1 to 0.5 T numbers higher during weakening, which has been discussed by others (Brown and Franklin 2002; Velden et al. 1998; Velden et al. 2006a), is also a rule that should at the very least be accounted for when assigning operational intensities. This rule, however, should likely be formally reevaluated and eventually modified for use in operations. This weakening issue is an example of something that has already been addressed by regional modifications to the DVKT. High-latitude DVKT intensity estimates are sometimes low biased due to cold cloud-top temperatures being warmer than in the deep tropics due to tropopause temperature and height variations. This shortcoming is easily understood and could likely be resolved by incorporating addition information either from global forecast model analyses or from recent satellite imagery. With respect to the size variations of intense cyclones (>95 kt), the DVKT underestimates the intensity of the average and small cyclones. Our results suggest that because different-sized tropical cyclones scale to one another (Fig. 9), the minimum requirements (cold cloud ring, eye temperature) used by the EIR DVKT for the higher intensities are more difficult to obtain for smaller storms. The relatively warm climatological tropopause temperatures in the Atlantic, when compared to the western Pacific, where most of the initial (i.e., Dvorak 1975) developmental data were collected (Harper 2002), also seem to be a factor in the DVKT's relative inability to discriminate strong category 4 from category 5 hurricanes in this Atlantic sample. While it is likely that similar biases are found in other TC basins, particularly those biases related to the intensity, 12-h intensity change, size (i.e., ROCI), and translation, caution should be used when applying these results blindly to those TC basins, particularly when regional modifications to the DVTK practices have also been made.

It is notable that the digital Dvorak technique (Zehr 1989; Dvorak 1995), which has been carried over to the objective Dvorak techniques described in Velden et al. (1998) and Olander and Velden (2007), does not require a minimum ring width and can be automated to estimate an intensity and T number associated with every available image. The use of all available images and some time averaging of the recent results may eventually enable the abandonment or at least the relaxation of the DVKT CI rules. The advanced Dvorak technique (ADT; Olander and Velden 2007), which already uses modified pressure–wind relationships developed by Kossin and Velden (2004) based on Atlantic aircraft data, also now makes use of microwave image information that will address center fix ambiguity as well as some of the intensity estimation uncertainty between 35 kt, 2.5 T number, and 55 kt, 3.5 T number. Other intensity estimation techniques, namely from the Advanced Microwave Sounding Unit (AMSU; e.g., Herndon and Velden 2004; Demuth et al. 2006), are being combined to form consensus estimates that will further improve operational intensity estimates (C. Velden 2010, personal communication).

The RMSEs associated with the DVKT are shown here to be primarily a function of intensity [Fig. 3, Eq. (2)]. The DVKT appears to be designed to produce RMSEs that are 0.5 T numbers when examined in terms of CI (i.e., given in Table 1). This result provides a measure of the expected accuracy of the DVKT, and because the DVKT is used as the primary intensity estimation tool at most times and in most tropical cyclone basins, it offers an estimate of the errors associated with the historical best tracks. Errors associated with the DVKT also can be further reduced by using a consensus of DVKT fixes from different agencies/analysts. Though a more comprehensive study is needed, this finding certainly suggests that having multiple agencies providing independently derived fixes to operations reduces the uncertainty associated with intensity estimation. Some coordination between agencies, in particular, on policies (i.e., consistent guidelines) as to when to consider initiating tropical cyclone fixes, would result in more uniform DVKT results. Improving the initiation time of fixes would likely result in more consistent, yet independent interagency intensity fixes. Independence is important because it leads to a better consensus estimate (Sampson et al. 2008, their appendix B). These topics merit further investigation. Also unresolved and deserving investigation is the potential error reducing effects of more frequent DVKT intensity estimation, which is now possible given the global availability to more timely geostationary satellite imagery.

Biases and RMSEs associated with TAFB and SAB DVKT estimates in the Atlantic basin during 1989–2008 have been quantified as a function of intensity in Eqs. (1) and (2). Biases in this sample were also shown to be a function of intensity, 12-h intensity trend, latitude, translation speed, and size in terms of ROCI in Eq. (3). Equation (3) has been applied to the eastern Pacific cases with aircraft-influenced best-track intensity estimates in those same 20 yr and has been shown to decrease the bias by about 40% and the RMSE by about 10%. This makes possible the creation of an intensity best track based solely on the DVTK estimates and routinely available operational information. The output would also contain information about the expected RMSE. It is also noteworthy that (1)–(3) are based on an Atlantic sample and from fixes from TAFB and SAB and thus are likely most applicable for DVKT estimates from those agencies and in the Atlantic basin.

In the process of preparing this manuscript, it also became clear that different agencies apply slightly different constraints to their fixes and use slightly different procedures when arriving at their intensity estimates or CIs. A discussion of regional modifications is included in Velden et al. (2006b). This would suggest that the RSMCs and other agencies, like SAB and JTWC, that make intensity fixes could communicate more efficiently and ultimately agree on one set of procedures to best arrive at the DVKT CI. This would be a good exercise for the World Meteorological Organization.

From a more practical standpoint, the information provided here should 1) provide reassurance that the DVKT is a skillful and internally consistent method that has biases that are small compared to the RMSEs, 2) provide some of the known biases and expected accuracies associated with making DVKT-based intensity estimates based on an Atlantic sample, and 3) provide some information as to where further studies are needed. It is noteworthy that studies such as this one would not be possible without the aircraft-based hurricane reconnaissance available from the U.S. Air Force Reserve and the National Oceanic and Atmospheric Administration (NOAA) Aircraft Operations Center. This fact highlights the desire for similar reconnaissance missions in other tropical cyclone basins to better validate this and similar studies. Despite the many caveats associated with this study, we feel the results of this research will prove useful for those in operational tropical cyclone forecast centers, those performing climatological analyses with the current best-track datasets, and those groups and individuals conducting best-track reanalyses.

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