Constraints in Dvorak Wind Speed Estimates: How Quickly Can Hurricanes Intensify?

SAMUEL J. SANGSTER

Department of Earth, Ocean, and Atmospheric Science, Florida State University, Tallahassee, Florida

CHRISTOPHER W. LANDSEA

NOAA/NWS/NCEP/National Hurricane Center, Miami, Florida

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ABSTRACT

The Dvorak technique is used operationally by meteorological agencies throughout the world for estimating tropical cyclone intensity and position. The technique consists of constraints that put a maximum threshold for which the final T-number, relating directly to intensity, can change during a certain time interval (6, 12, 18, and 24 h). There are cases when these constraints could be broken, especially during rapid intensification. This research tests whether the constraints used for intensity change are warranted or need to be changed. A database of cases with the largest intensity changes for 2000–17 Atlantic tropical cyclones was compiled. A reconnaissance or scatterometer ''fix'' is required within 3 h of both the beginning and ending of the period for each case to inform the best track and to be included for analysis. Dvorak classifications from the Tropical Analysis and Forecast Branch are noted for each case, which includes the initial and final T-numbers, current intensity numbers, and data T-numbers. Statistical parameters, including correlations, intensity errors, absolute intensity errors, root-mean-square errors, and significance tests are calculated and analyzed for each period. Results suggest that the T-number constraints for the 18- and 24-h periods could be increased to a 2.5 and a 3.0, respectively. However, results also suggest that the constraints for the 6- and 12-h time intervals should remain the same.

1. Introduction

The Dvorak satellite technique (Velden et al. 2006) is used operationally around the world to make estimations of tropical cyclone intensity—maximum sustained surface winds—and center location based upon the pattern of the clouds and set rules. The output from this technique results in a data T-number (DT) among other metrics. Typically, the DT is utilized most for intensity assessments except for unclear patterns or convective patterns that do not remain consistent over an hour or two up to synoptic time. The aforementioned set of rules are used for both intensification and dissipation phases. The current rules, or constraints, for intensification allow for a maximum change in the DT over a certain period of time to arrive at a final T-number (FT). The initial constraints in place (Dvorak 1984) were a DT change of 1.5 for the first 24 h of development, 2.0 over a 24-h period for DTs between 2.0 and 4.0, and 2.5 over a 24-h period for DTs 4 or greater. These rules were adjusted around 1990 based on an unpublished National Hurricane Center (NHC) study by Arthur Pike that allowed more intensification for weaker systems, such that a 2.0 change in DTs during the initial 24 h of a systems development is permissible (only 0.5 DT change per 6 h) and a 2.5 change in DTs over 24 h are applicable to all other tropical cyclones. These modified rules are set in place for 6-, 12-, 18-, and 24-h time periods for obtaining the FT (Table 1). For intensifying systems, the current intensity number (CI) is set to be equal to the FT. CI converts directly to an assessed intensity (Table 2). A change of one T-number per day is related to the climatological rate of change of intensity. Notice that the T-number versus intensity relationship is nonlinear with a greater T-number equaling greater intensity changes for more intense tropical cyclones. Knaff et al. (2010) evaluated the subjective Dvorak classifications when aircraft reconnaissance was available to inform the best tracks and found that the root-mean-square error ranged from 6 to 10 kt[1] for

Corresponding author: Samuel J. Sangster, ss19@my.fsu.edu

[1] 1 kt = 0.5144 m s^{-1}. Knot is the preferred unit discussed here as the HURDAT2 database (Landsea and Franklin 2013) is in knots.

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TABLE 1. Current constraints in the final T-number (FT) in place for each period used at the National Hurricane Center.

Time period	Max change in FT number allowed
6 h	1.0 T-numbers
12 h	1.5 T-numbers
18 h	2.0 T-numbers
24 h	2.5 T-numbers

TABLE 2. Estimated wind speeds based on current intensity (CI) number. During intensification, the CI number is always equal to the FT number.

	1-min mean sustained wind	
CI No.	In kt	In mph
1.0	25	29
1.5	25	29
2.0	30	35
2.5	35	40
3.0	45	52
3.5	55	63
4.0	65	75
4.5	77	89
5.0	90	104
5.5	102	117
6.0	115	132
6.5	127	146
7.0	140	161
7.5	155	178
8.0	170	196

tropical depressions and tropical storms and 11–14 kt for hurricanes.

The current rules have been used operationally for a couple of decades, allowing for time to consider how well the constraints verify for intensifying systems. A large amount of data on tropical cyclones is now available, especially for cases of rapid intensification (RI). Rapid intensification is considered to be at 30 kt of intensity gain or greater over a 24-h period (Kaplan and DeMaria 2003). Several of these cases demonstrating RI had the potential to break the constraints currently in place during intensification. A previous study (Cangialosi et al. 2015) confirmed that current Dvorak intensity constraints are set such that only 2% of strengthening tropical cyclones have intensity changes that break the constraints. When RI occurs close to the coast, it can pose a significant risk if not captured correctly by satellite methods. This study examines these constraints to determine whether they need to be relaxed, be removed, or stay the same in order to provide the most accurate and least biased Dvorak intensity estimate.

2. Data and methods

The National Hurricane Center's Atlantic basin hurricane database (HURDAT2) is used in this study to gather cases of largest intensity changes for 6-, 12-, 18-, and 24-h periods. The data are NHC's final (i.e., post-storm "best track") estimate of storm location and maximum winds (Landsea and Franklin 2013). Only tropical cyclones of at least tropical storm strength are included in the sample. Figures 1a and 1b show a case where the current rules constrained the estimated intensity. Figures 2a and 2b show a case where the current constraints did not need to be applied but did have a large enough intensity change to be included in the dataset. The study was confined to the years 2000–17 since the method to convert surface wind estimates from aircraft reconnaissance measurement has been performed consistently using the "Franklin 90% Rule," outlined in Franklin et al. (2003), since 2000. Note that "best tracks" are subjectively determined by individual hurricane specialists at NHC (Landsea and Franklin 2013) and intensity best tracks may differ from one forecaster to the next, even with the same raw observations available. Of some concern is the increasing reliance of best tracks upon the stepped frequency microwave radiometer (SFMR; Uhlhorn and Black 2003; Uhlhorn et al. 2007; Klotz and Uhlhorn 2014) for intensity since the instrument became operationally available aboard the Air Force C-130 aircraft reconnaissance beginning in 2008. The SFMR's relatively new availability, its evolving calibrations, and possible high bias for extreme hurricane winds in recent seasons (Avila et al. 2020) do indicate some concern for a nonstationary set of criteria for assessing best track intensities during the last couple of decades.

The first stratification of the database was to include only cases in the best track above a set minimum wind speed change over the period (i.e., at least 15 kt for 6 h, 20 kt for 12 h, 25 kt for 18 h, and 30 kt for 24 h). By stratifying this way, the more intense and rare situations that have the possibility of breaking constraints will all be examined. For the second stratification, only cases when an aircraft reconnaissance "fix" (center location and intensity estimate from airborne in situ measurement) or scatterometer pass was available within 3 h of the best track time are considered. This provides the most accurate database possible for intensity and also removes any direct influence of the Dvorak classifications on the intensity assessment in the best track (as intensity would, in these cases, be based almost exclusively on aircraft reconnaissance or scatterometer data). Landsea and Franklin (2013) and Torn and Snyder (2012) estimated that the uncertainty in the intensity best tracks for cases with aircraft reconnaissance present

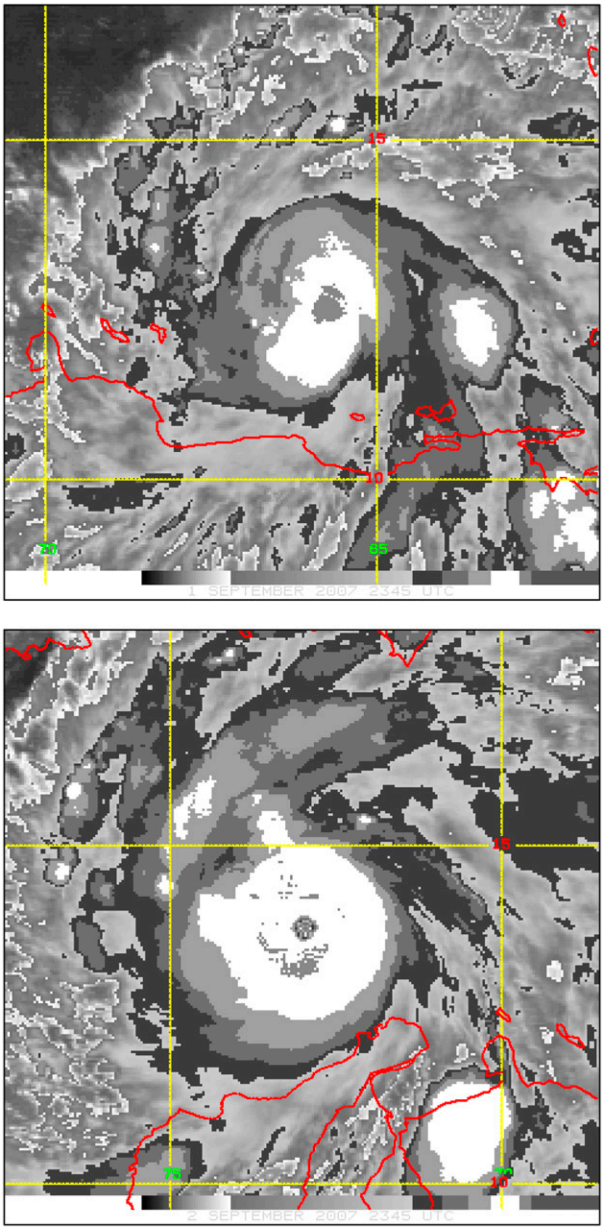

FIG. 1. (a) Hurricane Felix from 2007 at 2345 UTC 1 Sep. At this time, the DT was 3.5 and the FT was 3.5. The best track intensity was 65 kt. (b) Hurricane Felix 24 h later at 2345 UTC 2 Sep. At this time, the DT was 7.0 and the FT should be constrained to be 6.0. The best track intensity was 150 kt.

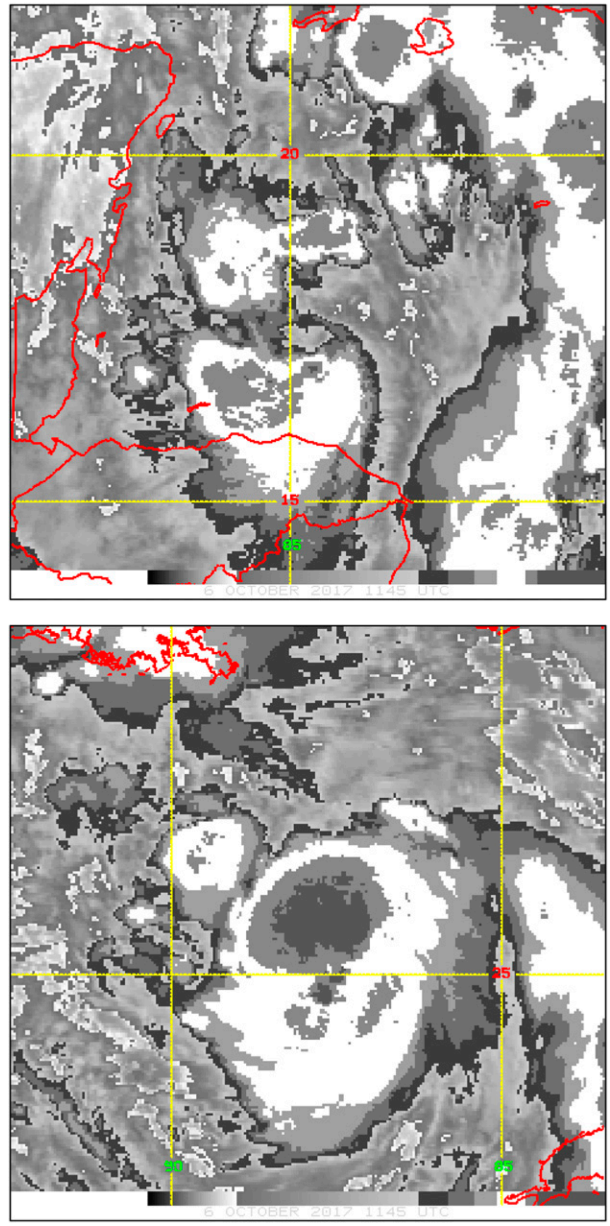

FIG. 2. (a) Hurricane Nate from 2017 at 1145 UTC 6 Oct. At this time, the DT was 3.0 and the FT was 3.0. The best track intensity was 40 kt. (b) Hurricane Nate 24 h later at 1145 UTC 7 Oct. At this time, the DT was 5.0 and the FT was 5.0. The best track intensity was 80 kt.

roughly ranges from 8 kt for tropical storms up to 11 kt for major hurricanes. It is important to note that an intensity value informed by a scatterometer pass be of no more than 50 kt. As intensity increases above 50 kt, the accuracy of the scatterometer data decreases (and a substantial low bias develops) due to the resolution of the instrument and reduced signal-to-noise ratio of the instrument, as seen in Brennan et al. (2009) using QuickScat and Ku radar band observations. After completing the stratification processes, initial and end time DT, FT, and CI numbers, as well as NHC's best track estimate were assembled for each tropical cyclone that met the above criteria at both the beginning and ending points of the period being examined. The DT, FT, and CI numbers of the Dvorak fixes were obtained from the Automated Tropical Cyclone Forecast

TABLE 3. Statistical parameters calculated for the 6-h period. Boldface numbers represent the best value for the parameter. Italicized constraint indicates current constraint level. The asterisk (*) indicates signficiantly different from the current constraint at the 90% significance level. The average initial FT implied intensity for these 45 cases is 77.1 kt with a standard deviation of 27.0 kt.

6-h time interval statistics, $n = 45$				
Level of constraint (No. of cases with possible broken constraints)	Correlation of estimated vs best track intensity	Average intensity error (bias)	Average absolute intensity error	RMSE
None (0)	0.9	**−4.4**	11.6	14.2
1.5 (0)	0.9	**−4.4**	11.6	14.2
1.0 (7)	**0.93**	−6.4	**10.7**	**13.3**
0.5 (16)	0.91	−10.9*	13.7	16.8

(ATCF) database (Naval Research Laboratory 2000; Sampson and Schrader 2000). The resulting sample size for the study were 45 cases for the 6-h period, 55 cases for the 12-h period, 38 cases for the 18-h period, and 30 cases for the 24-h period. The FT numbers are converted to an intensity based upon the scale shown in Table 2 (from Dvorak 1975) for direct comparison with the best track intensities.

Once the stratified data were organized by period, statistical analysis was performed to determine which Dvorak intensity estimate based on differing levels of constraints have the highest correlations, lowest errors, and smallest bias. The levels of constraints tested for each period included having no constraint, 0.5 T-numbers above the current constraint, the current constraint, and 0.5 T-numbers below the current constraint. Statistical analysis performed in this study includes correlation between best track intensity and estimated intensity, average intensity error or bias, average absolute intensity error (AAIE), and root-mean-square error (RMSE). These statistics were calculated separately for each period.

3. Results

a. 6-h period

Table 3 represents statistical values attained for the constraint levels tested. For this period, 45 cases were examined, with none that could have broken a +1.5 T-number constraint, 7 that could have broken a +1.0 T-number constraint, and 16 that could have broken a +0.5 T-number constraint. For correlation of best track intensity versus estimated intensity, having the current constraint in place (+1.0 T-number) showed the highest correlation. In addition, the lowest AAIE and RMSE were indicated for the current constraint. Although the bias was lowest with having no constraint, it was not significantly different from the bias for the current constraint used for this period. The percentage of cases for this time period that would have broken the current constraint is 20%. It is clear that making the constraints more stringent (i.e., only allowing at FT change of +0.5 T-numbers in 6 h) would not be warranted. Overall, the current constraint used for cases in this time interval shows the best values.

b. 12-h period

Unlike the 6-h period, the analysis results for the 12-h period was more equivocal, as seen in Table 4. Although having no constraint showed the best correlation between best track intensity and estimated intensity, it was rather close in value to having a constraint of +2.0 or +1.5 T-number change allowed. A similar situation is seen for the AAIE and RMSE, with having no constraint showing the lowest values. However, the bias is lowest for having a constraint +0.5 T-numbers higher than the current constraint. It is important to note that excluding the statistical values calculated for a +1.0 constraint, the values are quite similar in magnitude with negligible differences throughout. Compared to the 6-h period, approximately 8% cases break current constraints.

TABLE 4. Statistical parameters calculated for the 12-h period. Boldface numbers represent the best value for the parameter. Italicized constraint indicates current constraint level. Two asterisks (**) indicate significantly different from the current constraint at the 95% significance level. The average initial FT implied intensity for these 55 cases is 68.5 kt with a standard deviation of 22.1 kt.

12-h time interval statistics, $n = 55$				
Level of constraint (No. of cases with possible broken constraints)	Correlation of estimated vs best track intensity	Average intensity error (bias)	Average absolute intensity error	RMSE
None (0)	**0.89**	**0.5**	**10**	**12.6**
2.0 (3)	0.88	**−0.2**	10.3	13.1
1.5 (12)	0.88	−2.9	**10**	13.3
1.0 (26)	0.86	−8.7**	12.3	16.6

TABLE 5. Statistical parameters calculated for the 18-h period. Boldface numbers represent the best value for the parameter. Italicized constraint indicates current constraint level. The asterisk (*) indicates signficiantly different from the current constraint at the 90% significance level. The average initial FT implied intensity for these 38 cases is 65.0 kt with a standard deviation of 19.1 kt.

18-h time interval statistics, $n = 38$				
Level of constraint (No. of cases with possible broken constraints)	Correlation of estimated vs best track intensity	Average intensity error (bias)	Average absolute intensity error	RMSE
None (0)	**0.88**	0.9	**9.4**	**12.4**
2.5 (1)	0.87	**0.5**	9.7	12.8
2.0 (3)	0.86	**−0.5**	10.1	13.2
1.5 (16)	0.85	−5.8*	10.2	14.7

Based upon these errors and percentage of cases that break constraints, either raising the constraint by +0.5 T-numbers (to a +2.0) or keeping it the unchanged would be justifiable, as the performance of both is quite similar.

c. 18-h period

Table 5 shows the statistical values for the 18-h period intensity change cases. In contrast to both the 6- and 12-h periods, the best values were seen with having no constraint in place or having a constraint +0.5 T-numbers above the current constraint. The highest correlation, along with the lowest AAIE and RMSE, was evident with having no constraint in place. In addition, nearly 22% of cases included for this time period broke current constraints. It is clear that making the constraints more relaxed is warranted. The analysis supports raising the constraint for 18-h period by +0.5 T-numbers to make the new constraint +2.5 T-numbers.

d. 24-h period

Table 6 represents the statistics computed for cases compiled for the 24-h period. Similar to results from Table 5, it can be noted that having either no constraint or a constraint +0.5 T-numbers greater than the current constraint show the best statistical values with highest correlation, lowest AAIE, lowest RMSE, and smallest bias. Again, relaxing the constraints for this period is warranted, although only 16% of cases broke current constraints. The analysis supports raising the constraint for the 24-h period by +0.5 T-numbers to +3.0.

4. Summary and discussion

This study aims to determine the best constraints for intensity change using the Dvorak technique at 6-, 12-, 18-, and 24-h periods. Based on parameters computed in this study, the analysis supports continuing the current practice of current constraints for the 6- and 12-h period. However, given the more accurate values with raising the constraint for the 18- and 24-h period, adjusting operational practices with a larger constraint at those periods. Table 7 shows the recommended new constraints for intensification when using the Dvorak technique. When raising the 18- and 24-h constraints by 0.5 T-numbers each, more of the extreme cases could be better accounted for with their large intensity changes. For example, Hurricane Felix shown in Fig. 1 had aircraft-reconnaissance-informed intensities of 65 kt at 0000 UTC 2 September and 150 kt at 0000 UTC 3 September, 24 h later. By loosening the constraint at 24 h from +2.5 to +3.0 the Dvorak technique estimated intensity at 0000 UTC 3 September improved from 115 kt (CI of 6.0) to 127 kt (CI of 6.5), significantly closer to the best track value. In addition, by keeping the 6 and 12 h the same while raising the other two, the change in T-number allows increases evenly with time (i.e., the 12-h constraint of 1.5 T-numbers would be half of the new 3.0 T-numbers for 24 h). As outlined in

TABLE 6. Statistical parameters calculated for the 24-h period. Boldface numbers represent the best value for the parameter. Italicized constraint indicates current constraint level. The asterisk (*) indicates signficiantly different from the current constraint at the 90% significance level. The average initial FT implied intensity for these 30 cases is 54.6 kt with a standard deviation of 19.9 kt.

24-h time interval statistics, $n = 30$				
Level of constraint (No. of cases with possible broken constraints)	Correlation of estimated vs best track intensity	Average intensity error (bias)	Average absolute intensity error	RMSE
None (0)	0.91	**−0.6**	8.8	11.5
3.0 (3)	**0.93**	−1.9	**8.4**	**10.8**
2.5 (6)	0.91	−4.4	9.6	12.7
2.0 (16)	0.85	−10.9*	14*	18

TABLE 7. Recommendations for the Dvorak technique constraints, with accompanying top three largest intensity changes for each period. Boldface numbers show new recommendations for the 18- and 24-h periods and corresponding new change in intensity allowed.

Time period	Current max change in FT Number allowed	Suggested max change in FT Number allowed	Top three max intensity change observed	Current max intensity change allowed	Suggested max intensity change allowed
6 h	1.0 T-numbers	1.0	55 kt (Wilma) 35 kt (Felix) 35 kt (Maria)	30 kt	30 kt
12 h	1.5 T-numbers	1.5	75 kt (Wilma) 60 kt (Felix) 45 kt (Keith)	43 kt	43 kt
18 h	2.0 T-numbers	**2.5**	85 kt (Wilma) 65 kt (Felix) 65 kt (Maria)	55 kt	**68 kt**
24 h	2.5 T-numbers	**3.0**	90 kt (Wilma) 85 kt (Felix) 75 kt (Matthew)	68 kt	**80 kt**

Cangialosi et al. (2015), only 2% of cases broke constraints, compared to an average of 16% for all time periods combined in this study. Such changes of the constraints at the 18- and 24-h period are rare, occurring just a couple times each hurricane season on average. But by relaxing those constraints, analyses of intensity can be improved when done solely by satellite through the Dvorak technique, which remains the standard by Regional Specialized Meteorological Centers forecasting tropical cyclones around the world. It is possible that the frequency of RI events or very intense TCs in best track data for NHC's area of responsibility will change based on these recommendations.

These results can provide a way to answer the question poised in this paper's title: How quickly can hurricanes intensify? The average initial FT of the 24-h cases was 3.38, implying an intensity of 53 kt. Allowing a 3.0 change of the FT over 24 h would bring it to a FT of 6.38, or around 124 kt—an intensification of 71 kt in a day. For the strongest case possible—an initial FT of 5.0 going up to a FT of 8.0 in 24 h—would indicate an 80-kt intensification. This is close to the record of 90 kt recorded by Hurricane Wilma in 2005.

An area of future research following this study could focus on the validity of the constraints used in the Dvorak technique for weakening tropical cyclones, which is especially problematic in the eastern Pacific basin. As tropical cyclones there cross the sharp sea surface temperature gradient into cool waters, they quickly lose organized deep convection and rapidly weaken. How rapidly they weaken is also in part based on the Dvorak constraint rules which can also be tested and, if needed, revised as well.

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