The Advanced Dvorak Technique: Continued Development of an Objective Scheme to Estimate Tropical Cyclone Intensity Using Geostationary Infrared Satellite Imagery

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ABSTRACT

Tropical cyclones are becoming an increasing menace to society as populations grow in coastal regions. Forecasting the intensity of these often-temperamental weather systems can be a real challenge, especially if the true intensity at the forecast time is not well known. To address this issue, techniques to accurately estimate tropical cyclone intensity from satellites are a natural goal because in situ observations over the vast oceanic basins are scarce. The most widely utilized satellite-based method to estimate tropical cyclone intensity is the Dvorak technique, a partially subjective scheme that has been employed operationally at tropical forecast centers around the world for over 30 yr. With the recent advent of improved satellite sensors, the rapid advances in computing capacity, and accumulated experience with the behavioral characteristics of the Dvorak technique, the development of a fully automated, computer-based objective scheme to derive tropical cyclone intensity has become possible.

In this paper the advanced Dvorak technique is introduced, which, as its name implies, is a derivative of the original Dvorak technique. The advanced Dvorak technique builds on the basic conceptual model and empirically derived rules of the original Dvorak technique, but advances the science and applicability in an automated environment that does not require human intervention. The algorithm is the culmination of a body of research that includes the objective Dvorak technique (ODT) and advanced objective Dvorak technique (AODT) developed at the University of Wisconsin—Madison's Cooperative Institute for Meteorological Satellite Studies. The ODT could only be applied to storms that possessed a minimum intensity of hurricane/typhoon strength. In addition, the ODT still required a storm center location to be manually selected by an analyst prior to algorithm execution. These issues were the primary motivations for the continued advancement of the algorithm (AODT). While these two objective schemes had as their primary goal to simply achieve the basic functionality and performance of the Dvorak technique in a computer-driven environment, the advanced Dvorak technique exceeds the boundaries of the original Dvorak technique through modifications based on rigorous statistical and empirical analysis. It is shown that the accuracy of the advanced Dvorak technique is statistically competitive with the original Dvorak technique, and can provide objective tropical cyclone intensity guidance for systems in all global basins.

1. Introduction

In the early 1970s, scientists at the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) pioneered a technique to estimate tropical cyclone (TC) intensity using geostationary satellite data. This effort was led by Vern Dvorak, who continued the advancement of the technique into the 1980s (Dvorak 1984). The method of equating satellite cloud signatures and brightness temperature values to TC intensity became known as the Dvorak technique (DT). The DT has been used operationally at TC forecast centers worldwide since that time and is the primary tool for determining TC intensity when aircraft reconnaissance or other in situ measurements are not available [see Velden et al. (2006) for further information on the DT chronology].

The main shortcoming of the DT is its inherent subjectivity and the widely varying expertise levels of the TC forecasters who utilize it. In the late 1980s, Zehr (1989) developed an initial computer-based objective routine based on the analysis technique outlined by Dvorak (1984) using enhanced infrared satellite data. This "digital Dvorak" ("DD") method laid the founda-

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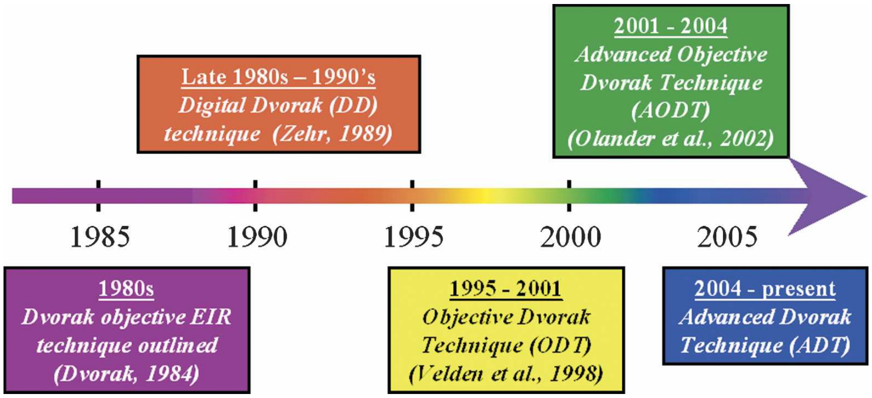


FIG. 1. Progression of objective Dvorak technique algorithms.

tion for the development of the objective Dvorak technique (ODT), which significantly expanded on the DD and for the first time implemented many of the rules and methods outlined in the DT into an objective algorithm (Velden et al. 1998). However, a major shortcoming of the ODT was its inability to estimate storm intensities below hurricane/typhoon strength. This deficiency was addressed in the advanced objective Dvorak technique (AODT), which operates on all TC intensity levels and also incorporates additional DT rules and constraints (Olander et al. 2002).

Further experimentation and refinement of the ODT/AODT led to several deviations from, and additions to, the basic DT concepts and rules. The exploitation of improved remote sensing capabilities, computing capacity, and analysis routines allowed for the development and evolution of an objective method that goes beyond the scope of the DT. For this reason, the ODT/AODT was renamed the advanced Dvorak technique (ADT): an automated, objective, and modified ("advanced") version of the original DT. The renaming of the algorithm to the ADT highlights the improvements and advancements but underscores the continued dependence upon the original DT concepts. The purpose of this paper is to outline the progression (see Fig. 1) from the ODT to the ADT, including many of the significant advancements, and present the current status and performance accuracy of the ADT algorithm.

2. Progression of the ADT algorithm development

The general goal in the development of this algorithm was to bring a highly successful empirical approach to the computer environment, thereby allowing the advantages of automation and objective analysis. A conceptual diagram of the algorithm(s) processes is presented in Fig. 2, and all three algorithm versions (ODT, AODT, and ADT) basically follow this logic tree. In the following subsections the three stages of ADT development and performance are summarized. For further details on the algorithm, please refer to the ADT Users' Guide located on the ADT Web site (available at http://cimss.ssec.wisc.edu/tropic/adt).

a. The ODT

The initial development of the ODT is chronicled in Velden et al. (1998). The original goal for constructing an automated, objective intensity estimation scheme was to create an analysis tool that would provide TC forecasters a uniform baseline estimate to which their subjective DT estimates could be compared. Forecasters at different TC analysis centers, possessing a wide variety of skill and experience levels, could obtain objectively produced intensity guidance on any TC globally. Presumably, this could help mitigate differences between DT analyses at different TC centers. Another original goal of the ODT algorithm was to (at a minimum) equal the performance accuracy of the DT. Statistical comparisons of the ODT intensity estimates versus aircraft reconnaissance measurements in the Atlantic Ocean and Caribbean Sea (Velden et al. 1998) showed the ODT intensity estimates to be competitive with TC estimates obtained with the subjective DT performed at operational forecast centers (OFCs) such as the Satellite Analysis Branch (SAB) of NOAA/NESDIS in Washington, D.C.; the Tropical Analysis and Forecast Branch (TAFB) of NOAA/National Centers for Environmental Prediction (NCEP) at the Tropical Prediction Center (TPC) in Miami, Florida; and the Air Force Weather Agency (AFWA) at Offutt Air Force Base in Omaha, Nebraska. These results were very encouraging; however, important technique limitations still existed. The ODT could only be applied

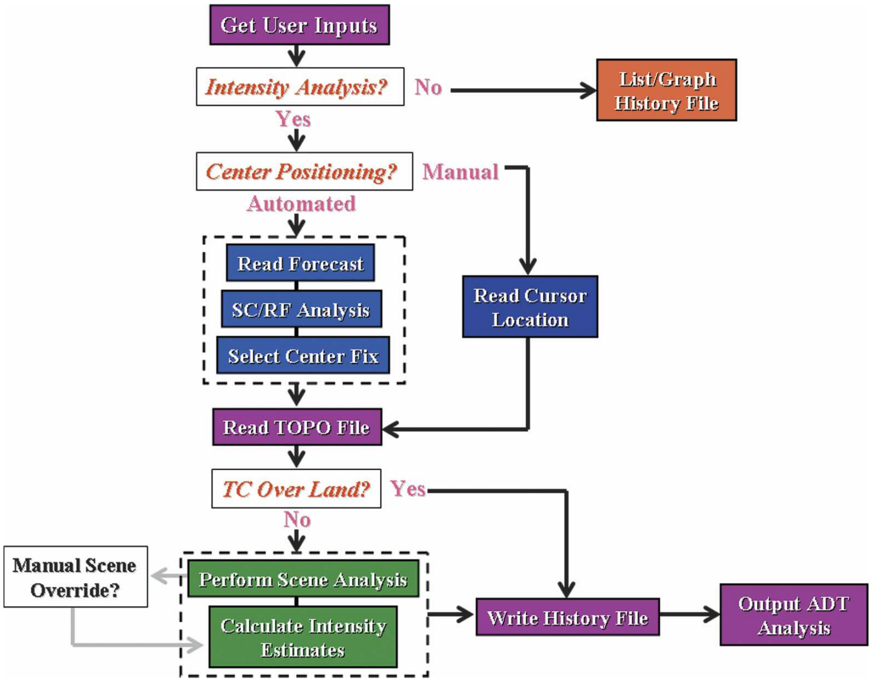


FIG. 2. ADT algorithm satellite image analysis methodology for tropical cyclone intensity estimation.

to storms that possessed a minimum intensity of hurricane/typhoon strength. In addition, the ODT still required a storm center location to be manually selected by an analyst prior to algorithm execution. These issues were the primary motivations for the continued advancement of the algorithm.

b. The AODT

As an intermediate step between the ODT and the ADT, the AODT significantly advanced the ODT on the following three fronts: 1) extension of the application to include tropical depression and storm stages, 2) implementation of several additional DT rules and methodologies, and 3) incorporation of an automated storm center determination methodology.

To expand the analysis capability of the ODT to cover all TC intensities, "pattern recognition" DT scene types were needed to classify weaker systems. The curved band (CB) scene type and accompanying image interpretation procedure is the primary DT method used to derive intensities from TCs in weaker stages (tropical depression/storm). The CB method relates TC intensity to the amount of curvature in the convective cloud field surrounding the storm center using either visible or infrared imagery; however, application of the procedure differs slightly between the two. Only the infrared CB procedure is utilized in the AODT. In the DT, the amount of curvature is measured using a 10° log spiral that is manually positioned over the satellite image. The TC forecasters also use this method to help determine the center position of the storm circulation when it is not clearly defined. However, the CB technique can be an exceptionally subjective technique because of differences in image interpretation methods among DT users. In spite of the challenges associated with the creation of an objective scheme from an inherently subjective technique, an automated routine was derived for the AODT algorithm that incorporated CB application ideas from various DT users. Other DT scene types were introduced into the AODT as well, all of which are still employed in the current ADT. These are listed in Table 1.

The second major AODT upgrade involved the implementation of additional DT rules. For example, the DT's step 8, which constrains the amount of intensity change allowed over selected time periods, was added to the derivation of the T# ("tropical" number). The T# is the metric used by the DT to denote intensity and intensity change (Dvorak 1984), and is related to TC maximum sustained winds and minimum sea level pressure (MSLP). The rule 8 constraints allow only a 1.0, 1.5, 2.0, and 2.5 T# change over 6, 12, 18, and 24 h, respectively, for stronger (hurricane/typhoon) storms, and 0.5 T# over 6 h for weaker storms. This DT value

TABLE 1. ADT scene types. Items listed in italics are new since the ODT.

Cloud-scene types	Eye-scene types
CDO	Clear (Eye)
Embedded Center (EmbC)	*Large (LrgEye)*
Irregular CDO (IrrCDO)	*Pinhole (PinEye)*
CB	
Shear	

(as used in the AODT as well) represents the initial estimate of the intensity of the storm obtained from the satellite image being interrogated prior to the application of time averaging or other DT rules. In the ODT/AODT/ADT, this DT value is called the "raw T#" value and represents the intensity of the TC prior to any operations utilizing previous intensity estimates stored in the history file. Incorporation of the DT step 8 constraints influenced two aspects within the AODT related to the derivation of intensity estimates. First, it lessened the impact of an incorrect scene-type identification when calculating the time-averaged "final T#" value in the ODT/AODT/ADT algorithm. Second, it allowed the time-averaging period to be reduced from 12 to 6 h. As discussed in Velden et al. (1998), a 12-h time-weighted averaging scheme was initially used by the ODT to reduce the amount of diurnal and/or short-burst convection variability not associated with the actual TC intensity. However, in the case of a rapid deepening event, such as Hurricane Opal in 1995, the 12-h averaging significantly hindered the growth of the final T#. Implementation of the DT step 8 constraints allowed for the time-averaging period to be reduced, and rapid intensity change events to be better captured.

In addition to the raw T# and final T# intensity values, a third intensity value is produced by the ODT/AODT/ADT algorithm, which represents the current intensity of the storm being investigated. This value is named the CI# and is derived from the time-averaged final T# value, but is subjected to further constraints during the weakening process of the TC life cycle. These constraints are derived from the DT's rule 9 that holds the intensity estimate to a higher (more intense) T# value than that obtained with the final T# value alone. The CI# is most often considered the value to be used for the final estimate of TC intensity.

The third AODT advancement involved the elimination of the final remaining subjective element of the ODT: the manual determination of the TC storm center location. A methodology was developed to utilize a TC short-term track forecast [provided by TPC or the Joint Typhoon Warning Center (JTWC)] as a first guess for the storm center location at a given analysis time. If the estimated storm intensity from the immediately preceding AODT history file record exceeds an empirically set threshold, and/or other criteria are met, image analysis techniques are conducted in an attempt to automatically reposition the storm center at a more precise location. A Laplacian technique (LT) was the original method applied to identify eye patterns in well-developed TC systems. This technique would attempt to identify closed, high-gradient regions in the cloud-top temperature field. These regions would generally correspond to the storm eye–eyewall interface, but other noneye regions could be incorrectly identified as the storm center. For example, features known as dry "moats" or "false eyes" caused by the ingestion of dry air into the inner storm circulation due to land interaction or an encounter with a sheared environment could often lead to misplaced centers (Fig. 3).

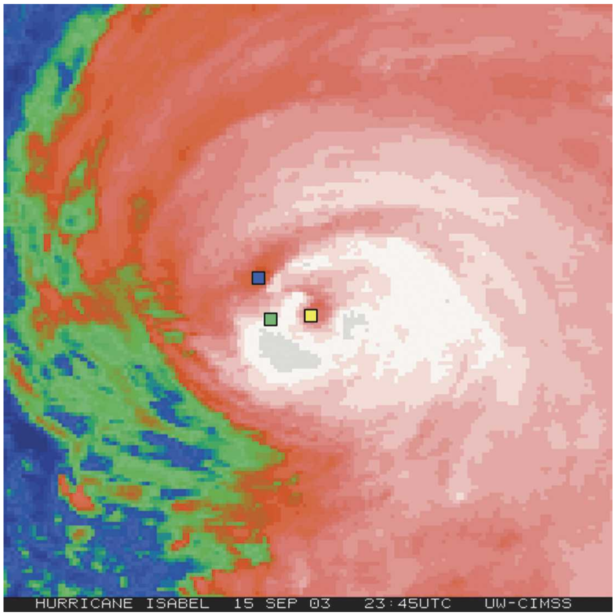


FIG. 3. Example of a false-eye situation in enhanced infrared imagery observed during Atlantic Hurricane Isabel (2003). The green dot indicates NHC-interpolated short-term forecast of the center position, with blue and yellow dots showing center positions determined objectively from the LT and new SC–RF technique, respectively. White areas in the IR image enhancement indicate the coldest cloud-top temperatures, while reds, greens, and blues indicate progressively warmer cloud-top temperature values.

Two new center-finding techniques were developed to alleviate the limitations of the LT and eventually replaced it completely (Wimmers and Velden 2004). The spiral-centering (SC) technique determines the center point by calculating the maximum alignment between the image temperature gradient field and a 5° log spiral vector. It focuses on the rotation-induced gradients of the entire storm rather than just the orientation of one spiral band, and mimics the DT CB methodology familiar to experienced TC forecasters. It also has the bonus of not being drawn toward false-eye regions in the image because it utilizes the entire TC structure, unlike the original LT.

A second methodology is employed following the completion of the SC method. The ring-fitting (RF) technique attempts to further reposition the storm center location by searching for intense ring-shaped gradients in the cloud-top temperature field (storm eyewall) around the position determined by the SC method. This method will work for not only symmetric, well-defined eye features but has also been tuned to locate oblong, ring-shaped gradients in partially obscured eyes. The SC–RF center finding combination is a significant advancement over the original LT, providing more accurate storm center estimates in a larger variety of situations. Figure 3 presents an example of a false-eye region that was incorrectly identified as the storm center during Hurricane Isabel (2003) by the LT technique, with the proper storm center being determined by the SC–RF technique.

Use of additional satellite channels/instruments, such as microwave imagery, could be employed to further enhance the accuracy of the automated center-fixing technique in situations not currently handled well when utilizing only infrared imagery. This will be explored as part of a merged multispectral algorithm being developed (Velden et al. 2004).

One other specific but significant AODT performance modification should be noted here. A user-requested feature was added to allow an analyst to manually override the objectively determined position or scene type prior to the determination of the final intensity estimate. While this option reintroduces a source of subjectivity to the intensity estimation process, it has been found through independent analysis (M. Turk 2005, personal communication) that occasional selective position or scene-type modification by an experienced analyst can improve the accuracy of the intensity estimates in some cases. This is especially true during the weaker stages of TC development, when consistent, objectively determined scene types are more difficult (discussed further in section 3).

c. The ADT

An original goal of designing an objective Dvorak algorithm (such as the ODT) was to mimic the original method (DT) to the greatest extent possible. However, especially in the later years of development, new approaches, rules, and various statistically based adjustments have been implemented that deviate from the basic DT procedures. In other words, the algorithm has become more than just an objective version of the DT. For this reason, the latest version of the algorithm is now being referred to as the advanced Dvorak technique. The term advanced in this case encompasses the automation of the DT into a fully objective scheme, while also inferring the algorithm has progressed beyond the original scope. A summary of the major algorithm advancements implemented since the original ODT version is presented in Table 2.

Table 2. ADT additions and modifications to the original ODT technique documented in Velden et al. (1998).

Primary ADT upgrades since the original ODT description
Expanded analysis range to operate on tropical depression/tropical storm stages of TC life cycle
Added new scene-type categories for cloud and eye regions (Table 1)
Modified intensity determination scheme for eye and CDO scenes (regression-based determination with new predictors)
Added a modified DT step 9 (weakening rule)
Added a modified DT step 8 (constraint rule)
Implemented new constraints dependent on situation and scene types
Modified surrounding cloud region temperature determination scheme (coldest ring average instead of warmest pixel temperature on ring)
Modified scene-type determination scheme
Implemented improved automated storm center determination techniques
Added latitude bias adjustment to MSLP
Added RMW determination scheme
Modified time-averaging technique period from 12 to 6 h (3 h in eye scenes)
Added user scene override capability
Added new graphical and Automated Tropical Cyclone Forecasting System format output options

Most of the ADT functionalities that deviate from the original approaches have to do with the DT rules and constraints. Several new rules have been introduced that work with the time-averaging scheme to limit or open up the allowable intensity change over selected periods of time. Other changes involve amendments to how existing DT rules are applied in certain situations. In every case, the implementation of a new rule, or modification of one of the DT rules, was preceded by a rigorous statistical analysis of the performance impact on the ADT. Such analyses include a detailed breakdown of the impact of the proposed modification regarding each storm stage (formation, mature, or dissipation), applicable ADT scene type(s), and a detailed assessment over a complete array of storm life cycles (depressions through major hurricanes). A quantitative evaluation of the current ADT performance is given in the next section.

Beyond the procedural modifications, the ADT also improves on the original DT by introducing new concepts. One such example is the adjustment to the TC mean sea level pressure (MSLP) intensity estimate based upon the storm latitude position. This adjustment was implemented after a latitude-dependent bias was noted in the DT estimates of MSLP (Kossin and Velden 2004). It was found that this bias is related to the slope of the tropopause (and corresponding infrared channel cloud-top temperature measurement change) with latitude. This adjustment is only applied to intensity estimates for specific scene types, such as eye(s), central dense overcast (CDO), and embedded center, which are derived using digital infrared channel cloud-top temperature information. The inclusion of this bias adjustment results in a small reduction in ADT MSLP estimate errors, especially during the dissipation stage of the storm life cycle (primarily when the storm is at higher latitudes).

Modifications to the intensity determination scheme for eye and CDO scene types using regression-based equations represent another significant ADT advancement. These equations relate several measured environmental parameters to storm intensity, such as cloud region convective symmetry, cloud region size, and an eye region minus cloud region temperature difference. The chosen parameters were determined from extensive regression analysis of multiple cloud and eye region variables. Significantly improved correlation accuracies are obtained with the use of the new regression equations over the previous techniques that basically employed only the cloud and eye temperature values (based on DT methods). When compared with aircraft reconnaissance intensity measurements, intensity estimates obtained with the new CDO equation produce an increase in correlation from 0.28 to 0.50, while the new eye equation intensity estimates result in a correlation increase from 0.62 to 0.70. In addition, the ragged and obscured eye scene types are made obsolete with this new methodology, and have been eliminated.

Some of the largest ADT intensity estimate errors result from storms with very small eyes, often referred to as "pinholes." Pinhole eye cases represent situations where the eye is sufficiently small to be improperly sampled by current geostationary satellite infrared imagery with spatial resolutions of ~4 km, but can otherwise be observed with other higher-resolution channels (visible). These cases typically result in significant underestimates of intensity by the ODT/AODT algorithms because of incorrect scene-type identifications, such as with Hurricane Wilma in 2005 (Fig. 4). In this example, misidentification of the scene type as a CDO resulted in a T# intensity estimate of 4.5. Reconnaissance aircraft measured MSLP at that time to be 960 mb (approximately T# 5.5), and 6 h later the MSLP had fallen rapidly to 901 mb (T# 7.6). Proper identification of the ADT scene type as a pinhole eye increases the T# intensities to 6.2 and 7.2, respectively, and would have alerted analysts to the rapid intensification event underway. A pinhole eye identification scheme has been implemented into the latest version of the ADT.

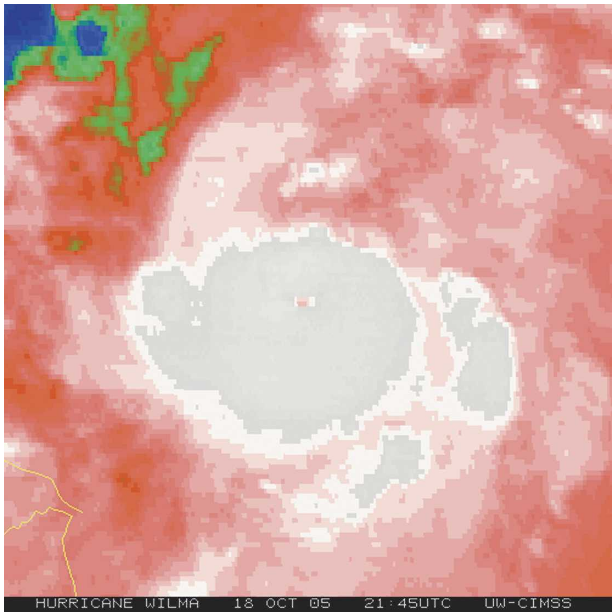


FIG. 4. Example of a pinhole eye observed in enhanced infrared imagery during Atlantic Hurricane Wilma (2005). White areas in the IR image enhancement indicate the coldest cloud-top temperatures, while reds, greens, and blues indicate progressively warmer cloud-top temperature values.

A new functionality has been added to the ADT algorithm to present additional wind field information (beyond just the DT estimate of maximum sustained wind). The routine provides an estimate of the radius of maximum wind (RMW) for clear-eye scenes only. This method interrogates the infrared channel cloud-top temperature field in four directions from the storm center location to locate the critical temperature value that is highly correlated with the radius of maximum wind position as obtained from a statistical analysis of aircraft reconnaissance measurements. The average distance along each axis is then computed and used to determine the RMW. This technique is being extended to operate on scenes without eyes (Kossin et al. 2005). A correlated/adjunct algorithm is being designed to estimate the near-storm two-dimensional surface wind field based on the ADT intensity estimate, the satellite image cloud-top temperature field, and the current storm motion. This routine is still under development but will be an added output option by the ADT, and can be displayed using any graphical software package (see Kossin et al. 2005 for more information).

The above discussion on the algorithm evolution highlights the shift in approach from a simple "recreation" of the DT in a computer environment to a more sophisticated attempt to build on and improve the original DT. The latest version of the algorithm (ADT) reflects the latter goal and therefore the ADT terminology will be used in the remainder of this article.

3. ADT algorithm performance evaluation

In this section we assess the accuracy of the ADT, both in an absolute sense and relative to the operational DT. Atlantic basin aircraft reconnaissance measurements of TC intensity, provided by the U.S. Air Force "Hurricane Hunters" Reserve Unit of the 53d Weather Reconnaissance Squadron and the NOAA Aircraft Operations Center, constitute the ground truth for the evaluation. The operational DT intensity estimates are obtained from three OFCs: the NOAA/NCEP/TAFB, the NOAA/NESDIS/SAB, and the AFWA. ADT statistics utilize the CI# produced by the algorithm, which represents the final intensity value after the various constraints and time averaging has been applied.

For the statistical analysis, an aircraft reconnaissance report must be within 1 h of an ADT estimate, while an OFC DT estimate must be within 30 min of the same ADT estimate. Most of the successful matches have multiple OFC estimates. In these cases the resulting OFC estimates used in the comparisons are averaged and represent a consensus of the available DT estimates. This is an important point because such a consensus can be statistically superior to estimates obtained from the OFCs individually (Velden et al. 1998) by inherently smoothing out some of the subjective DT variability. In addition, although difficult to quantify, it is likely in most cases that the satellite analysts working the respective tropical desks had real-time knowledge of the aircraft reports, which could have influenced their DT estimates (as documented by Martin and Gray 1993). Therefore, this validation approach represents a stringent test of the ADT.

A point of emphasis should be made regarding the ADT and how it is evaluated in this paper. Verification statistics are based on comparisons with aircraft reconnaissance measurements of intensity in terms of MSLP and not aircraft-estimated maximum sustained surface wind speed (Vmax). These two intensity measurements, although related, can vary significantly from the empirical pressure–wind (*P*–*W*) relationships on which the Dvorak technique relies (e.g., Table 3). The ADT estimates MSLP and then obtains Vmax using the *P*–*W* defined for the Atlantic (Dvorak 1995) and west Pacific (Shewchuck and Weir 1980), but these relationships do not always reflect estimated values obtained by aircraft. This could be due to aircraft Vmax sampling issues, or asymmetric wind structures in the storm that can cause deviations from the empirically derived relationships. For these reasons, in our study and algorithm development, MSLP is utilized as the sole performance metric. A direct Vmax estimate from the ADT, instead of reliance on the *P*–*W* relationship, is an avenue for future ADT research.

TABLE 3. Empirical relationship between Dvorak CI number, MSLP, and Vmax for Atlantic tropical cyclones (Dvorak 1995).

CI No.	MSLP (hPa)	Vmax (kt)
1.0	—	25
1.5	—	25
2.0	1009	30
2.5	1005	35
3.0	1000	45
3.5	994	55
4.0	987	65
4.5	979	77
5.0	970	90
5.5	960	102
6.0	948	115
6.5	935	127
7.0	921	140
7.5	906	155
8.0	890	170

a. *Overall ADT performance*

The impact of the advancements on the algorithm accuracy and performance through the progression to the ADT can be assessed by a comparison of the original ODT with that latest version of the ADT. This comparison, on a homogeneous sample of cases, is shown in Table 4. Only storms in the dependent dataset that obtained hurricane strength were considered in this comparison because of the limitations of the ODT. All statistics in Table 4 were obtained in a fully automated and objective manner (i.e., no manual intervention or overrides).

Table 4 clearly illustrates the improvement of the ADT over the ODT. The largest errors associated with the ODT can be attributed to incorrect storm center positions. To demonstrate this, the ODT was rerun with the same center positions as determined by the new ADT SC–RF scheme (ODT-A). The impact of the new autocentering techniques is significant, with a reduction in the bias and RMSE by 6–8 hPa. The modifications to the scene-type determination and intensity estimate

TABLE 4. Raw T# (top) and final CI# (bottom) TC intensity estimate (MSLP) comparisons between ADT and ODT vs aircraft reconnaissance measurements for a homogeneous sample of 1116 Atlantic cases from 1996 to 2005. ODT-A indicates ODT using storm center positions determined from ADT autocenter determination techniques. Positive bias indicates underestimate of intensity by the ODT/ADT techniques. Units are in hPa.

Raw T#	Bias	RMSE	Avg error
ODT	16.83	26.07	19.93
ODT-A	10.78	20.07	16.00
ADT	2.78	15.47	12.11
Final CI#	**Bias**	**RMSE**	**Absolute error**
ODT	12.67	20.45	15.00
ODT-A	4.26	14.21	10.20
ADT	0.52	13.16	10.25

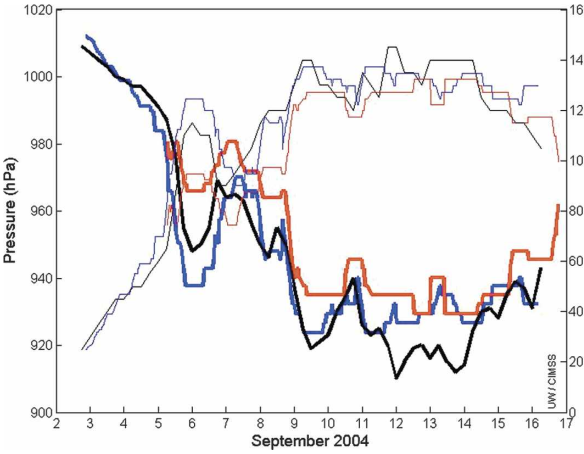


FIG. 5. Time series plot of ODT (red) and ADT (blue) intensity estimates vs NHC/TPC best-track estimates (black) of MSLP (thick lines) and Vmax (thin lines) for Atlantic Hurricane Ivan (2004).

schemes account for the remaining reduction of the bias and RMSE from the ODT-A to the ADT in both the T# and CI# statistics.

A good example of the improved performance of the ADT over the ODT is illustrated in Figs. 5 and 6, which present a comparison of the two algorithm versions for Hurricane Ivan (2004). The intensity estimates of MSLP obtained by the ODT and ADT algorithms are compared with the NHC/TPC best-track and reconnaissance estimates of MSLP. It is very apparent that the ADT estimates for Ivan match the observations better, and this case is typical of the sample.

It is again noted that the intensity estimates in this validation study were obtained using a completely automated version of the ADT and ODT algorithms. However, as mentioned previously, the ADT possesses a manual override functionality that can be applied by an analyst to adjust the initial position or scene type. Comparisons between intensity estimates obtained from the ADT using manual (provided by an experienced analyst) versus automated storm center positioning demonstrate an ~10% improvement in the overall accuracy (Table 5) using the manual overrides. It is emphasized that an experienced satellite analyst can still "add value" to the ADT by making intelligent adjustments on selected cases.

Having established the superiority of the ADT over the original ODT algorithm, we now focus on its performance relative to the existing operational DT. Table 6 shows ADT intensity estimate results for two samples: development, or dependent (1996–2005 Atlantic storms), and independent (1995 Atlantic storms) tests. The dependent dataset was chosen to include cases from 2005 because of the large number of intense storms in that year. In each case, ADT estimates are compared with concurrent OFC DT estimates and verified against reconnaissance measurements of MSLP central pressure. The results in Table 6 indicate that the ADT eliminates the systematic bias in the DT, but the error variance metrics suggest the OFC DT estimates can still add value compared with a completely automated and objective tool such as the ADT in certain situations. Interestingly, the independent test yields a weak bias in both the ADT and OFC estimates, but the RMSE values are somewhat more similar. A closer examination of the independent results indicates that the dataset contained many cases from Hurricane Felix, a long-lived and well-sampled (by reconnaissance) storm. For reasons that are not well understood, the Dvorak methods underestimate the intensity. However, it is encouraging that the overall ADT RMSE for the independent test is competitive with the operational DT consensus value, even given the strict comparison conditions mentioned above.

It is informative to ascertain in what situations the ADT performs the best and worst. In the following two sections the statistics are stratified by storm stage and ADT scene type in order to glean further information on the ADT behavior.

b. *ADT performance by TC stage*

The performance statistics presented above are stratified in relation to three stages of TC life cycle: formation, mature, and dissipation. The mature stage is defined as the period between the first and last appearance of a "significant" eye cycle. Significant is defined as any ADT-determined eye scene type lasting for at least 6 consecutive hours. The formation and dissipation stages are the periods prior and subsequent to the

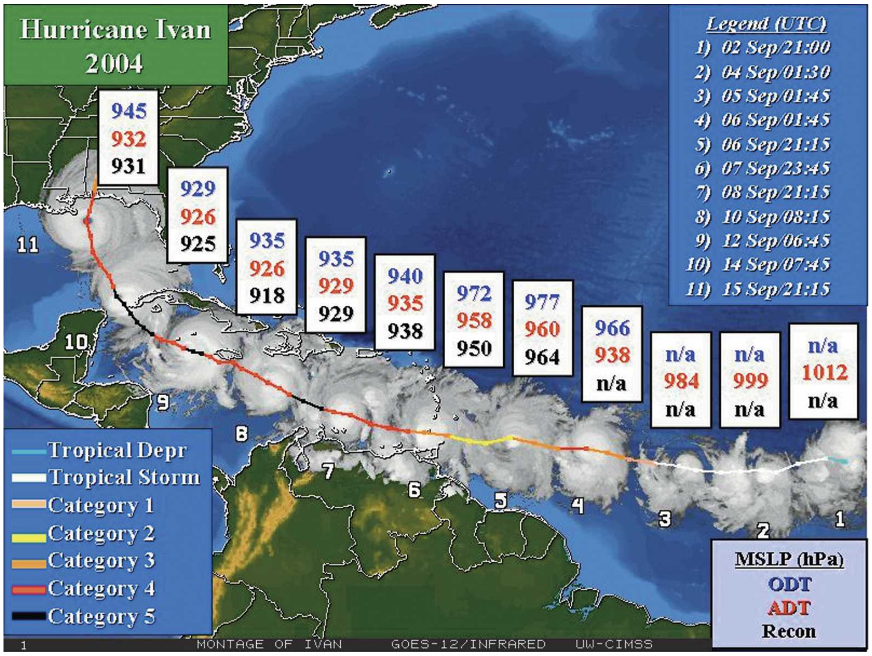


FIG. 6. Satellite montage image of Atlantic Hurricane Ivan (2004) with ADT and ODT intensity estimates of MSLP vs aircraft reconnaissance measurements (hPa).

mature stage, respectively. If a particular storm in the sample does not acquire an eye (mature stage) during its life cycle, the stratification is limited to formation/dissipation and is done using the peak intensity. If a storm exhibits multiple eye cycles, the first and last appearances of an eye are used to define the formation and dissipation stages, respectively.

Results shown in Table 7 reflect the performance of the ADT as compared with the consensus OFC DT during each of the three stages of TC development. As expected, the ADT performs similarly to the OFC DT estimates during the mature (most intense) TC stage, since the ODT/ADT was first developed for storms of hurricane/typhoon strength. In addition, the treatment of eye patterns/scenes remains the closest ADT element to the original DT methodology. These results suggest the ADT can be reliable as an objective guidance tool for TC analysts during mature stages of TCs.

The reduction in ADT skill relative to the OFC DT during the formation and dissipation stages is not unexpected considering the difficulties associated with automating the somewhat subjective pattern recognition DT techniques (such as the curved band analysis) needed for these stages. Also, the process of extratropical transition of TCs (common during the dissipation stage, as we define it) is not explicitly defined in the ADT. These results suggest that the ADT should be used with more caution in the weaker intensity stages of TCs.

An important aspect of the results in Table 7 should be noted. As mentioned earlier, the DT uses the T# as a metric to denote TC intensity. However, the conversion between T# and MSLP is not linear; instead, the representative MSLP spread between T#s becomes larger as the T# value increases. For example, T# values of 3.0 (4.0) would yield MSLP values of 1000 (987) hPa

TABLE 5. Comparison of ADT manual vs automated storm center selection on estimates of TC intensity (MSLP). Atlantic aircraft reconnaissance measurements are used for the validation. Negative bias indicates overestimate of intensity. Units are in hPa.

	Bias	RMSE	Avg error	Sample size
ADT-Auto	−3.06	11.89	8.96	280
ADT-Manual	−3.66	10.40	8.39	280

TABLE 6. Dependent (D; Atlantic TC cases from the years 1996 to 2005) and independent (I; cases from 1995) homogeneous comparisons between the ADT and OFC DT estimates vs aircraft reconnaissance measurements of TC intensity (MSLP). Positive bias indicates an underestimate of intensity. Units are in hPa.

	Bias	RMSE	Avg error	Sample size
ADT-D	0.40	12.53	9.19	2093
OFC-D	2.47	9.86	7.35	2093
ADT-I	6.61	11.95	9.86	359
OFC-I	5.81	10.56	8.23	359

TABLE 7. Homogeneous comparisons (1996–2005 Atlantic TC dataset) between the ADT and consensus OFC DT intensity estimates (MSLP; hPa) for different TC stages (defined in the text). Aircraft reconnaissance measurements are used for the validation. Positive (negative) bias indicates an underestimate (overestimate) of intensity.

Overall	Bias	RMSE	Avg error	Sample
ADT	0.40	12.53	9.19	2093
OFC	2.47	9.86	7.35	2093
Formation stage	Bias	RMSE	Absolute error	Sample size
ADT	1.30	9.94	7.31	816
OFC	−0.33	7.98	5.23	816
Mature stage	Bias	RMSE	Absolute error	Sample size
ADT	−0.77	13.87	10.62	945
OFC	5.54	12.27	9.52	945
Dissipation stage	Bias	RMSE	Absolute error	Sample size
ADT	1.51	10.97	8.43	332
OFC	0.60	9.01	6.34	332

TABLE 8. As in Table 7, but values are in terms of T# after converting validating reconnaissance MSLP reports to T# using the Dvorak conversion for the Atlantic basin. Positive (negative) bias values indicate overestimate (underestimate) of intensity (opposite of MSLP comparisons in Table 7).

Overall	Bias	RMSE	Absolute error	Sample
ADT	−0.02	0.70	0.53	2093
OFC	−0.09	0.55	0.43	2093
Formation stage	Bias	RMSE	Absolute error	Sample
ADT	−0.06	0.69	0.47	816
OFC	0.04	0.55	0.41	816
Mature stage	Bias	RMSE	Absolute error	Sample
ADT	0.05	0.63	0.45	945
OFC	−0.23	0.52	0.41	945
Dissipation stage	Bias	RMSE	Absolute error	Sample
ADT	−0.14	0.88	0.69	332
OFC	−0.04	0.65	0.52	332

(Atlantic basin), whereas T# values of 6.0 (7.0) would yield MSLP values of 948 (921) hPa. Intensity estimate errors are magnified as the T# increases due to the increased MSLP spread. Thus, an error assessment in terms of MSLP values alone is informative in an absolute sense, but can be misleading when directly comparing the algorithm performance between storm stages. For example, a 10-hPa intensity estimate error may be reasonable for a 920-hPa category-5 hurricane, but unacceptably large for a 990-hPa hurricane or tropical storm. In this context, perhaps a better way to intercompare ADT situational behavior is through an error assessment in terms of the T#, the actual estimate metric.

Table 8 presents the results of Table 7 in terms of T# values. The validating reconnaissance MSLP observations are converted/interpolated to T#, in effect normalizing the intensity-dependent spread of MSLP values. From this viewpoint, both the DT and ADT perform best in mature stages (i.e., storms with well-defined eyes, especially). The ADT is within 0.07 T# of the OFC estimates (RMSE) during the mature stage, but loses performance accuracy during the weaker stages. This further supports the need for continued research efforts to be conducted to improve the accuracy of the ADT during weaker stages of TCs.

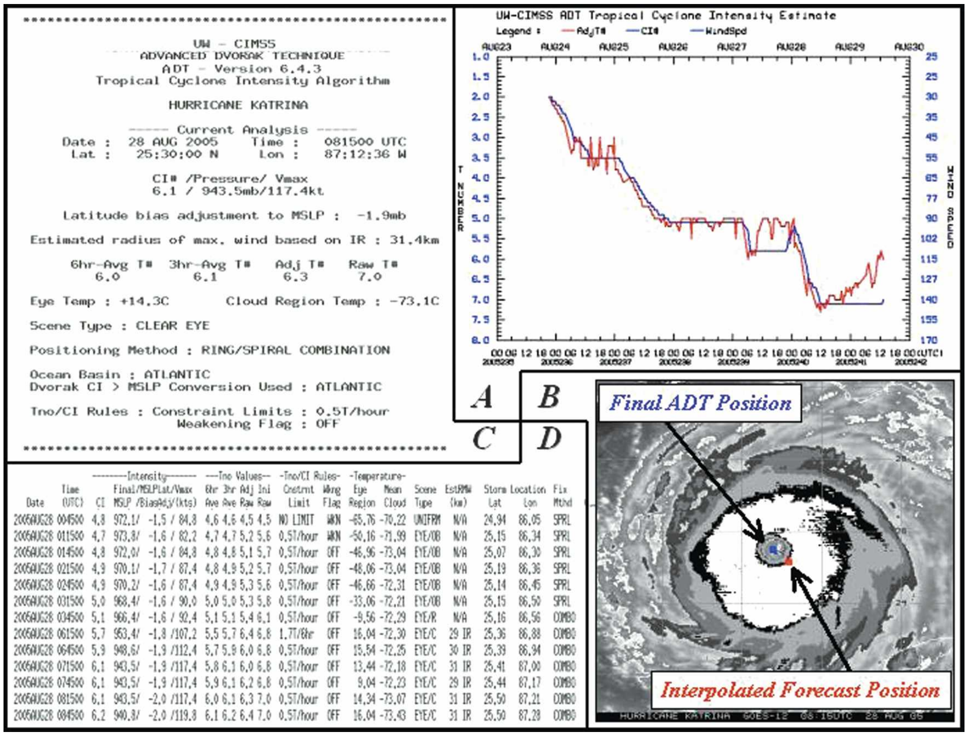
c. *ADT performance by selected scene type*

To better understand the ADT behavioral characteristics noted above, the performance statistics were evaluated by individual ADT scene types. Not surprisingly, the more established ADT scene types exhibit the best skill in estimating TC intensity versus reconnaissance aircraft measurements of MSLP. Eye scene types, originally developed within the ODT/AODT and modified/expanded within the ADT, yield an overall RMSE accuracy of about one-half of a T#. "Formative stage" scene types, such as curved band, shear, CDO, and embedded center show RMSE accuracies of between 0.6 and 0.8 T# while displaying near-zero biases. The increased estimate variance associated with these scene types is a target for future ADT algorithm improvements.

4. ADT status

Because the ADT is a "living" algorithm (constantly being upgraded), various versions are currently operating in real time at all three of the aforementioned OFCs. The TAFB at the TPC in Miami is running the algorithm within the National Weather Service National Centers Advanced Weather Interactive Processing System (N-AWIPS) computer environment. Upgrades are delivered to the NOAA/Computing Development Branch (CDB) for integration into N-AWIPS, and CDB distributes upgrades to the TPC. Implementation of the ADT at the TPC within the N-AWIPS architecture was driven by the U.S. Weather Research Program Joint Hurricane Test Bed project.

The ADT is being used at NOAA/NESDIS/SAB and the AFWA to support their operational tropical cyclone duties. SAB first obtained the Man computer In-



```
*****************************************************************
                          UW - CIMSS
                 ADVANCED DVORAK TECHNIQUE
                     ADT - Version 6.4.3
             Tropical Cyclone Intensity Algorithm

                      HURRICANE KATRINA

                  ----- Current Analysis -----
         Date :  28 AUG 2005      Time :    081500 UTC
          Lat :   25:30:00 N       Lon :    87:12:36 W

                   CI# /Pressure/ Vmax
                   6.1 / 943.5mb/117.4kt

       Latitude bias adjustment to MSLP :  -1.9mb

  Estimated radius of max. wind based on IR : 31.4km

       6hr-Avg T#  3hr-Avg T#   Adj T#   Raw T#
          6.0         6.1         6.3      7.0

  Eye Temp : +14.3C        Cloud Region Temp : -73.1C

  Scene Type : CLEAR EYE

  Positioning Method : RING/SPIRAL COMBINATION

  Ocean Basin : ATLANTIC
  Dvorak CI > MSLP Conversion Used : ATLANTIC

  Tno/CI Rules : Constraint Limits : 0.5T/hour
                      Weakening Flag : OFF

*****************************************************************
```

```
                      --------Intensity-------  ---Tno Values--  -Tno/CI Rules-  -Temperature-
             Time          Final/MSLPLat/Vmax   6hr 3hr Adj Ini   Cnstrnt  Wkng   Eye    Mean   Scene  EstRMW  Storm Location  Fix
   Date      (UTC)  CI  MSLP /BiasAdj/(kts)     Ave Ave Raw Raw    Limit   Flag  Region  Cloud  Type    (km)    Lat     Lon    Mthd
2005AUG28 004500 4.8  972.1/  -1.5 / 84.8  4.6 4.6 4.5 4.5  NO LIMIT   WKN  -65.76 -70.22 UNIFRM  N/A    24.94  86.05  SPRL
2005AUG28 011500 4.7  973.8/  -1.6 / 82.2  4.7 4.7 5.2 5.6  0.5T/hour  WKN  -50.16 -71.99 EYE/OB  N/A    25.15  86.34  SPRL
2005AUG28 014500 4.8  972.0/  -1.6 / 84.8  4.8 4.8 5.1 5.7  0.5T/hour  OFF  -46.96 -73.04 EYE/OB  N/A    25.07  86.30  SPRL
2005AUG28 021500 4.9  970.1/  -1.7 / 87.4  4.8 4.9 5.2 5.7  0.5T/hour  OFF  -48.06 -73.04 EYE/OB  N/A    25.19  86.36  SPRL
2005AUG28 024500 4.9  970.2/  -1.6 / 87.4  4.9 4.9 5.3 5.6  0.5T/hour  OFF  -46.66 -72.31 EYE/OB  N/A    25.14  86.45  SPRL
2005AUG28 031500 5.0  968.4/  -1.6 / 90.0  5.0 5.0 5.3 5.8  0.5T/hour  OFF  -33.06 -72.21 EYE/OB  N/A    25.15  86.50  SPRL
2005AUG28 034500 5.1  966.4/  -1.6 / 92.4  5.1 5.1 5.4 6.1  0.5T/hour  OFF   -9.56 -72.29 EYE/R   N/A    25.16  86.56  COMBO
2005AUG28 061500 5.7  953.4/  -1.8 /107.2  5.5 5.7 6.4 6.8  1.7T/6hr   OFF   16.04 -72.30 EYE/C   29 IR  25.36  86.88  COMBO
2005AUG28 064500 5.9  948.6/  -1.9 /112.4  5.7 5.9 6.0 6.8  0.5T/hour  OFF   15.54 -72.25 EYE/C   30 IR  25.39  86.94  COMBO
2005AUG28 071500 6.1  943.5/  -1.9 /117.4  5.8 6.1 6.0 6.8  0.5T/hour  OFF   13.44 -72.18 EYE/C   31 IR  25.41  87.00  COMBO
2005AUG28 074500 6.1  943.5/  -1.9 /117.4  5.9 6.1 6.2 6.8  0.5T/hour  OFF    9.04 -72.23 EYE/C   29 IR  25.44  87.17  COMBO
2005AUG28 081500 6.1  943.5/  -2.0 /117.4  6.0 6.1 6.3 7.0  0.5T/hour  OFF   14.34 -73.07 EYE/C   31 IR  25.50  87.21  COMBO
2005AUG28 084500 6.2  940.8/  -2.0 /119.8  6.1 6.2 6.4 7.0  0.5T/hour  OFF   16.04 -73.43 EYE/C   31 IR  25.50  87.28  COMBO
```

FIG. 7. Sample ADT output during Atlantic Hurricane Katrina (2005). (a) Time series display of ADT intensity estimates, (b) example of autocentering adjustment, (c) intensity bulletin output for single-image analysis, and (d) history file output listing.

teractive Data Access System based version (original) of the ODT algorithm in the late 1990s and has since provided invaluable feedback and suggestions with regard to performance statistics, proposed new ADT features, and answers to general DT interpretation questions. Current use of the algorithm at AFWA has been achieved through implementation into the U.S. Air Force Satellite Imagery Display and Analysis System computer system. Versions of the ADT are also being made available through alternative methods such as Web-based applications and the SeaSpace Corporation TeraScan computer environment.

The ADT is also being run locally in a research mode at University of Wisconsin—Madison's Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) in a completely automated environment, for all global TC systems. The real-time ADT intensity estimates are performed at a 30-min or hourly frequency (depending on image acquisition availability), and are accessible from the UW-CIMSS Tropical Cyclone Web site (http://cimss.ssec.wisc.edu/tropic/adt). See Fig. 7 for a graphical example of the CIMSS ADT real-time output. This Web site also contains additional information related to the ADT including the current performance statistics, historical storm listings, users' guides, and various ADT-related scientific articles.

5. Future directions

ADT research efforts have focused on optimizing the use of geostationary satellite infrared imagery in order to provide objective intensity estimates of tropical cyclones. Efforts to improve the ADT using preexisting DT-defined methods will be continue to be explored; however, further research will focus on new image analysis techniques.

While the ADT currently provides forecasters with an objective tool based on IR imagery, the use of supplementary spectral information has the potential to advance satellite-based intensity estimation considerably further than can be achieved with the IR band alone. For example, polar-orbiting microwave sensors are being used to denote TC structure and infer intensity (Herndon and Velden 2004; Demuth et al. 2004; Edson and Lander 2002; Spencer and Braswell 2001; Hawkins et al. 2001; Bankert and Tag 2002). Employment of these instruments and methods in conjunction with the existing ADT into an integrated algorithm (Velden et al. 2004) should provide TC analysts with an even more powerful tool for estimating tropical cyclone intensity.

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