The Validity of Dvorak Intensity Change Constraints for Tropical Cyclones

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ABSTRACT

The Dvorak technique is used operationally worldwide for tropical cyclone intensity analysis. This study tests Dvorak intensity change constraints, using a database of simultaneous aircraft and satellite fixes for tropical cyclones (TCs) in the 1998–2012 period. Results indicate that, in the vast majority of cases, Dvorak intensity constraints are valid with only a small percentage of strengthening TCs violating the constraints. Of the small sample that broke the constraints, most had initial intensities ranging from moderately strong tropical storms to minimal hurricanes.

1. Introduction

The Dvorak satellite technique (Velden 2006) provides manual subjective estimates of tropical cyclone (TC) intensity based on assessments of the cloud pattern's organization and a series of rules, with output in the form of a T number.[1] These rules have evolved as the technique has changed over time (Dvorak 1972, 1984, 1995). In addition, satellite analysts at the National Hurricane Center (NHC) have also modified the rules. One modification involving strengthening TCs came from an unpublished empirical study of a sample of storms by A. Pike, which allowed for earlier use of constraints that Dvorak restricted to TCs of hurricane strength. A second modification for weakening storms was established by Lushine (1977). The current set of the constraints (Table 1) allows for a maximum final T-number change over set time intervals of 24 h or less, and these have been accepted at the NHC as conventional guidelines for the analysis of TC intensity change since that time. These constraints are believed to better represent the more extreme cases of rapid intensification or weakening, while giving the analyst the necessary flexibility to best estimate TC intensity.

The current constraints have been used operationally for several decades, giving analysts and observers time to consider their validity. A wide spectrum of cases of both TC intensification and weakening providing good ground truth are now available, many more than were available in the original sample. TCs that have apparently violated the newer constraints have generated discussion about whether the current constraints are optimal or could be improved. This study analyzes modern-day data to determine whether the constraints are appropriate for use.

2. Data and methodology

The NHC Atlantic hurricane database (HURDAT) from 1998 to 2012 is used for this study. The data are archived every 6 h (at 0000, 0600, 1200, and 1800 UTC) and include reports of storm position and maximum winds for the period of study (Landsea and Franklin 2013). Only data when aircraft reconnaissance data were also available within 3 h of the best-track time are considered for this study, while all systems with best tracks over land in any portion of the same time interval are excluded from the study. The selected best-track intensities from HURDAT are converted into a corresponding T number by interpolating the value from the Dvorak scale (Table 2). The T-number change was then computed for 6-hourly periods through 24 h and compared to the existing Dvorak constraints (Table 1).

[1] A T number is a discrete representation of TC intensity on a scale ranging from 1 to 8 corresponding to tropical cyclone intensities from 25 to 170 kt.

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TABLE 1. The max potential change of the Dvorak final T number at various time intervals. [Reproduced from Dvorak (1984).]

Dvorak final T-number constraints used at NHC
1.0 T numbers over 6 h
1.5 T numbers over 12 h
2.0 T numbers over 18 h
2.5 T numbers over 24 h

These cases were then stratified into groups of weakening and intensifying TCs at each time period to determine any distinguishing characteristics. The criteria for strengthening and weakening TCs is an intensity change of 5 knots (kt; $1\,\mathrm{kt} = 0.51\,\mathrm{m\,s^{-1}}$) or greater.

The proportion of cases breaking constraints is calculated for strengthening TCs at each time interval (6, 12, 18, and 24 h). Confidence intervals were then computed to rigorously approximate the proportion of cases $\hat{P}$ violating the constraints. The variance of this value can be approximated using a simple but widely used equation (Jolliffe 2007) to compute the confidence interval, with $Z\alpha$ representing the Z score (Garthwaite et al. 2002) at the 99% confidence level and n representing the sample size:

$$\hat{P} \pm Z\alpha/2\sqrt{\hat{P}(1-\hat{P})/n}\,.$$

Theoretically, since the frequency (i.e., $\hat{P}$) is close to zero in this case, large values of n are needed for the approximation to be valid. Ideally, the approximation would approach the true distribution as n approaches infinity. With the sample size around or above 500 at each time interval, we can assume that n is sufficiently large to produce a robust confidence interval at the 99% confidence level. In addition, the application of the equation produces results that do not include negative values and are thus physically meaningful.

3. Results and discussion

Figure 1 shows that the final T-number change for all TCs is nearly normally distributed at all times through

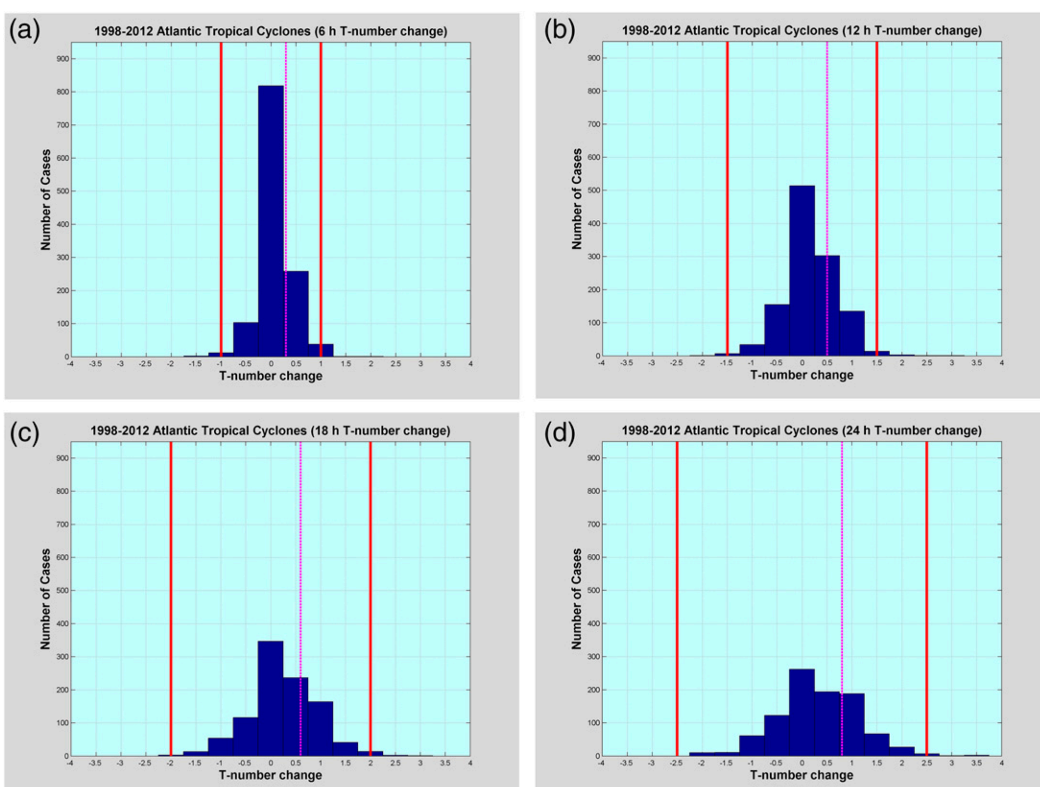

FIG. 1. Histograms depicting the distribution of the final T-number change in half T-number bins at (a) 6, (b) 12, (c) 18, and (d) 24 h. The X axis shows the final T-number change and the Y axis shows the number of cases in each bin. The solid red lines represent the developing and weakening Dvorak constraints as shown in Table 1, while the dashed pink lines show the respective median values. Positive values represent strengthening TCs, while negative values represent the weakening subset.

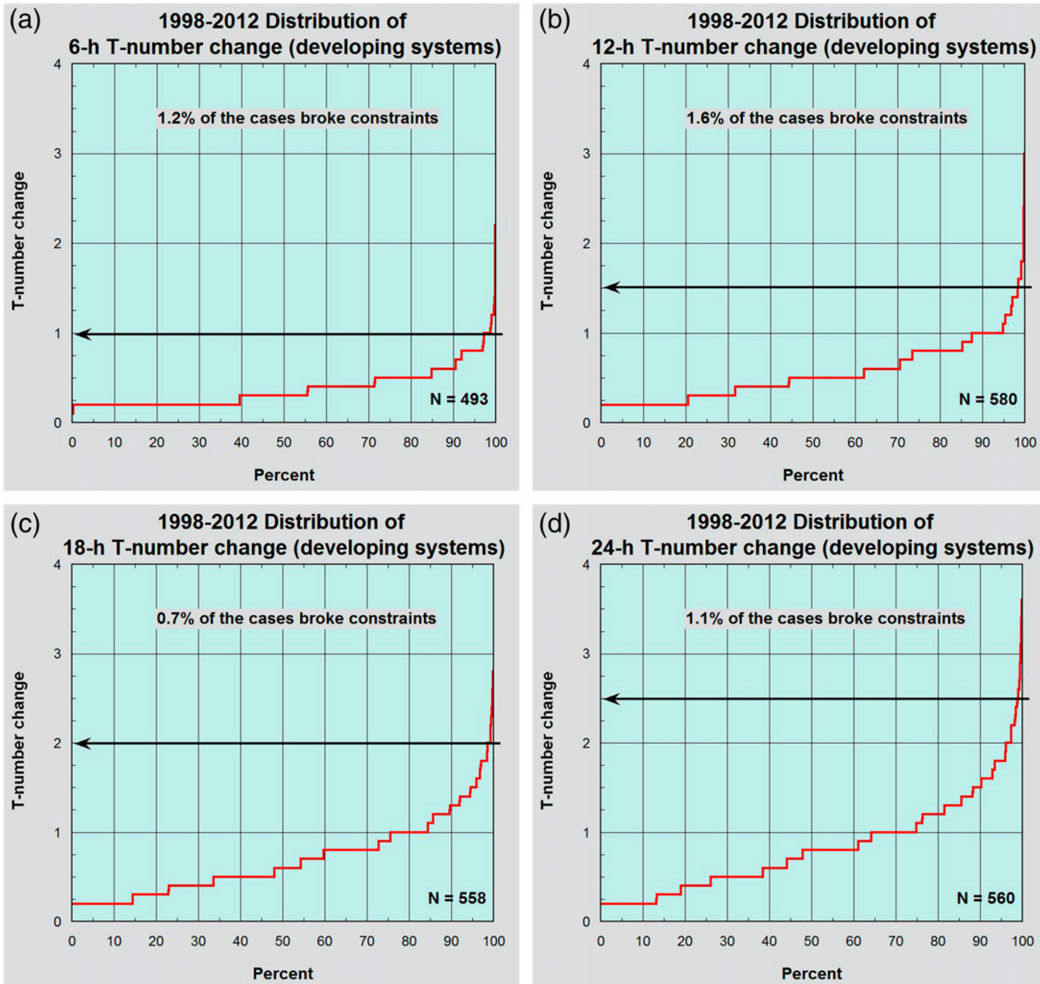

FIG. 2. Frequency diagrams showing the likelihood of the final T-number change for developing systems at (a) 6, (b) 12, (c) 18, and (d) 24 h. The X axis indicates the expected frequency (%) and the Y axis indicates the final T-number change. The number of cases is indicated in the lower right. The red line depicts the current Dvorak constraint.

24 h, with median values at 0.3 (6 h), 0.5 (12 h), 0.6 (18 h), and 0.8 (24 h). The last value suggests that the climatological rate of development of TCs is about a T number per day, which agrees well with Dvorak (1984). The tails of the distribution are generally quite narrow and indicate that a small number of cases break constraints. In fact, less than 2% of the total population breaks current constraints at any time interval (Fig. 2). A list of TCs breaking constraints during the period of study is provided in Table 3. Confidence intervals were computed at the 99% confidence level for strengthening TCs, and the results are presented in Table 4. The fairly large sample size of about 500 cases or more at each time interval for the strengthening TCs and relatively narrow range in the confidence interval suggests that the results are robust. There were too few cases of weakening TCs that broke Dvorak intensity change constraints to analyze (Fig. 3).

Figures 1 also shows a skewness toward positive final T-number change in intensity, suggesting that there are many more cases of (near) rapid intensification than rapid weakening. Since the cases in the database are random (the only requirement is that satellite and aircraft fixes were available concurrently), the results indicate that in the Atlantic basin breaking Dvorak constraints is essentially a phenomenon primarily for strengthening TCs. In the eastern Pacific basin, where TCs generally encounter sharp gradients of sea surface temperatures later in their life cycles and could rapidly weaken, breaking Dvorak constraints for weakening could also be an issue. Future studies could explore this topic further if

TABLE 2. Dvorak T number (to the nearest 1/10th) and corresponding TC intensity.

Dvorak T number	Wind speed (kt)
1.5	25
2.0	30
2.5	35
2.8	40
3.0	45
3.3	50
3.5	55
3.8	60
4.0	65
4.2	70
4.4	75
4.6	80
4.8	85
5.0	90
5.2	95
5.4	100
5.6	105
5.8	110
6.0	115
6.2	120
6.4	125
6.6	130
6.8	135
7.0	140
7.2	145
7.3	150
7.5	155
7.7	160
7.8	165
8.0	170

the dataset of satellite and aircraft data for this subset of TCs becomes larger.

TCs breaking constraints were binned by intensity to determine whether there are distinguishing behavioral characteristics of weak versus strong TCs (Fig. 4). The intensities at which tropical cyclones broke constraints generally fall into a narrow range running from moderately strong tropical storms to minimal hurricanes (55–90 kt). These data confirm the findings of others (e.g., Kaplan and DeMaria 2003) that there is something special about this range of TC intensity with regard to rapid intensification. It is in this intensity range that eye formation typically takes place in TCs, and several researchers have shown that the formation of an eye often coincides with, or is followed by, a period of rapid intensification (Malkus 1958; Yanai 1961; Mundell 1990; Weatherford and Gray 1988; Shapiro and Willoughby 1982; Willoughby 1990; Vigh et al. 2012). Theoretical studies have shown that there is an upper bound on TC intensity (Emanuel 2004). However, additional research is needed to estimate the upper bound on the TC intensification rate.

TABLE 3. List of TCs that violated the Dvorak constraints.

Storm name (yr)	Initial intensity (constraints broken)
Developers	
Bret (1999)	80 kt (12 h) and 90 kt (6 h)
Iris (2001)	80 kt (12 h) and 90 kt (6 h)
Felix (2007)	65 kt (24 h), 85 kt (18 h), 90 kt (12 and 18 h), and 115 kt (6 h)
Humberto (2007)	55 kt (12 h)
Gustav (2008)	85 kt (12 h)
Keith (2000)	75 kt (12 h)
Katrina (2005)	105 kt (12 h)
Lorenzo (2001)	30 kt (12 h)
Wilma (2005)	55 kt (24 h), 60 kt (18 and 24 h), and 75 kt (12 and 24 h)
Dean (2007)	90 kt (18 h)
Weakeners	
Paloma (2008)	125 kt (6 h)
Henri (2009)	50 kt (6 h)
Lili (2002)	125 kt (12 h)

4. Summary

The current Dvorak constraints of intensity change for operational TC classifications in the Atlantic basin were tested in hopes of answering the following question: How valid are Dvorak constraints for tropical cyclone intensity change? Only TCs where aircraft- and satellite-based data were available are examined in this study. The current constraints (Table 1) are shown to be appropriate in the overwhelming majority of cases. In addition, the frequency of constraint-breaking TCs is extremely low (less than 2%), with this result shown to be statistically significant at the 99% confidence level. Although the validity of the current constraints is reassuring, what do the constraints really mean? The Dvorak constraints represent arbitrary bounds intended to realistically capture the maximum amount of strengthening or weakening observed in TCs within a 24-h period. Interestingly, these bounds were not chosen because of any known physical basis, yet they are so infrequently violated that the question of why this is the case deserves further study. From an operational point of view, the validity of the constraints is of fundamental importance. Since the constraints are rarely broken,

TABLE 4. Confidence intervals of the proportion of strengthening TCs breaking Dvorak constraints at various time intervals.

Time period (h)	Cases that violated constraints (%)	99% confidence interval (%)	Sample size
6	1.22	0.00–2.50	493
12	1.55	0.23–2.87	580
18	0.72	0.00–1.64	558
24	1.07	0.00–2.20	560

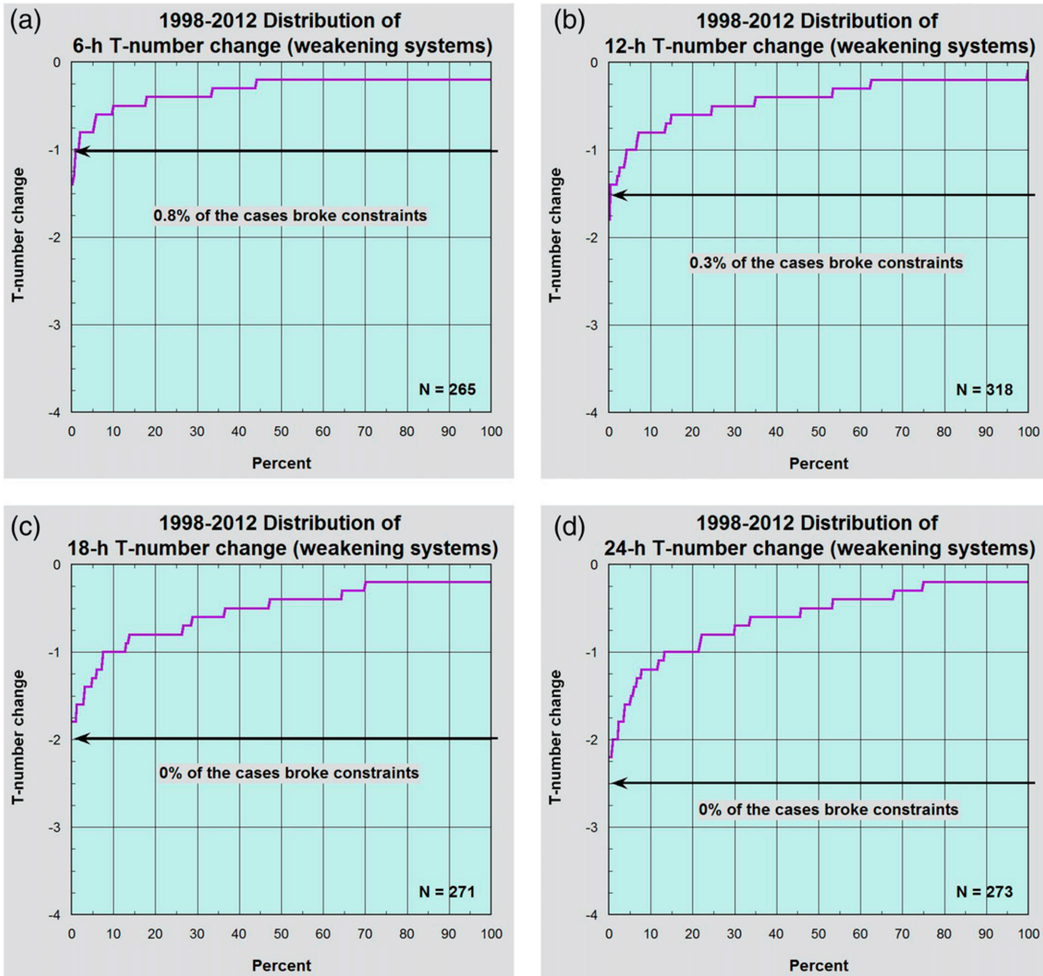

FIG. 3. Frequency diagrams showing the likelihood of the final T-number change for weakening systems at (a) 6, (b) 12, (c) 18, and (d) 24 h. The X axis indicates the expected frequency (%) and the Y axis indicates the final T-number change. The number of cases is indicated in the lower left. The black line depicts the current Dvorak constraint.

operational forecasters should have confidence that the Dvorak classification rules for limiting TC intensity change are likely to be sound in the vast majority of cases.

5. Future work and discussion

Another area of future research could focus on how well subjective Dvorak intensity estimates from the Tropical Analysis and Forecast Branch (TAFB) and the Satellite Analysis Branch (SAB) verify, given a strict adherence to intensity change constraints for the final T number. Such a study would attempt to answer the question of whether analysts who honor Dvorak constraints produce the best possible intensity estimates or not. Another question to follow from that analysis would be: Should we not apply the Dvorak constraints for TC intensity change at all? Finally, the study should also consider the trade-offs between the probability of detection of rapidly strengthening or weakening TCs and false alarms.

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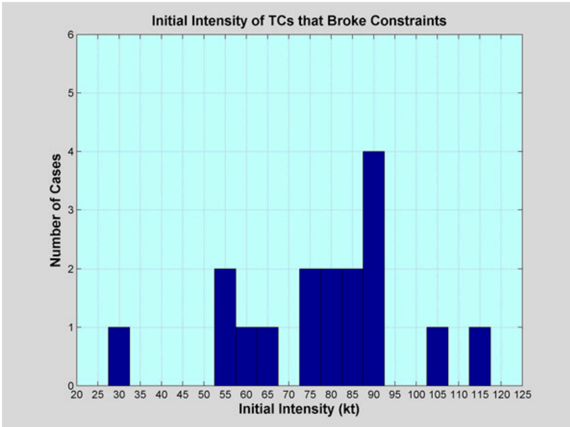

FIG. 4. Histogram displaying the initial intensity of developing systems that broke the constraints.

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