THE DVORAK TROPICAL CYCLONE INTENSITY ESTIMATION TECHNIQUE

A Satellite-Based Method that Has Endured for over 30 Years

BY CHRISTOPHER VELDEN, BRUCE HARPER, FRANK WELLS, JOHN L. BEVEN II, RAY ZEHR, TIMOTHY OLANDER, MAX MAYFIELD, CHARLES "CHIP" GUARD, MARK LANDER, ROGER EDSON, LIXION AVILA, ANDREW BURTON, MIKE TURK, AKIHIRO KIKUCHI, ADAM CHRISTIAN, PHILIPPE CAROFF, AND PAUL MCCRONE

This document is a supplement to "The Dvorak Tropical Cyclone Intensity Estimation Technique: A Satellite-Based Method That Has Endured for over 30 Years," by Christopher Velden, Bruce Harper, Frank Wells, John L. Beven II, Ray Zehr, Timothy Olander, Max Mayfield, Charles "Chip" Guard, Mark Lander, Roger Edson, Lixion Avila, Andrew Burton, Mike Turk, Akihiro Kikuchi, Adam Christian, Philippe Caroff, and Paul McCrone (*Bull. Amer. Meteor. Soc.*, **87,** 1195–1210) • ©2006 American Meteorological Society • Corresponding author: Christopher Velden, UW-CIMSS, 1225 W. Dayton St., Madison, WI 53706. • E-mail: chrisv@ssec.wisc.edu • DOI: 10.1175/BAMS-87-9-Velden

The success of the Dvorak technique has been enhanced by numerous local modifications in the last quarter-century. We will now describe many of these modifications from around the world.

Each of the three Australian Tropical Cyclone Warning Centers (TCWC) uses a different wind–pressure relationship. While they recognize there is little scientific justification for this, the absence of aircraft reconnaissance data has made it difficult to resolve the differences. The Perth and Darwin TCWCs also use the pressure–wind relationships in their Δp form. The changes in ambient pressure from one tropical cyclone (TC) to the next, and the changes that occur as a TC moves into higher latitudes are seen as small but significant sources of variance that can be explicitly accounted for by this simple modification.

A number of Australian TC forecasters have come to the conclusion that the Embedded Center (EMBC) scene type temperature ranges generally give higher-than-warranted data tropical numbers (Tnums). In the absence of reconnaissance data this perception has arisen from noting discontinuities in Tnums as the scene type changes, and the lack of agreement between the Tnum derived from EMBC cloud temperature measurements and that obtained by applying the Dvorak development/decay model. Given that the Dvorak technique is otherwise noted for its internal consistency, this has lead forecasters to speculate on possible reasons for the poorer performance of the EMBC scene type in the Southern Hemisphere. Two factors relating to tropopause temperatures have been identified. Tropical cyclones tend to occur at lower latitudes (higher tropopause) in the Southern Hemisphere, leading to colder cloud-top temperatures. Additionally, the Southern Hemisphere Tropics have colder warm season tropopause temperatures than the Northern Hemisphere Tropics, particularly in the Australian region (Kossin and Velden 2004). In response to this, Australian forecasters are prepared to weight the final estimate toward the model-expected T number (MET) when using the EMBC pattern (Burton 2005).

At the Japanese Meteorological Agency (JMA) Regional Specialized Meteorological Center (RSMC) in Tokyo, the original Dvorak (1982, 1984) relationships were employed until 1990. Koba et al. (1990) then used WestPac reconnaissance data (1981–86) to account for regional use of a 10-min-averaged wind, and also amended the actual shape of the Dvorak (1984) relationship. This modified relationship is used at JMA today.

JMA has also introduced a modification for TCs making landfall (while there is no formal reference by Dvorak in regards to applying his technique on landfalling TCs, many tropical centers do not employ it once a TC intersects a major landmass). Under normal conditions, the Dvorak (1984) Step 9 holds the CI constant for 12 hours during the weakening stages (Fig. S1a). However at landfall, the actual TC intensity tends to decrease with the Tnum without a time lag, something Dvorak did not consider. Koba et al. (1989) analyzed the intensity trends of 13 TCs that made landfall in the Philippines and developed additional rules to suit the observed conditions as follows:

1) If the Tnum is steady or increasing at landfall, but decreases immediately after landfall, the 12-h time-lag rule to determine the CI number is not applied, and the CI number is assumed to equal the Tnum (Fig. S1b).
2) If the Tnum is decreasing prior to landfall, and continues that way after landfall, then the CI number is decreased by the same amount as the Tnum (Fig. S1c).
3) Maintain the above relationships even if the TC reemerges over the sea until signs of redevelopment become apparent.

The satellite analysts at the JTWC utilize Dvorak's methods extensively to fulfill global TC reconnaissance requirements. Over the years, analysts have gained familiarity in ascribing Dvorak intensities to tropical systems throughout numerous basins and varying meteorological conditions. Satellite position and intensity fixes are produced at JTWC for five different geographical basins: north-central Pacific, northwest Pacific, South Pacific, North Indian Ocean, and the South Indian Ocean. The JTWC satellite analysts slightly vary the Dvorak technique application to each basin.

In 1990, the JTWC was tasked with issuing warnings on 25-kt tropical depressions. Since the lowest Dvorak Tnum represents 25 kt, analysts had no specific index to estimate the strength of weak, organizing systems. Thus, JTWC implemented the use of the T0.0, which signifies less than 25 kt. In a similar manner, the Tropical Prediction Center (TPC) and the Satellite Analysis Branch (SAB) generally use the criteria "too weak to classify" for systems with an

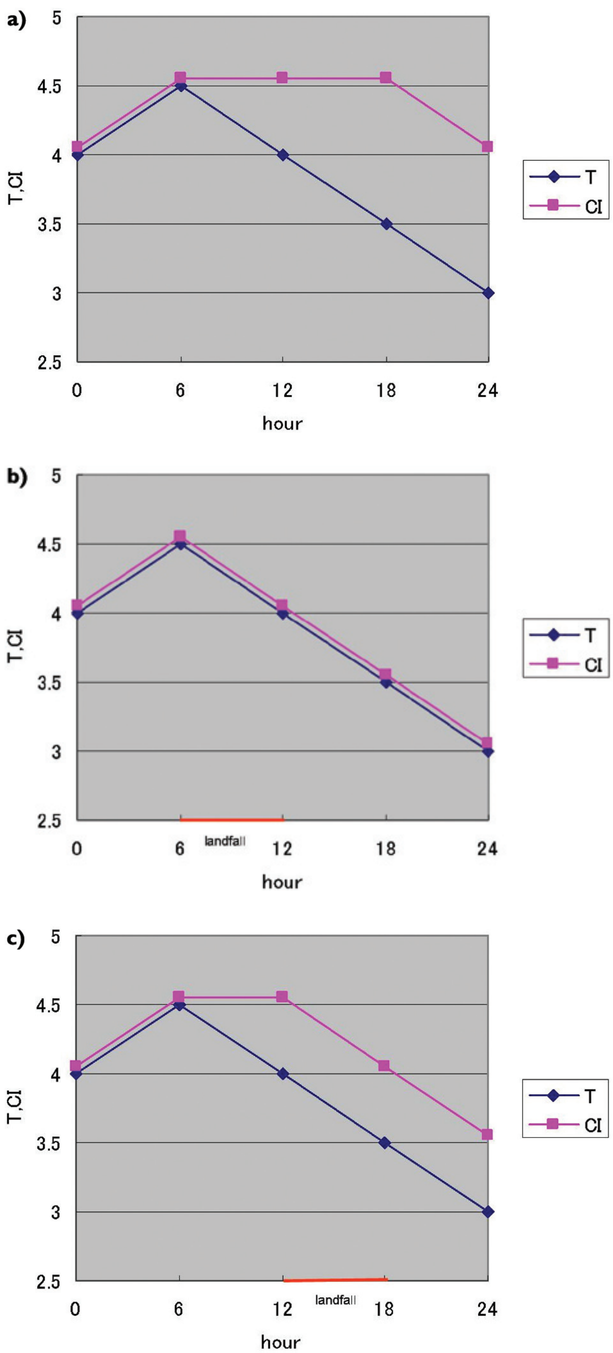

Fig. S1. (a) Normal Dvorak rule for holding the CI constant for 12 h following a weakening trend. (b) JMA-modified rule assuming landfall at any point on the red line. The CInum = Tnum. (c) JMA-modified rule assuming landfall at any point on the red line. Weakening preceded the landfall so the CInum is decreased at an equal rate to the Tnum.

identifiable center but insufficient convection for a Dvorak classification.

During extratropical transition phases, classification using the Dvorak method can yield unrepresentative intensity estimates. A JTWC rule of thumb is to compare the Dvorak technique intensity to the extratropical (XT) technique intensity as the TC transitions to a baroclinic low. At some point during the transition the two values will be the same, usually near T3.5, and from that point on the system is classified using the XT technique (Miller and Lander 1997).

Satellite analysts in the Tropical Analysis and Forecast Branch (TAFB) of the TPC in Miami have been using the Dvorak technique for over 30 years and continue to mostly adhere to the basic constraints originally developed by Dvorak in 1984 for both developing and weakening systems. Two of the more significant modifications to the original constraints are as follows: 1) A study by Lushine (1977) limits the rate of weakening of a system by holding the CI number up to the highest Tnum attained during the past 12 h but never more than 1 Tnum above the current Tnum. 2) A more recent study by Brown and Franklin (2002) suggests that this rule does not weaken systems fast enough. They suggest that this rule be applied for a period of only 6 h. This modification also allows the Tnum to change by up to 1.0 Tnum over 6 h, 1.5 Tnums over 12 h, 2.0 Tnums over 18 h, and up to 2.5 Tnums over 24 h. A follow-up study by Brown and Franklin (2004) further suggests that an intensity based on the average of the Tnum and CI also reduces the bias during weakening systems. These modifications are especially applicable to systems that weaken rapidly, such as are common in the east Pacific basin.

The SAB in Washington, D.C., has derived the position and intensity for tropical disturbances in all basins for over 30 years. The SAB employs the Brown and Franklin (2002) modifications in all basins on a case-by-case basis. Even with these adjustments there are still anomalous TC cases exhibited by intensity change at steep rates. In such cases, it is left to the discretion of the analyst as to whether the situation warrants breaking all constraints in an effort to arrive at the current intensity. It is important to note, however, that the use of these local rules may at times be the result of a previous erroneous estimate. For example, if the estimated intensity 6 h previous to the current analysis was held the same when it should have been increased (only confirmed after postanalysis), the next analyst may need to employ local rules (or break all constraints) to accurately assess the current intensity.

At the U.S. Air Force Weather Agency (AFWA) in Omaha, Nebraska, the primary concern in the Meteorological Satellite (METSAT) Applications Branch is the use of the Dvorak (1984) constraint system to modify TC intensity estimates (a rather consistent theme among global tropical analysis centers). During cases with a clear sign of rapid intensity change, AFWA analysts often temporarily suspend the implementation of the Dvorak (1984) constraints. The constraints appear to be particularly problematic when a TC intensifies from the T2.5 (weak storm stage) to T4.0 (initial hurricane intensity). As with other TC analysis centers, rapidly weakening systems also present a significant challenge to AFWA analysts.

After initial trials from 1977 to 1979, the Dvorak technique was officially adopted at the RSMC-La Reunion in 1981. The wind–pressure relationship associated with the Dvorak intensity estimates chosen for the southwestern Indian Ocean (SWIO) basin was the one originally designed for the WestPac. However, as the 10-min-averaged wind was adopted at La Reunion, a conversion factor of 0.8 was applied to the original MSW scale, while a gust factor of 1.5 was applied to the MSW to estimate peak gusts. These conversion factors were later reconsidered based on a small sample of observed SWIO TC winds by synoptic reports at or near landfall. Starting with the 1999–2000 TC season in the SWIO, these conversion factors were modified to 0.88 (this conversion factor is now more or less being used by all agencies in the Southern Hemisphere) and 1.41, respectively. These latest modifications lead to a ~10% increase in the average MSW. This issue of wind-averaging periods and related conversion factors is still a question in the SIO region, and an important matter directly connected to the regional use of the Dvorak technique. As for MSLP, La Reunion analysts recently began to take into account the size of the TC and adjust the Dvorak-estimated MSLP, raising it for small systems, similar to the Australian approach.

Procedures at La Reunion also include a modification for small systems at strong intensity: the inertia lag time of 12 h before lowering the winds may be reduced to 6 h. Also, during weakening phases associated with extratropical transitioning TCs, it has also been recognized that Dvorak estimates are not appropriate.

The regional applications and modifications to the basic Dvorak methods are perhaps a precursor to an evolutionary transition of satellite-based TC analyses from a single technique to a multispectral approach. Observations from passive microwave sensors often reveal more accurate positions than just visual or infrared imagery alone. At AFWA, for example, the approach has been to take advantage of this multispectral information and incorporate it into the Dvorak intensity estimation process. Experience has shown that if an eye feature is seen in microwave, the pattern Tnum can be selected to reflect that occurrence, in lieu of the data Tnum, to indicate a greater intensity. On a broader scale, it must be noted that while Dvorak intensity estimates remain an important input to archived best-track analyses, other satellite-based sources are having an increasing influence. The optimal fusion of all-available and emerging satellite observations as a direction for TC analysis and intensity estimation is discussed further in the section on looking ahead.

REFERENCES

Burton, A. D., 2005: Notes on the application of the Dvorak technique. Meteorological Note 225, Bureau of Meteorology, National Meteorological Library, 8 pp.

Koba, H., S. Osano, T. Hagiwara, S. Akashi, and T. Kikuchi, 1989: Determination of intensity of typhoons passing through the Philippine Islands (in Japanese). *J. Meteor. Res.,* **41,** 157–162.

——, T. Hagiwara, S. Osano, and S. Akashi, 1990: Relationship between the CI-number and central pressure and maximum wind speed in typhoons (in Japanese). *J. Meteor. Res.,* **42,** 59–67.

Lushine, J., 1977: A relationship between weakening of TC cloud patterns and lessening of wind speed. NOAA Tech. Memo NESS 85, 12 pp.