THE DVORAK TROPICAL CYCLONE INTENSITY ESTIMATION TECHNIQUE

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

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> **This insight, which expresses itself by what is called Imagination, is a very high sort of seeing, which does not come by study, but by the intellect being where and what it sees, by sharing the path, or circuit of things through forms, and so making them translucid to others.**
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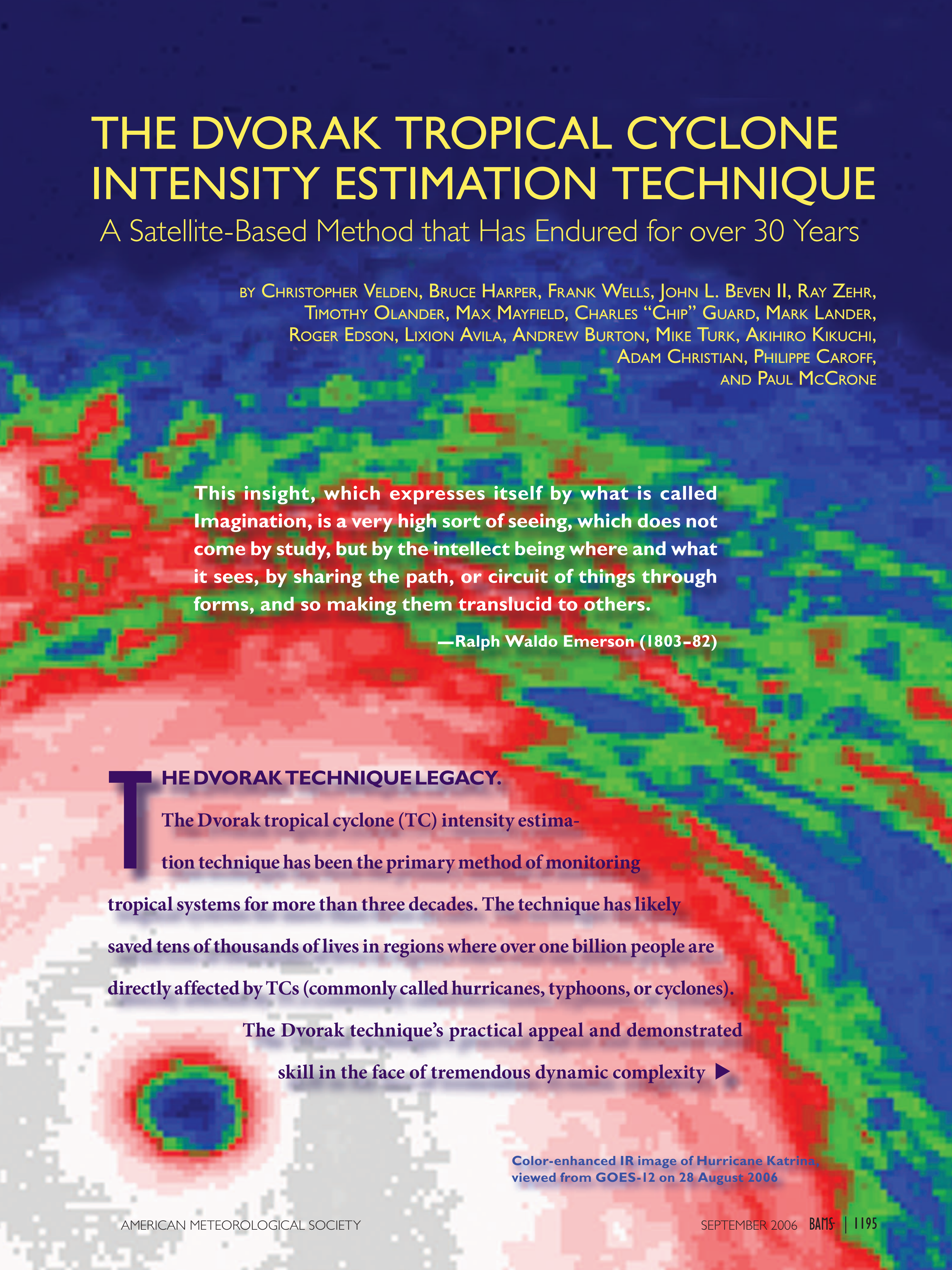
> **—Ralph Waldo Emerson (1803–82)**

THE DVORAK TECHNIQUE LEGACY. The Dvorak tropical cyclone (TC) intensity estimation technique has been the primary method of monitoring tropical systems for more than three decades. The technique has likely saved tens of thousands of lives in regions where over one billion people are directly affected by TCs (commonly called hurricanes, typhoons, or cyclones).

The Dvorak technique's practical appeal and demonstrated skill in the face of tremendous dynamic complexity ▶



Color-enhanced IR image of Hurricane Katrina, viewed from GOES-12 on 28 August 2006 place it among the great meteorological innovations of our time. It is difficult to think of any other meteorological technique that has withstood the test of time and had the same life-saving impact.

The Dvorak technique has been more than a critical analysis and forecasting tool. It has become the most important input to our highly valuable present-day TC archives. Historical TC best-track (post processed for archives) datasets are the cornerstone for the estimation of risks from TCs in regions without routine aircraft reconnaissance, with applications in engineering, climate change assessments, insurance, and other fields. The future evolution of the Dvorak and similar satellite-based TC intensity estimation methods is of vital interest to the meteorological and coastal communities, and the continued improvement should be a top research priority in the atmospheric sciences.

Vernon Dvorak (circa: late 1970s).

We examine the development of the Dvorak technique, review its basic assumptions, and relate them to the technique's success. We also identify some limitations and common misapplications of the technique, and briefly discuss selected regional modifications and enhancements.

Laying the foundation. By the late 1960s, polar orbiting satellites with visible and limited IR capabilities were providing TC forecasters with coarse-resolution imagery several times a day. At this time there were no enhancement or animation capabilities. Early work by Fett (1966), Fritz et al. (1966), and Hubert and Timchalk (1969) was generally unsuccessful in inferring TC intensity from this type of imagery. The National Oceanic and Atmospheric Administration (NOAA), National Hurricane Center (NHC; in Miami, Florida), and the Joint Typhoon Warning Center (JTWC; until recently located on Guam) were primarily using satellite imagery for TC positioning and directing weather reconnaissance aircraft to developing convective areas. No reliable intensity estimation techniques existed.

As the number of satellites increased and their capabilities improved (Table 1), it became clear that the science of deploying remote sensing in space was outpacing the ability of meteorologists to apply it. From his Washington, D.C., office in the Synoptic Analysis Branch of the Environmental Science Services Administration (the precursor to NOAA), scientist Vernon Dvorak developed his cloud pattern recognition technique based on a revolutionary conceptual model of TC development and decay. Dvorak and his colleagues derived an empirical method relating TC cloud structures to storm intensity using a simple numerical index [the current intensity (CI)], corresponding to an estimate of the maximum sustained (surface) wind (MSW), as shown in Table 2. The earliest internal NOAA reference to this work is Dvorak (1972), followed by an update (Dvorak 1973). Dvorak worked in an operational environment, and

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both of these technical memorandums focused on providing forecasters with a straightforward and logical methodology immediately suited for operational use—a strength that remains to this day.

The basics behind the method. The brilliance of the Dvorak technique lies in its elegant mix of absolute accuracy (50% of the MSW estimates are within 5 kt of reconnaissance aircraft measurement-aided best-track estimates; Brown and Franklin 2004) and internal consistency. The technique relies on four distinct geophysical properties that relate organized cloud patterns to TC intensity. Two are kinematic, vorticity and vertical wind shear, and two are thermodynamic, convection and core temperature. The strength and distribution of the circular winds (and by implication, vorticity) in a TC organizes the clouds into patterns that Dvorak relates to the MSW. External (environmental) shear is a kinematic force that acts to distort the vorticity (and hence, the cloud pattern). Dvorak found that the degree of distortion was also related to the MSW. Convection in the bands of the outer core of the cyclone also figures in the cloud pattern recognition and scene type assignment. Using satellite-measured IR cloud-top temperatures in the TC inner core, the technique relates convective vigor to intensity. In cases of TCs with eyes, the technique determines the temperatures of the eye and surrounding clouds (eyewall) using IR data and relates them to intensity, with warmer/cooler eye/cloud temperatures indicating greater intensities. Visible imagery can also be very useful in these cases.

TABLE 1. Chronology of early satellite milestones and TC intensity papers (1957–84)

Papers[a]	Year	Satellite	Comments
	1957	*Sputnik* (USSR)	1st man-made Earth satellite
	1958	*Vanguard II*	1st U.S. satellite
	1959	*Explorer*	1st used for weather obs
	1960	*TIROS I*	1st successful metsat ([b])
	1964	*NIMBUS I*	Daily day/night imagery
	1965	*TIROS IX*	1st global view of clouds
F + FHT	1966	*ESSA-1*	Last use of TV (APT) ([c])
	1966	*ATS-1*	1st use of WEFAX ([d])
	1970	DAPP	Use of nighttime visible ([e])
HT	1969		
	1970	*ITOS*-1	Use of scanning radiometers
	1971	DMSP	High-resolution VIS/IR ([f])
Dvorak (TM NESS 36)	1972		
Dvorak (TM NESS 45)	1973		
	1974	*SMS-1*	1st NOAA geostationary
Dvorak (MWR, 103), HP	1975		
	1977	METEOSAT + GMS	Geostationary satellites ([g])
	1978	*TIROS-N*	1st polar orbiter with AVHRR
Dvorak (NESS Training)	1982		
Dvorak (TR NESDIS 11)	1984		

[a] F = Fett (1966), FHT = Fritz et al. (1966), HT = Hubert and Timchalk (1969), and HP = Hebert and Poteat (1975)

[b] Meteorological satellite with TV (APT) visual and low-resolution infrared

[c] Developed by NASA, managed by ESSA

[d] NASA geostationary satellite

[e] DOD weather satellite with nighttime low-light visible imagery

[f] DOD follow-on to DAPP. Started using OLS in 1976

[g] METEOSAT (European Space Agency) and GMS (Japan)

TABLE 2. Summary of the Dvorak (1984) Atlantic and WestPac wind–pressure relationships.

CI	MSW (kt)	Atlantic MSLP (hPa)	WestPac MSLP (hPa)
1.0	25		
1.5	25		
2.0	30	1009	1000
2.5	35	1005	997
3.0	45	1000	991
3.5	55	994	984
4.0	65	987	976
4.5	77	979	966
5.0	90	970	954
5.5	102	960	941
6.0	115	948	927
6.5	127	935	914
7.0	140	921	898
7.5	155	906	879
8.0	170	890	858

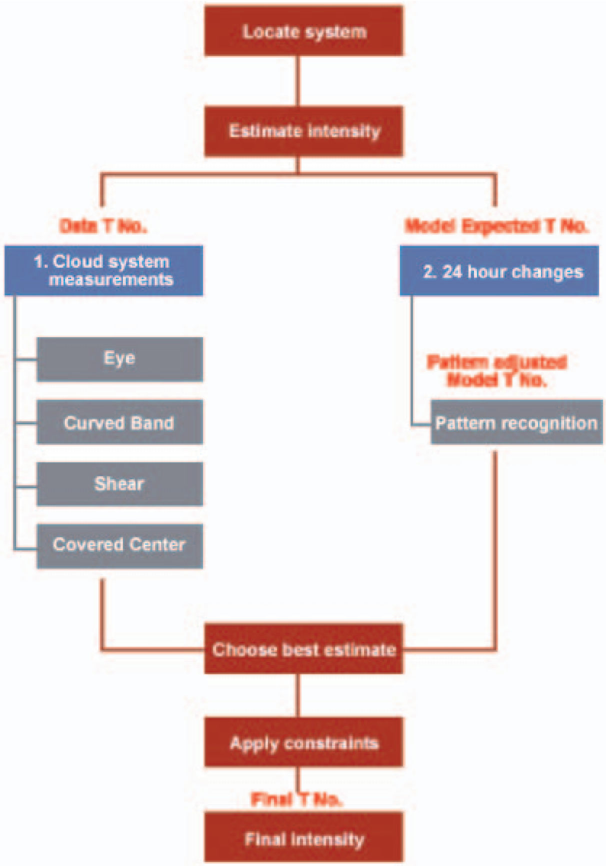


FIG. 1. The basic steps in the Dvorak technique.

The basic steps in the Dvorak technique can be summarized as follows (Fig. 1):

1) Determine the TC center location.
2) Make two quasi-independent estimates of the intensity of the TC.
3) Choose the best intensity estimate.
4) Apply selected rules to determine the final estimate of intensity.

Following Fig. 1, the Dvorak technique analyst first assigns T-numbers "tropical" ("T") numbers (hereafter Tnum) and relates these to storm intensity (Dvorak 1975, 1984). One Tnum unit represents a typical one-day intensity change based on climatological data (see Fig. 2 for examples related to cloud patterns). Figure 3 illustrates where the primary patterns are typically assigned in relation to Tnum and TC intensity ranges. While the Tnum is generally a good first guess at the TC intensity, Dvorak observed that convection in some weakening TCs degenerates faster than the corresponding MSW. Thus, the Tnum does not always relate directly to TC intensity. Instead the Tnum is converted into the CI number. For developing or steady-state storms, the Tnum and CI are usually identical or close. A standard table is used to convert CI to MSW, and a wind–pressure relationship is then used to assign the corresponding estimated minimum sea level pressure (MSLP; Table 2). Very weak, pregenesis tropical disturbances are assigned T1.0 (Tnum = 1.0). Minimal tropical storm intensity (MSW of 35 kt) is T2.5. Minimal hurricane intensity (65 kt) is T4.0, T5.0 = 90 kt, T6.0 = 115 kt, and T7.0 = 140 kt. The rare T8.0 = 170 kt is the top of the scale.

The Tnum and CI approach helps alleviate the problem of unreasonable intensity assignments due to poor-quality images or unrepresentative image analysis. The Tnum also is an effective tool for normalizing intensity change according to the current intensity of a storm. For example, a 5-kt increase of maximum wind speed from 30 to 35 kt is an equivalent change in terms of Tnum to a 15-kt increase from 140 to 155 kt. This normalization helps improve the evaluation of environmental forcing on intensity change.

The evolution of the technique. The Dvorak technique evolved significantly during the 1970s and 1980s, and has continued to be modified by regional centers since then. Originally the technique was largely reliant on pattern-matching concepts and the application of Dvorak's development/decay model. Later revisions (Dvorak 1982, 1984) shifted the emphasis toward measurement of cloud features.

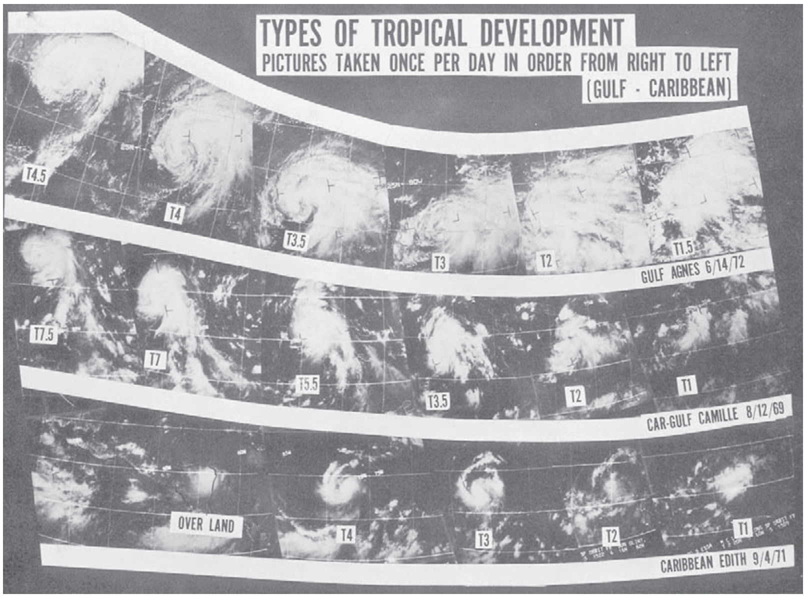


Fig. 2. Examples of characteristic cloud patterns of developing TCs (from Dvorak 1973).

By basing the technique on observed 24-h changes in cloud pattern and intensity, Dvorak (1975) addressed the problem of short-term changes in cloud structure (i.e., diurnal cycles) that might be unrepresentative of true intensity change. Images 24 h apart are used to determine if the TC has developed, weakened, or retained intensity. The observed trend in cloud features is then applied to the Dvorak model of development and decay to obtain an estimate of intensity. In Dvorak (1984) this was more rigorously quantified into the mode-expected T number (MET). Although the development/decay model remains integral to the Dvorak technique, the significant revisions of 1982 and 1984 shifted the emphasis of the technique toward direct measurement of cloud features. Dvorak (1984) states, "when the measurement (of cloud features) is clear-cut giving an intensity estimate that falls within prescribed limits, it is used as the final intensity." If this measurement is not clear-cut, the analyst then relies on the development/decay model in conjunction with pattern matching.

Several innovations allowed the shift toward greater reliance on cloud feature measurement. First, the introduction of cloud pattern types such as the curved band (CB) and shear patterns allowed analysis of TCs without an eye or central dense overcast (CDO). The CB pattern has become the most widely used pattern type for TCs below hurricane strength. Second, IR imagery was applied for the first time. This brought about yet another pattern type—the embedded center (EMBC), or the IR equivalent to the CDO. Third, this revision created the enhanced IR (EIR) eye pattern, in which TC intensity is related to the cold cloud-top IR temperatures surrounding the center and the warm IR temperatures in the eye. This is the most objective of all Dvorak measurements and has led to attempts to automate the intensity analyses (Zehr 1989; Velden et al. 1998).

All versions of the Dvorak technique have featured a system of rules, or constraints. Many of these rules/constraints have changed somewhat unsystematically between versions. Others have evolved based on verification studies and practical application. For example, the original technique had no set criteria for when a tropical disturbance should be classifiable. Criteria were subsequently introduced in Dvorak (1975) and more rigorously quantified in Dvorak (1984).

Perhaps most controversial are the constraints on allowable intensity change over specific periods of 24 h or less. The technique has always had such limits. However, Dvorak (1984) quantified maximum allowable 6-, 12-, 18-, and 24-h changes in Tnum, with the maximum allowable 24-h change of 2.5 Tnums. These constraints usually work well, but experience has shown that rapidly intensifying TCs can change Tnum by 3.0 or more in 24 h, and systems in strong shear or moving over colder sea surfaces can weaken

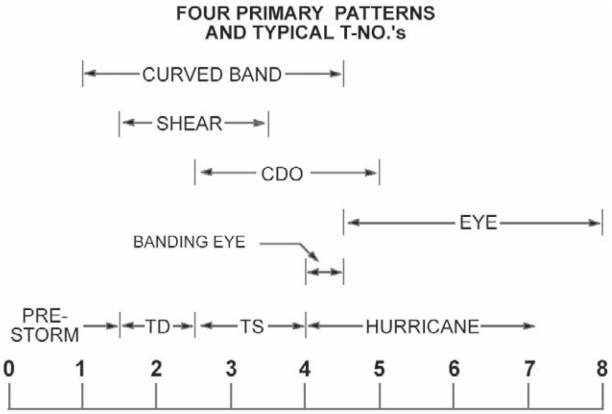


Fig. 3. Primary Dvorak cloud patterns in relation to Tnum and TC intensity ranges that they are typically assigned.

much faster than the constraints allow. In these cases, contemporary Dvorak analysts relax the constraints somewhat compared to Dvorak (1984), as discussed in a later section.

Defining the pressure/wind relationships, and validation. Dvorak (1973) states that the original relationships between the satellite-based CI and MSW "were determined empirically, with most of the data coming from the western North Pacific region. . . ". The only comment made about the link between the CI and TC radial wind structure was that the 40-kt wind had been found to normally enclose the outer limits of the TC central dense overcast or the quasi-circular bands. The 30-kt wind is similarly noted as normally enclosing the outer vortex "feeder bands." The averaging period of the MSW is also never explicitly stated, but has been historically interpreted as a 1-min-sustained wind. The later and more widely available work, Dvorak (1975), notes that parallel work by Erickson (1972) had been influential in suggesting modifications to the relationships that eventually formed the quantitative backbone of the method.

The Erickson (1972) study provides useful insight into the development of the basic Dvorak technique, but also supplies the first published set of verification statistics whereby 11 forecasters made independent estimates of CI for 33 tropical storms and disturbances in the Atlantic and Pacific. The study concludes that the technique was much better for estimating change in TC intensity than for estimating absolute intensity. It was also found that the basic classification system was moderately consistent between different analysts, although the greatest differences were found in the midintensity range. Overall, Erickson concluded that the mean absolute error in estimating MSW from CI was in the range of 11–16 kt.

In summary, Erickson (1972) provides some important details behind the early development of the Dvorak technique:

- The original technique was based entirely on western Pacific Ocean (WestPac) data.
- MSW was initially the only parameter of forecast interest.
- The early technique tended to underestimate winds for small but intense storms.
- The relation between CI and MSW was found, on average, to be reasonably reliable.
- The CI actually correlated better with minimal sea level pressure (MSLP) than MSW; but in the experiment, direct estimation of MSW from CI achieved slightly greater accuracy.
- Estimating the MSW had a greater degree of error in midrange (50–100 kt) TC intensities than in weaker or stronger storms.
- Different relationships for estimating MSW versus MSLP were warranted for the WestPac and Atlantic basins.

Dvorak (1975) notes that the Erickson experiment prompted changes in the original MSW–CI relationship, as chronicled in Fig. 4. In presenting the first wind–pressure relationship associated with the method, Erickson appears to advocate estimating pressure over wind. This is supported by the fact that, although significant differences were found between the WestPac and Atlantic MSW values, Dvorak's own best fit of CI versus MSLP (Fig. 5) from the 1973 study shows two closely parallel relationships with much less scatter than the MSW curves. Strangely, the possibility of different ambient (environmental) pressures between the two basins was not raised at this time, but if the relationships are plotted in Δp space they appear very similar. This was undoubtedly apparent to Dvorak when he published the 1973 wind–pressure tabulations, where the indicated difference in MSLP between the two basins for a given MSW is simply an offset of 6 hPa, with the WestPac pressures being lower. Because the MSW–CI relationships were altered, Fig. 5 shows that the resulting wind–pressure curves became a little less similar.

Sheets and Grieman (1975), the second major verification study, referenced Dvorak (1973), and used

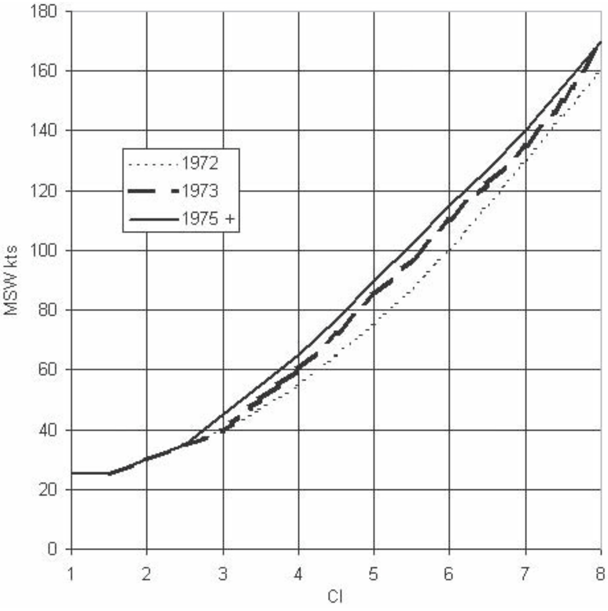


Fig. 4. The evolution of the early Dvorak MSW–CI relationships.

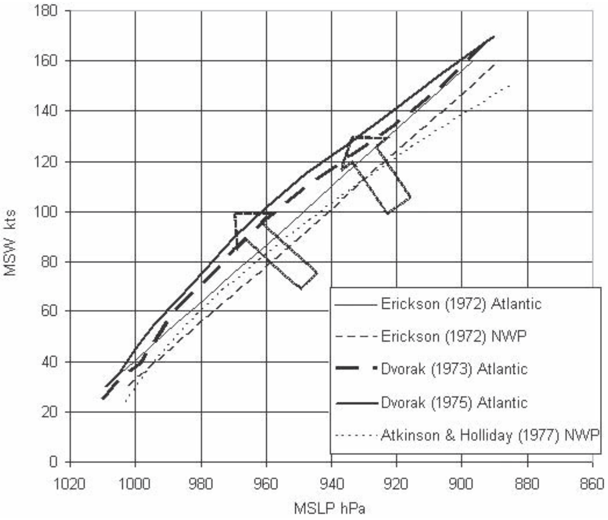


Fig. 5. The evolution of the adopted wind–pressure relationships (from Harper 2002). Arrows indicate trend over time.

data from polar-orbiting satellites. Both WestPac and Atlantic datasets were considered, with the WestPac again being the larger set. Like Erickson, Sheets and Grieman strongly preferred the use of MSLP rather than MSW as a measure of storm intensity because of the variability in wind speed measurement techniques used for validation (e.g., sea state, radar, and inertial systems), differences in experience and application between aircraft crews, and also the inherent variability in MSW measurements due to convective-scale influences. Accordingly, only central pressures were considered in the analyses with the following conclusions about the Dvorak (1973) CI–MSLP relationship:

- In the Atlantic, there was a clear tendency (bias) to overestimate the intensity by 5–10 hPa.
- In the WestPac, strong storms (< 920 hPa) underestimated by as much as 20 hPa, but the overall result was very close to the assumed curve (no bias).

The next significant contribution was a separate wind–pressure relationship for the WestPac based on Atkinson and Holliday (1975, 1977), whose 28-yr dataset was then considered the most significant climatological review of WestPac TC intensity. The decision to adopt the Atkinson and Holliday (AH) wind–pressure curve for operational application in the WestPac was apparently based on revised Dvorak technique validation studies by Lubeck and Shewchuk (1980) and Shewchuk and Weir (1980). They used 396 cases during 1978–79, covering the full range of intensities. The reference best-track dataset included subjective sources such as the AH relationship (which, because it was used operationally by the JTWC to derive surface winds since 1974, influenced best-track data). The reports conclude that the mean absolute intensity error was less than one CI number and that the developing TC stages were more accurately estimated than the weakening stages.

The final recommendation of Shewchuk and Weir (1980) was to replace the Dvorak (1975) wind–pressure relationship by AH for the WestPac (Fig. 5). This occurred in 1982 (Dvorak 1982, 1984). The original relationship was retained for the Atlantic. The final relationships are presented in Table 2. Significantly, no further changes were made to the Dvorak (1975) MSW–CI relationship, although Dvorak (1984) for the first time notes rather candidly that the archive tracks themselves may now have become biased by the application of the technique itself, especially in the WestPac.

The importance of defining and validating the wind–pressure relationships is exemplified by the operational impact of the Dvorak intensity estimates on the JTWC warnings in the WestPac during the 1970s and 1980s (Fig. 6; Guard et al. 1992). Over a 16-yr period from 1972 to 1987, dedicated aircraft reconnaissance gradually declined, and was roughly balanced by increased operational reliance on satellite reconnaissance, thanks to the Dvorak intensity estimates. During this time the aircraft reconnaissance was available to provide an invaluable measure of ground truth. The aircraft reconnaissance program, provided by the 54th Weather Reconnaissance Squadron based at Andersen AFB, Guam, was deactivated in the summer of 1987. This put added pressure on the robustness of the Dvorak technique in the

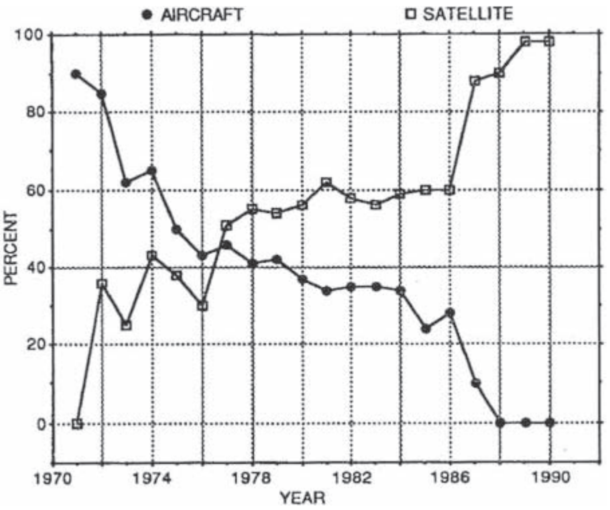


Fig. 6. Reconnaissance platforms used for JTWC warnings in the WestPac (from Guard et al. 1992).

WestPac. While the satellite technique development at JTWC helped offset the elimination of aerial reconnaissance and accelerate the exploitation of remotely sensed data, it should be emphasized that the satellite-derived estimates were (or are) not as accurate as aircraft in situ measurements. Atlantic basin reconnaissance information remains a vital and necessary component of the U.S. TC warning system.

Additional validation studies were carried out in the 1980s. In a first comparison, Gaby et al. (1980) found that the average difference between satellite-derived and aerial reconnaissance-based best-track maximum sustained wind speeds was approximately 7 kt. During the late 1980s, in response to the withdrawal of reconnaissance aircraft from the western North Pacific, Sheets and Mayfield studied the accuracy of geostationary satellite data, while Guard studied polar orbiting satellite data (both summarized in OFCM 1988). The authors evaluated internal consistency and absolute accuracy of the Dvorak technique, using independent analysts to provide the sample of estimates on past TCs. Their findings on the accuracy of the technique were similar to those of Gaby et al., and their internal consistency results showed that 85% of the independent common fixes were within 0.5 Tnum.

In summary, the basic principles of the Dvorak technique evolved during 15 yr of active experimentation (1969–84) and were empirically derived from several hundred WestPac and Atlantic basin TC cases. During this period, improved satellite imagery, proficiency in its use, and, to a lesser extent, greater aircraft accuracy in measuring TC winds (for empirical development) all contributed to enhancing the technique's effectiveness. Meanwhile, several significant verification studies contributed to refining the method.

Limitations of the Dvorak technique. The Dvorak technique does not directly measure wind, pressure, or any other quantity associated with TC intensity. It infers them from cloud patterns and features. This primary limitation leads to two basic sources of error. First, the technique is physically restricted due to natural variability between the remotely sensed cloud patterns and the observed wind speed. Second, the method is subject to analyst interpretation and/or misapplication (which has motivated the development of an objective version, that is addressed in a subsequent section).

Perhaps the most limiting factor is the reliance on IR images [when the visible (VIS) is not available] in which cirrus can obscure TC organization. Often the central dense overcast as presented in the IR will cover a weak eye and/or developing eyewall structure. This can lead to underestimates of the true TC intensity. The Dvorak embedded center scene type attempts to recognize this condition, but is difficult to apply and imprecise due to uncertainties in locating the exact center. Furthermore, concentric eyes and associated eyewall replacement cycles (Willoughby et al. 1982), which have been recently linked to intensity change, can also be obscured in the IR, and were not part of the original Dvorak model. The potential application of microwave imagery to addressing these issues is discussed in a later section.

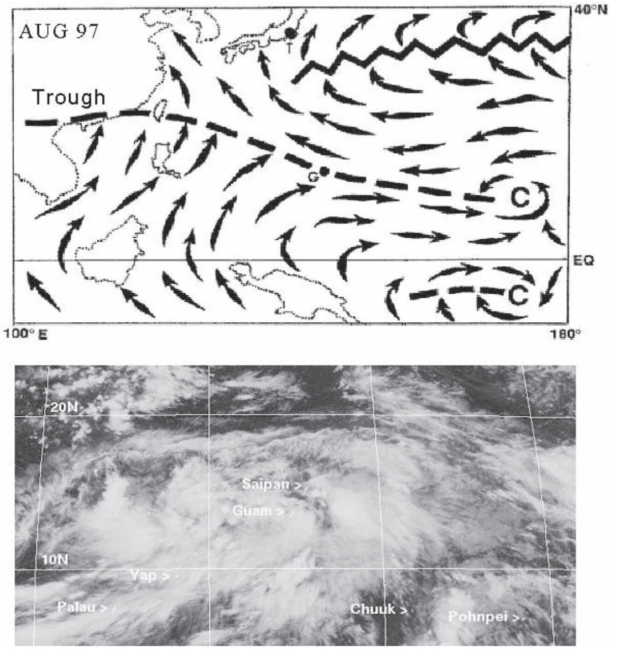


Fig. 7. (top) A schematic illustration of a commonly observed flow pattern: the low-level circulation in the monsoon trough during the northern summer in the WestPac. The "C" symbols indicate cyclonic gyres, and the "G" symbol shows a likely place for TC genesis within the trough. (bottom) Satellite IR image example from August 2001.

A common limitation in applying the technique using geostationary satellite imagery involves the scan angle, or the viewing angle from the satellite subpoint. At large scan angles, TCs with small eyes can be underestimated using the Dvorak EIR method because the eye and attending warm brightness temperature is partially or fully obscured by the eyewall. A good example was Atlantic Hurricane Hugo in 1989. The subjective Dvorak classification at 1800 UTC 15 September estimated MSW of 115 kt and a minimum pressure of 948 hPa (i.e., CI 6.0). Data from reconnaissance aircraft indicated 140 kt with a minimum pressure of 919 hPa (equivalent to CI 7.0). Experienced analysts reduce the confidence in Dvorak estimates on well-developed TCs at large scan angles from geostationary satellites. Alternatively, polar orbiter imagery with higher spatial resolution can be employed to better resolve small eyes.

For rapidly weakening TCs moving over strong sea surface temperature gradients to cool waters—commonly observed in the eastern North Pacific—convection rapidly dissipates. The Dvorak rules for holding the CI number constant for 12 h during weakening often lead to the method getting "behind the intensity curve." Proposed solutions to this occurrence are given in a following section.

Synoptic-scale features such as monsoon troughs (Fig. 7) and large cyclonic gyres (Fig. 8) can often complicate the Dvorak pattern recognition by breeding TCs within a larger envelope of disturbed weather. Many times these TCs are very small (often called midget TCs), so that the Dvorak steps and rules simply cannot be applied (or are misapplied). In addition, many WestPac TCs form from the monsoon depressions/gyres themselves. Because of the large size of monsoon depressions, and the initial lack of deep convection close to the center, analysts either avoid using Dvorak's techniques to classify these systems, or else assign them Tnums that are equal to wind speeds that are too low. As monsoon depressions acquire persistent central deep convection, they may already possess extensive areas of gales, and are often classified as tropical storm intensity in the initial advisory. In summary, the Dvorak method does not explicitly account for varying TC scales.

The Dvorak developmental sample included only "classic" TCs; however, TCs are part of a vortex continuum and often form from "hybrids" such as subtropical cyclones. Determining when a subtropical (baroclinic) cyclone becomes a (barotropic) TC is open to debate. Unlike a TC, a subtropical cyclone does not have persistent deep convection near the center. Hebert and Poteat (1975) recognized that the Dvorak technique would not work well on these systems, and developed a separate satellite classification technique for subtropical cyclones. This method remains operational today.

Similarly, in the transition to an extratropical system, TCs begin to lose their deep central convection, and the intensity estimates using Dvorak's techniques often fail. In an attempt to overcome this problem, Miller and Lander (1997) developed an extratropical (XT) technique that utilized satellite imagery to specifically derive the intensity of TCs undergoing extratropical transition.

Finally, the Dvorak technique does not explicitly account for the motion of the TC when estimating the maximum winds. A mean TC motion (based on Dvorak's sample) is implicit in the technique; however, nearly stationary or very fast moving storms (>15 kt) will inherit small biases in the estimated maximum winds.

Regional modifications. As experience and confidence in the Dvorak method increased in the 1980s and 1990s, and the limitations became more apparent, local forecast centers considered adding regional adjustments to ameliorate some of the deficiencies. It should be noted that some of these applications are simply rules of thumb, and are not rigorously proven

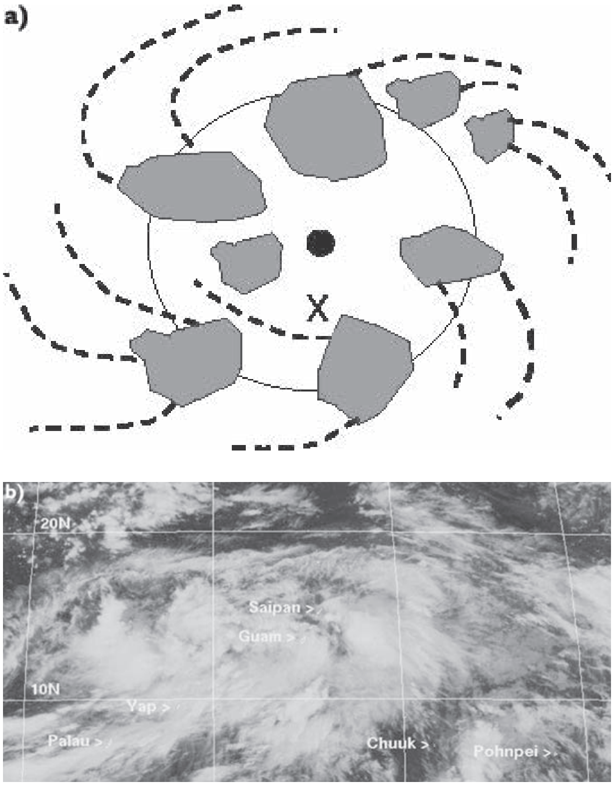


Fig. 8. (a) A schematic illustration of a typical monsoon depression in the WestPac. Several mesoscale convective systems (gray) are distributed in a large area (the circle diameter is 1200 n mi). Cirrus outflow from the deep convection forms a well-defined anticyclonic pattern. The center of a symmetry of the cirrus outflow (black dot) is often displaced to the north of the low-level circulation center (X). Operationally, this is often evident only after the first morning visual satellite image reveals that the actual low-level center is some 60–80 n mi southeast of the center position that resulted from nighttime IR image analysis. (b) Example of a typical monsoon depression in IR satellite imagery.

or published results. A brief summary of some of the local modifications applied to the basic Dvorak technique by regional TC analysis centers can be found online (http://dx.doi.org/10.1175/BAMS-87-9-Velden).

The period of automation. Dvorak (1984) describes an initial attempt to create an objective approach to his method. The intensity (Tnum defined to the nearest 0.1) for an eye pattern is assigned according to two IR temperature measurements, with an approach analogous to the EIR technique. The only measurements needed are the warmest IR pixel within the eye and the warmest IR pixels on a prescribed TC-centric ring (55-km radius in the original method). The warmer the eye and the colder the surrounding eyewall temperature, the more intense the TC estimate will be. The typical ranges of the two temperatures and their sensitivity to the intensity estimate are quite different. For example, as the surrounding temperature decreases from −64° to −75°C, the intensity increases 1.0 Tnum, while an eye temperature increase from −45° to +15°C is needed for a 1.0-Tnum increase.

Several modifications to this method have improved the intensity estimation results (Zehr 1989; Dvorak 1995):

1) The 55-km-radius ring can be well inside the coldest IR ring (eyewall convection) of TCs with large eyes. The method was modified to compute an average IR temperature for a range of ring sizes (R = ~25–125 km) and uses the coldest.
2) In many situations, estimates fluctuate widely over a relatively short time, primarily due to localized or semidiurnal convective flareups. Averaging the computations (over 3–12 h) can produce more realistic intensity trends.
3) The original Dvorak (1984) digital IR table was amended to cover anomalous "cold" eyes; cases with no warmer "eye" pixels in the TC central overcast. In these events, the eye temperature is set equal to, or can even be colder than, the surrounding central overcast ring temperature.

Evaluation of the original Dvorak digital method showed that it did not perform as well prior to IR eye formation. In the late 1980s, Zehr (1989) developed an objective technique using enhanced IR satellite data. This digital Dvorak (DD) method laid the foundation for the more advanced algorithms of today.

The primary motivation for developing an automated, objective intensity estimation scheme was to lessen subjectively introduced estimate variability due to analyst judgment from Dvorak (1984). The most prominent subjectivity involves cloud pattern (scene) typing. In the 1990s, additional incentive for automation was the increased availability of higher-resolution, real-time global digital satellite data, and improved computer processing resources capable of furnishing sufficient analysis capabilities. This led to the development of the objective Dvorak technique (ODT; Velden et al. 1998), which began with a careful assessment of the DD algorithm. It was found that the DD performance was satisfactory only for well-organized TCs of minimum hurricane/typhoon or greater intensity. Reasonably accurate intensity estimates were possible when the storm possessed an eye structure. Eventually, through a procedure involving a Fourier transform analysis of the center and surrounding cloud-top regions in the IR imagery, the ODT incorporated the four primary Dvorak scene types: eye, central dense overcast, embedded center, and shear. By using these four scene-type designations, a proper branch in the basic Dvorak logic tree could be followed to more accurately, and objectively estimate TC intensity.

Eventually, a history file containing previous intensity estimates and analysis parameters was implemented for subsequent image interrogations by the ODT algorithm. A time-averaged Tnum replaced the traditional Tnum, removing much of the fictitious short-term intensity variability. In addition, specific Dvorak (1984) rules, such as the rule controlling the weakening rate of a TC after maximum intensity, were implemented to more closely follow the governing principles.

Statistically, the ODT was shown to be competitive with TC intensity estimate accuracies obtained with the subjective technique at operational forecast centers such as the Satellite Analysis Branch (SAB), the Tropical Analysis and Forecast Branch (TAFB), and the U.S. Air Force Weather Agency (AFWA; Velden et al. 1998). These statistics were only valid for Atlantic basin TCs where aircraft reconnaissance MSLP measurements were available. The ODT was tuned for WestPac TCs using cases in the 1980s when aircraft validation was available. With selected threshold adjustments, the method performs reasonably well.

The original goal of the ODT was to achieve the accuracy of the subjective Dvorak (1984) EIR method using computer-based, objective methodology. This goal was accomplished, however, with important limitations. The ODT could only be applied to storms at or greater than minimal hurricane/typhoon strength (storms meeting EIR criteria). Also, the ODT still required manual selection of the storm center.

Thus, development continued and an advanced objective Dvorak technique (AODT; Olander et al. 2004) emerged.

The Dvorak (1984) curved band analysis is the primary tool for prehurricane/typhoon intensity TCs. The CB relates TC intensity to the amount of curved cloud banding surrounding the storm center. This amount is measured using a 10°log spiral (manually rotated). Defining the cloud field region over which the spiral is placed is quite subjective, but after discussions with numerous TC forecasters, and considerable trial and error, initial skepticism was overcome and an objective scheme was incorporated into the AODT.

The final remaining subjective element was the manual determination/positioning of the TC center location. This proved to be the most challenging aspect of the AODT transition. A method was developed to utilize a short-term track forecast (provided by NHC or JTWC) as a first guess for the storm center location. Then objective center-determination schemes search for curvature patterns and strong, localized gradients in the image brightness temperature (BT) field surrounding the interpolated forecast position (Wimmers and Velden 2004). Such BT gradient fields are typically associated with TC eyes, but can also be applied to EMBC and some CB scene types. If the objective center-estimation scheme locates a region that exceeds empirically determined thresholds, the region's center is used as the AODT storm center location. On average, the AODT intensity estimates produced using the automated center location routine are only slightly worse than those obtained using manual storm center placements (Olander et al. 2004; Olander and Velden 2006).

Additional Dvorak (1984) rules were incorporated into the AODT, including the constraint on TC intensity estimate growth/decay rate over set time periods. This modification reduced the averaging period for the AODT intensity calculation from 12 to 6 h. Another recent addition followed the discovery by Kossin and Velden (2004) of a latitude-dependent bias in the Dvorak estimates of MSLP. This bias is related to the slope of the tropopause (and corresponding cloud-top temperatures) with latitude. With the introduction of a bias adjustment into the AODT, the MSLP estimate errors were reduced (Olander et al. 2004). Interestingly, Kossin and Velden (2004) found that no such latitude-dependent bias exists in the Dvorak-estimated MSW.

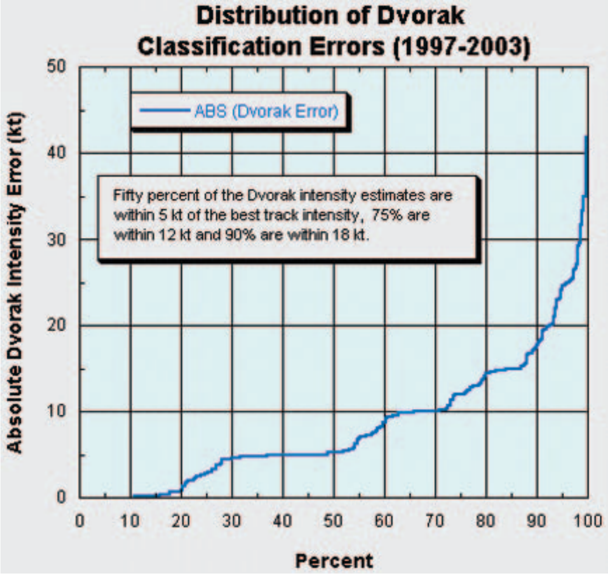
The most recent version of the objective algorithm progression is the advanced Dvorak technique (ADT). Unlike ODT and AODT, which attempt to mimic the subjective technique, the ADT research has focused on revising digital IR thresholds and rules, and extending the method beyond the original application and constraints (Olander and Velden 2006). The ADT, which has its heritage in Dvorak (1984), Zehr (1989), Dvorak (1995), Velden et al. (1998), and Olander et al. (2004), is fully automated for real-time analysis.

Today. As a testament to its success, the Dvorak technique continues to be used today at TC warning centers worldwide. In addition to the regional TC analysis centers mentioned earlier, other centers such as those in Fiji, India, and the Central Pacific Hurricane Center in Hawaii, also employ the method as their primary TC intensity analysis tool. Even at the TPC in Miami where reconnaissance aircraft observations are often available, the technique continues to be the chief method for estimating the intensity of TCs when aircraft data are not available, including most storms in the eastern Pacific, and TCs in the Atlantic east of ~55°W.

Given the global applications, and the local modifications to advance the technique, it is informative to ask how accurate the current Dvorak estimates are. Brown and Franklin (2004) took a fresh look at the technique's accuracy. Figure 9 shows the error frequency distribution of Dvorak MSW estimates compared to intensities derived from reconnaissance-based best-track data for Atlantic TCs between 1997 and 2003. Half of the errors were 5 kt or less, 75% were 12 kt or less (0.5 Tnums at tropical storm intensities), and 90% were 18 kt or less. Thus, the Dvorak-estimated MSW in the Atlantic basin are on the whole quite good, although Brown and Franklin (2002, 2004) mention occasional large outliers do exist.

These recent studies along with those mentioned earlier attest to the consistency of the technique over its 30-yr life span, but remind us that the technique is far from perfect, and still suffers from its limitations. Hurricane Charley (2004) in the Atlantic was a good example of a storm whose intensity was significantly underestimated due to an eyewall replacement cycle and contraction of the eye to dimensions below the viewing capability of the Geostationary Operational Environmental Satellite (GOES). Cases like this compel Tropical Prediction Center (TPC) forecasters to rely heavily on aircraft reconnaissance data in landfalling TC situations.

In TC basins outside of the Atlantic, evaluation of the Dvorak technique performance is hindered somewhat by the lack of in situ validation. Organized field campaigns in these basins would provide a significant



Fifty percent of the Dvorak intensity estimates are within 5 kt of the best track intensity, 75% are within 12 kt and 90% are within 18 kt.

Fig. 9. Dvorak estimates of MSW vs reconnaissance-based best-track estimates in the Atlantic TC basin for the period 1997–2003 (from Brown and Franklin 2004).

opportunity to validate the Dvorak technique and other emerging satellite-based algorithms.

LOOKING AHEAD.

The complementary spectral information from today's meteorological satellites affords an opportunity to advance the VIS/IR-based Dvorak technique. For example, polar-orbiting microwave sensors help denote TC structure (Hawkins et al. 2001; Edson 2000) and intensity (Herndon and Velden 2004; Bankert and Tag 2002). An algorithm integrating these instruments/methods with the existing AODT should provide a powerful consensus tool for estimating tropical cyclone intensity (Velden et al. 2004). Several ways in which microwave data can either supplement or help calibrate the Dvorak intensity technique and eventually help lead to an integrated remote sensing technique are given below.

Special Sensor Microwave Imager (SSM/I) polar-orbiting data have been available for over 15 yr; however, the relatively low spatial resolution (15 km at 85 GHz) and lack of continuous coverage make these data unlikely to be a full replacement for the Dvorak technique. With the launch of the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager in 1997, both the number of available overhead passes and the spatial resolution (7 km at 85 GHz) have greatly improved. This now increases the viability of a microwave technique to at least supplement the Dvorak technique. Microwave imagery (MI) allows analysts to see rain and ice particle patterns within TC rain bands that are normally blocked by mid- to upper-level clouds in the IR and VIS imagery. This enables forecasters to more directly estimate TC intensity with the empirical Dvorak patterns (Guard 2004). In studies such as Cocks et al. (1999) and Edson and Lander (2002), MI patterns have been compared with similar Dvorak patterns through the entire TC life cycle. When the TC lower-cloud structure is not readily apparent in VIS or IR data, MI and scatterometer data can often help reveal the center location and best pattern (e.g., banding versus shear) to use in the Dvorak classification.

Dvorak (1984) identified several environmental precursors to rapid development (such as the shape of the outflow jet), but there is little discussion on the character of the convective organization during the crucial period when rapid intensification often begins. These features are frequently obscured under the central overcast in the VIS and IR. However, clear convective patterns often exist in the MI, showing increasing organization and early eye development. Features such as concentric eyewalls and eyewall replacement cycles (Fig. 10) are prevalent in the MI data (Hawkins and Helveston 2004), and are often linked with current or imminent rapid intensity fluctuations. This information can alert analysts to adjust the Dvorak estimates.

Another difficult assessment for the satellite analyst is the estimation of surface winds during extratropical transition (ET), when the deep convection often detaches and becomes asymmetric relative to the center. The effect on the surface winds depends upon the wind structure prior to ET, the speed of movement of the TC, and the ability of the remaining weaker convection to transfer momentum down into the boundary layer. Scatterometer data and MI show promise of indicating the evolving wind field structure and whether strong winds still exist at the surface.

In addition to qualitative applications of MI to TC intensity analysis, several attempts have been made to develop objective aids. For example, at the Naval Research Laboratory in Monterey, Bankert and Tag (2002) experimented with an objective, computer-based algorithm to objectively match SSM/I 85-GHz signatures with TC intensity levels. More recent work on this algorithm has yielded promising results as a potential TC estimation tool (J. D. Hawkins 2005, personal communication). Several groups have utilized the Advanced Microwave Sounding Unit (AMSU) flown on NOAA polar-orbiting satellites to develop algorithms to estimate TC intensity (Brueske and Velden 2003; Herndon and Velden 2004; Demuth et al. 2004; Spencer and Braswell 2001). These tech-

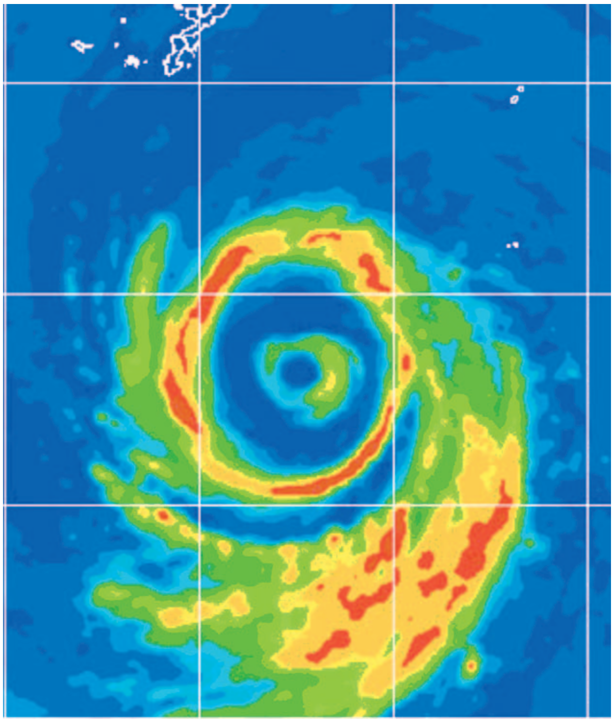


Fig. 10. Example of concentric eyewalls in SSM/I imagery for Typhoon Dianmu (2004). (Courtesy of Naval Research Lab TC Web site.)

niques take advantage of the tropospheric profiling capability of the AMSU to depict TC warm cores, and statistically relate these measurements through hydrostatic assumptions to intensity. AMSU-based methods currently perform on par with the Dvorak technique, and could in time supplant it. However, microwave instruments are currently aboard low-earth-orbiting satellites that have limited data availability and timeliness. Thus, the Dvorak technique, which uses abundantly available geostationary satellite imagery, will likely be employed well into the twenty-first century.

Ultimately, the optimal approach to satellite-based TC monitoring will likely be a consensus algorithm that exploits the advantages of each individual technique, whether VIS/IR or MI based (Fig. 11). Initial attempts at such an algorithm are showing great promise (Velden et al. 2004). As an example, TC MSLP estimates from the AODT and the AMSU techniques have been weighted by their situational performance into a consensus estimate for a large sample of TC cases (Herndon and Velden 2006). Preliminary results show that the weighted consensus is superior in performance to either of its individual elements. It is anticipated that by adding new technique members to the consensus, the accuracies will further improve. It also seems clear that any efforts to modernize the Dvorak technique approach should attempt to retain the basics of the method and be used in combination with the microwave methods. This consensus approach should improve satellite-based TC intensity estimates, and also make possible reliable analyses of the entire TC surface wind field.

SUMMARY. For the past three decades, Vernon Dvorak's practical insights and tools for estimating TC intensity from satellite data have proven to be invaluable in forecast applications. Despite the inherent limitations to an empirical method, and the opportunities for misapplication, the Dvorak technique remains the most widely applied TC intensity estimation method in the world. A U.S. Air Force (1974) report identifies a key to the longevity of the technique: "The [Dvorak] model will provide reliable estimates with data of poor quality, with conflicting evidence, inexperience on the part of the analyst, and

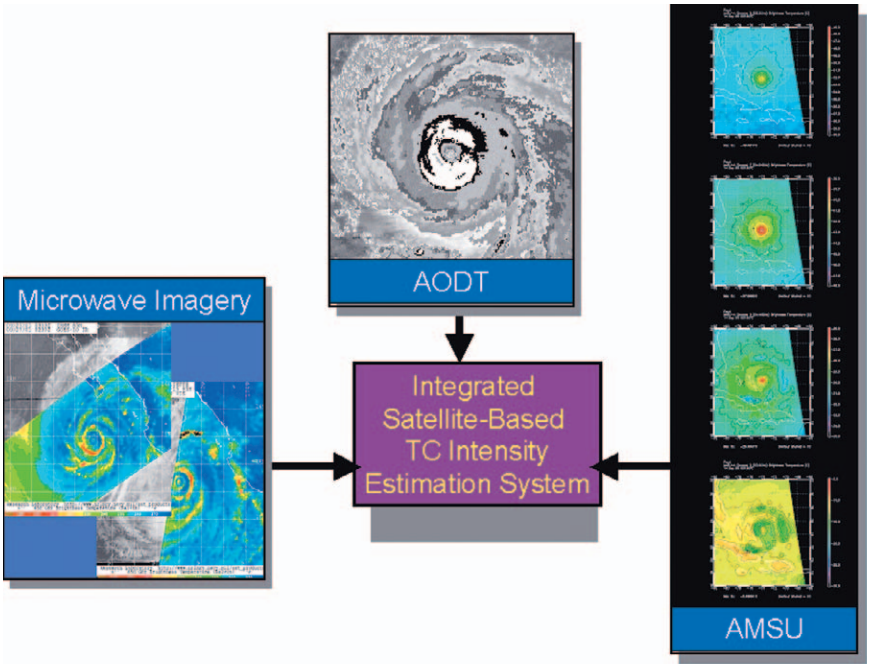


Fig. 11. Conceptual model of a satellite-based TC intensity analysis algorithm based on multispectral observations (Velden et al. 2004).

variations in satellite camera system." However, as identified in that report, a fundamental issue remains for the science to address: "There has been no satisfactory theoretical basis developed to explain intensity changes predicted by the [Dvorak] model, or departures from expected changes which are observed in rapidly developing or weakening storms."

The Dvorak method has also been an extremely important tool for the development of our highly valuable TC archives. The increasing demand for greater certainty of environmental risk from TCs has pushed the commissioning of critical reviews of the possibility for systematic bias in the historical TC datasets (e.g., Harper 2002). These reviews show a potentially contentious emerging issue: the historical datasets have unavoidably inherited any biases that are implicit in the Dvorak technique. Those responsible for national data archives should make every effort to ensure that all possible storm parameters are documented and retained for future reanalysis (e.g., Dvorak *T* and CI numbers and landfall data). The World Meteorological Organization (WMO) has addressed this need in the western North Pacific basin with the development of the Extended Best Track Database [compiled and maintained at the Regional Specialized Meteorological Center (RSMC), Tokyo, Japan].

The practical appeal and demonstrated skill in the face of tremendous dynamic complexity place the Dvorak technique for estimating TC intensity from satellites amongst the greatest meteorological innovations of our time. Empirical techniques such as the Dvorak method intrinsically rely on new generations of analysts as champions to ensure they continue to improve. Dvorak's greatest gift may have been to give us time to continue providing reasonably consistent daily products to operations while we try to understand the underlying physics of tropical cyclone intensity. The future of the Dvorak method is of vital interest to the meteorological community, and its continued evolution ranks as a global priority in tropical weather analysis and forecasting.

ACKNOWLEDGMENTS. The inspiration for this paper derives from the inventor of the technique itself, Vern Dvorak. The authors' gratitude on behalf of the meteorological community and TC-prone populations cannot be overstated. There is little question that the achievements of Mr. Dvorak have paved the way for advancements in applications of remote sensing to tropical cyclone research and forecasting. We would also like to acknowledge the many researchers and forecasters whom have contributed to the evolution and advancement of the Dvorak technique over the years. Finally, the U.S. Air Force and the NOAA Aircraft Operations Center have provided crucial TC aircraft reconnaissance data from which the Dvorak method development and evaluation has benefited. The "Storm Trackers" and "Hurricane Hunters" of the USAF Weather Reconnaissance Squadrons C-130s and NOAA WP-3s are to be commended not only for providing invaluable in situ data for operational forecasting, but also ground truth measurements for remote sensing applications. The views, opinions, and findings contained in this report are those of the author(s) and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

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