

Development of an Objective Scheme to Estimate Tropical Cyclone Intensity from Digital Geostationary Satellite Infrared Imagery

CHRISTOPHER S. VELDEN AND TIMOTHY L. OLANDER

Cooperative Institute for Meteorological Satellite Studies, Madison, Wisconsin

RAYMOND M. ZEHR

Regional and Mesoscale Meteorology Branch, NOAA/NESDIS, Fort Collins, Colorado

(Manuscript received 17 July 1996, in final form 10 August 1997)

ABSTRACT

The standard method for estimating the intensity of tropical cyclones is based on satellite observations (Dvorak technique) and is utilized operationally by tropical analysis centers around the world. The technique relies on image pattern recognition along with analyst interpretation of empirically based rules regarding the vigor and organization of convection surrounding the storm center. While this method performs well enough in most cases to be employed operationally, there are situations when analyst judgment can lead to discrepancies between different analysis centers estimating the same storm.

In an attempt to eliminate this subjectivity, a computer-based algorithm that operates objectively on digital infrared information has been developed. An original version of this algorithm (engineered primarily by the third author) has been significantly modified and advanced to include selected "Dvorak rules," additional constraints, and a time-averaging scheme. This modified version, the Objective Dvorak Technique (ODT), is applicable to tropical cyclones that have attained tropical storm or hurricane strength.

The performance of the ODT is evaluated on cases from the 1995 and 1996 Atlantic hurricane seasons. Reconnaissance aircraft measurements of minimum surface pressure are used to validate the satellite-based estimates. Statistical analysis indicates the technique to be competitive with, and in some cases superior to, the Dvorak-based intensity estimates produced operationally by satellite analysts from tropical analysis centers. Further analysis reveals situations where the algorithm needs improvement, and directions for future research and modifications are suggested.

1. Introduction

Tropical cyclones (TC) are marine events that are often poorly observed by conventional data sources. Remote sensing from geostationary meteorological satellite platforms is frequently the only method available to determine or estimate TC characteristics. Infrared (IR) imagery is routinely employed in a subjective way to analyze storm position, movement, development, and evolution.

Accurate intensity estimates are of utmost importance for marine warnings and landfall evacuation planning and decision making. The western extent of the Atlantic basin is currently the only region to benefit from routine aircraft reconnaissance flights that can provide detailed observations of TC intensities. The eastern and central Atlantic, as well as other global TC basins, must rely mainly on satellite techniques to estimate TC intensities.

The most widely used satellite technique was developed by Dvorak (1975, 1984). This technique employs image pattern recognition and empirically based rules to derive an estimate of TC intensity in "T numbers." This parameter was developed to be representative of a simple model of hurricane evolution such that T-number increments correspond to typical observed changes in intensity. The T number may be adjusted in certain situations (such as weakening events). Therefore, Dvorak defines the CI (current intensity) number as the final adjusted value, which is related to conventional intensity quantities as shown in Table 1. This relationship (valid for Atlantic TCs) was statistically derived from a large sample of cases when reconnaissance aircraft measurements were available as ground truth. See Dvorak (1975, 1984) for further details on applications of the method.

In certain situations, an image enhancement curve is used with the IR data to isolate discrete temperature levels and derive a T number from a combination of two satellite-measured parameters: the temperature at the storm center (usually a relatively warm eye) and the temperature of the cold convective cloud environment. While this "EIR" (enhanced IR) variation of the stan-

Corresponding author address: Christopher Velden, UW-CIMSS, 1225 West Dayton St., Madison, WI 53706.
E-mail: chrisv@ssec.wisc.edu

TABLE 1. Empirical relationship between the Dvorak CI (current intensity) number, and the maximum surface wind speed (MWS) and the minimum sea level pressure (MSLP) for Atlantic tropical cyclones (from Dvorak 1995).

CI number	MWS (kt)	MSLP (hPa)
1.0	25	
1.5	25	
2.0	30	1009
2.5	35	1005
3.0	45	1000
3.5	55	994
4.0	65	987
4.5	77	979
5.0	90	970
5.5	102	960
6.0	115	948
6.5	127	935
7.0	140	921
7.5	155	906
8.0	170	890

standard technique yields reasonable estimates of intensity in most cases, analyst judgment on pattern or rules interpretation can occasionally lead to discrepancies between different tropical analysis centers estimating the same storm.

To eliminate this subjectivity, a purely objective technique is desirable. The remainder of this article will describe and evaluate a technique that was introduced by Dvorak (1984) and discussed by Zehr (1989). The Objective Dvorak Technique (ODT) utilizes automated computer-based algorithms to objectively identify pattern types, calculate the eye/convection temperatures, apply selected rules, and derive intensity estimates. Several new constraints and important modifications have been incorporated into the original technique evaluated by Zehr (1989).

ODT estimates of minimum sea level pressure (MSLP) were calculated for 10 storms during the 1995 and 1996 Atlantic seasons. Performance comparisons between the original and modified algorithms are first presented. Reconnaissance aircraft measurements of minimum surface pressure are used as validation. The modified ODT estimates are then compared with coincident operational estimates derived from the standard Dvorak method at three independent tropical analysis centers. Despite the fact that Dvorak also developed empirical relationships with maximum surface winds (Table 1), only MSLP is considered in the present evaluation due to ambiguities in reconnaissance reports of maximum winds, and uncertainties in pressure–wind relationships.

2. The Objective Dvorak Technique (ODT)

The concept of using digital IR data was originally proposed by Dvorak (1984). Based on these ideas, a computer-based algorithm was developed by the third author and is contained within Man–Computer Inter-

active Direct Access System (McIDAS) architecture (Santek et al. 1991). It utilizes specific McIDAS functions to read and analyze geostationary satellite IR data, and compute and output an intensity estimate for a targeted tropical cyclone. The technique is not applicable to weak tropical systems such as depressions or minimal tropical storms. The only user input is the specification of the storm center location.

Once the center location is chosen, this basic version of the ODT algorithm proceeds to extract two temperatures from the IR data in order to obtain an intensity estimate (similar to the EIR variation discussed earlier). The ODT first determines the eye temperature of the storm by using the warmest pixel temperature within a 40-km radius of the chosen storm center (warm values represent ocean surface or low cloud within the eye). The methodology for eye temperature determination is justifiable in those cases in which the eye is well defined and large enough to be resolved by the satellite sensors. As will be shown later in the text, when an eye feature is not clearly present such as in a shear environment, the methodology is less reliable. A “no eye” condition can be identified by the ODT during situations of a central dense overcast (CDO), in which the temperatures near the storm center are dominated by cold cloud tops and a warm eye is not resolvable. In these conditions, the value of the pixel at the user-defined storm center location is used as the eye temperature.

The ODT then analyzes temperatures on concentric rings (1 pixel wide) centered on the eye between 24 and 136 km from the eye location (this range was empirically determined by many observations of coldest ring radii). For Geostationary Operational Environmental Satellite (GOES) data with 4-km pixel resolution, this results in a total of 28 rings that are analyzed to determine the “surrounding temperature.” This parameter is a proxy for the vigor of the eyewall convection, which is associated with storm intensity. Stronger eyewall convection is generally associated with colder cloud-top temperatures. In addition, a continuous ring of cold temperatures surrounding the eye is more indicative of an organized (and more intense) storm than one with breaks in the convection. Therefore, the warmest temperature found on each ring is identified and stored, with the coldest of these retained as the final surrounding temperature value. An important note: for ring calculations, the original version of the ODT repositions the storm center at the location of the warmest core temperature in the event an eye is determined to exist. The modified version (discussed later in this section) does not reposition the storm center, since it has been found that the subsequent analysis of the surrounding temperature field may be improperly influenced by this adjustment in some cases (“false” eyes).

After identifying the eye and surrounding temperatures, the basic (original) ODT utilizes a lookup table (Dvorak 1995) to estimate the intensity. This table is based on statistical comparisons with aircraft reports of

intensity that relate the temperatures to tropical cyclone strength estimates in terms of T numbers. The T numbers (and intensity estimates) increase as the eye temperature gets warmer and also as the surrounding temperature gets colder. However, the intensity estimates are much more sensitive to changes in the surrounding temperature than the eye temperature in most conditions.

Selected empirically determined constraints are imposed upon the final derivation of the estimate, such as confining the minimum T number to be no less than 3.5 and limiting the maximum intensity of noneye storms (CDO patterns) to a T number of 5.0. (Given the first constraint, it is emphasized that the ODT should not be used in very weak tropical systems.) In addition, those cases that have a maximum eye temperature less (colder) than the surrounding temperature (e.g., a strongly sheared environment) are automatically set to a T number of 4.5. These constraints are not specific rules within the original Dvorak EIR analysis routine, but are incorporated within the ODT algorithm to closely approximate the intensity values derived with the EIR analysis method. Upon determination of the T-number value (in this application, T number and CI number are considered equal), TC intensity is estimated in terms of MSLP from Table 1.

Modifications to the original ODT algorithm have focused on alleviating certain deficiencies and integrating selected rules of the standard Dvorak scheme. The major change involves the methodology on the derivation of the T number, which in the original version was controlled by the lookup table. This table is replaced with an integration (coded approximation) of the original Dvorak EIR rules for various cloud patterns (Dvorak 1995). Determination of the cloud pattern is performed objectively by examining areal histograms of cloud-top temperatures and corresponding Fourier analysis for the eye region and surrounding cloud region (as defined earlier). Based on this analysis, four scene patterns are categorized: eye, central dense overcast, embedded center, and shear. The initial T number is then based on the scene pattern type and surrounding temperature, with the eye temperature used only in the adjustment of the T number in certain situations (Dvorak 1984).

In very special cases, the surrounding temperature is replaced with the temperature of the histogram bin that contains the maximum number of surrounding cloud-top temperature values. The “peak histogram temperature” is only used if it exceeds an empirically determined threshold (-75°C), the surrounding temperature exceeds -70°C , and the scene pattern type is not classified as a CDO. This modification is introduced in order to emphasize those cases with an eye and a significant amount of very cold surrounding cloud temperatures that are not sufficiently captured by the basic ODT “ring” methodology (which chooses the warmest pixel on each ring).

For example, Hurricane Opal was characterized by

the appearance of *very* cold cloud-top temperatures (rigorous convection), which were highly correlated with a rapid deepening phase of the storm (described further in section 5). These very cold clouds, while a dominant feature, did not completely form a symmetric ring around the eye and were, therefore, ignored by the surrounding ring temperature methodology. This contributed to an underestimation of the strength of the hurricane by the ODT algorithm as it rapidly deepened (the lack of a strong eye feature was the primary factor, as discussed in section 5). Replacing the surrounding temperature with the peak histogram temperature results in an increase of about one T number.

In the 10 storm cases analyzed, this “very cold cloud” characteristic was sufficiently unique to Opal so that the general application of this rule did not appreciably affect the results from the other 9 storms. This signature may be an indicator of rapid deepening associated with an eye contraction cycle, but further cases are necessary to evaluate this hypothesis.

Once the initial T number is determined, a linear-weighted time-averaging scheme is invoked. The scheme weights the current T number with those from the previous 12 h. This time interval was chosen since it was found to most effectively dampen much of the short-term variability observed in successive ODT intensity estimates. Suspected rapid intensity fluctuation situations (i.e., Opal) are given special considerations. The time averaging is discussed further in section 4.

The time-averaged T number is used as the final value for Table 1 unless the storm being analyzed has recently undergone a significant strengthening period and is currently weakening. If this condition is met, an approximation to the Dvorak EIR analysis “step 9” (Dvorak 1984) is invoked, which holds the T number constant for 12 h, then keeps it one full T number higher than the time-averaged value. This value is then used for the final intensity estimate (Table 1) and corresponds to the CI number of the standard Dvorak method. By introducing this modification into the ODT algorithm, the weak bias observed with the original ODT is significantly reduced (section 5).

3. Storm center location

Insight into the sensitivity of the ODT algorithm to the proper selection of the storm center location is examined by considering two methods of determining eye locations. The original ODT was used in this analysis in order to establish a baseline prior to modifications to the algorithm.

The first method resolves the center locations by analyst evaluation of IR imagery, including use of animation and digital enhancements (such as the Dvorak hurricane curve “BD” routinely employed in TC classification). Storm centers are determined independent of outside information such as reconnaissance reports or operational fix locations. This method provides realism

TABLE 2. Evaluation of the sensitivity of storm center location on the ODT intensity (MSLP) estimates. In this evaluation, the original ODT (before subsequent modifications) is employed. Analyst = analyst estimate of storm center based on satellite imagery, and recon. = centering based on interpolated reconnaissance aircraft reports. Bias and rmse statistics (hPa) are based on validation from reconnaissance measurements of MSLP. The statistics represent 127 matches with aircraft reports (within ± 1 h) and the sample is homogeneous for the two methods.

MSLP estimate	Bias	Rmse
ODT-analyst	6.84	15.42
ODT-recon.	6.95	15.30

to the scenario that will be encountered by operational tropical analysis centers that may employ the ODT algorithm.

The second method determines storm center locations exclusively from aircraft reconnaissance reports linearly interpolated from the report times to the image times. This method provides completely independent estimates of storm location for comparison purposes and to assess the effects of analyst center-fixing on the ODT algorithm.

The results of this comparison are shown in Table 2. It is encouraging that the ODT algorithm overall is relatively insensitive to the method of center fixes. The differences in bias and root mean square error (rmse) statistics of MSLP estimates resulting from the two methods are not statistically significant (reconnaissance aircraft reports of MSLP are used as validation). However, an examination of individual cases does reveal a few instances where the ODT intensity estimates were notably different. To fully automate the ODT, it is desirable to develop an objective method to locate or select the storm center, and this will be an area of future research. The analyst-determined storm center locations are used in the remainder of this study.

4. Time averaging

Fluctuations in successive ODT T numbers can occur over short time intervals and can be smoothed through temporal averaging to more effectively estimate real intensity trends. The fluctuations are due to the sensitivity of the algorithm to fleeting variations in the eye and surrounding cloud temperatures. In order to evaluate the optimal time interval to employ, time-averaged values of ODT estimates of MSLP are calculated using the current and previous T numbers over the past 6, 12, and 24 h, respectively. For this study, ODT estimates are only evaluated at 3-h intervals. In practice, ODT estimates will be available more frequently, and this may allow the averaging time interval to be reduced. The dependence of more frequent sampling on the determination of the optimum time averaging interval will be addressed in future research.

Comparisons between the original and time-averaged ODT estimates relative to reconnaissance aircraft vali-

TABLE 3. Comparison of selected time averaging on the performance of the original ODT algorithm. Coincident reconnaissance aircraft reports of MSLP are used for the validation. Bias and rmse are in hPa. The statistics are based on a homogeneous sample of 55, which includes several during Hurricane Opal's rapid deepening cycle.

MSLP estimate	Bias	Rmse
ODT-original method	10.91	17.84
ODT-6-h avg	10.33	15.65
ODT-12-h avg	10.04	14.74
ODT-24-h avg	9.98	15.32
ODT-12-h weighted avg	10.24	15.14

dation are shown in Table 3 (the unmodified version of the ODT was used in this experiment). As expected, the time averaging acts to reduce the variability in the raw ODT estimates and results in a lower overall rmse. The rmse statistics indicate the ODT performance is superior when 12-h time averaging is employed. At longer time intervals, performance begins to decrease as real intensity fluctuations are damped. Based on this result, 12-h averaging is used in the modified version of the ODT.

While the 12-h averaging yields the best overall ODT results, the fact that rapid fluctuations in real intensity (i.e., Opal) will be smoothed and result in the ODT estimates being "behind the curve" is a cause for concern. For this reason, two additional modifications are added. First, the time-averaging scheme weights the current T number to a greater degree (linearly) than the previous estimates over the 12-h interval (i.e., the current T number is weighted 12 times more than the T number from 12 h previous). As indicated in Table 3, this modification results in a compromise between damping short-term observation variance and allowing more observation "freedom" in situations when real rapid intensity fluctuations are suspected. Second, if the satellite temperature data show extremely cold eyewall cloud tops and suggest a rapid deepening event may be under way (as discussed in section 2), the averaging scheme shifts to a 6-h weighted mean. This scheme was tested on Hurricane Opal with satisfying results during the period of rapid intensification (not shown).

5. Evaluation of the ODT performance

Intensity estimates (in terms of MSLP) are derived from both the original and modified versions of the ODT algorithm for selected 1995 and 1996 Atlantic TCs during periods when reconnaissance reports were available for validation. Only strong tropical storms and hurricanes are considered for evaluation since the ODT algorithm does not classify storms weaker than a T number of 3.5 (994 hPa). ODT intensity estimates are derived from consecutive GOES IR images at intervals ranging from 1 to 3 h apart for six storms during the 1995 season (Felix, Iris, Luis, Marilyn, Opal, and Roxanne) and four storms during the 1996 season (Bertha, Edouard, Fran, and Hortense). Intervals of greater than

TABLE 4. Comparison of objective Dvorak techniques to estimate Atlantic TC intensity (MSLP). OODT is the original algorithm, and MODT is the modified version as discussed in the text. The comparison represents 349 matches when a satellite estimate is coincident (within 1 h) with a reconnaissance aircraft report. The bias and rmse are in hPa, and the positive bias indicates the satellite estimates are weaker than the coincident reconnaissance aircraft validation.

MSLP estimate	Bias	Rmse
OODT	5.53	14.86
MODT	0.31	8.31

3 h occur during several storms primarily due to satellite eclipse events between approximately 0400 and 0800 UTC. MSLP estimates from the ODT algorithms are interpolated between the values given in the Dvorak empirical relationship (Table 1) since estimates in tenths of a T number are produced after the time averaging is performed.

a. Algorithm comparison

In order to evaluate the modifications to the ODT discussed above, the original (OODT) and modified (MODT) versions are compared. Bias and rmse of the intensity estimates (MSLP) from each version are calculated for the ensemble of cases from the 10 storms. Coincident (within 1 h) reconnaissance aircraft MSLP reports are used as validation. The results of the comparison are given in Table 4. The statistics in Table 4 include 349 matches between each ODT version (homogeneous match set) and coincident reconnaissance reports. The MODT performance shows a significant reduction in the bias and rmse over the original version. The improvement to the weak bias can be primarily attributed to the incorporation of the Dvorak step 9, which holds the T number up in weakening storms. The reduction in the rmse can be directly attributed to the algorithm modifications and also the time-averaging scheme, which reduces much of the short-term variability.

It is apparent that the modifications to the original ODT have resulted in a significant improvement to the technique. Given the results presented above, the remainder of this article will focus on the performance of the modified algorithm (hereafter, ODT will represent the modified version).

b. Overall performance

It is informative to assess the ODT performance relative to the operational tropical analysis centers (TAC) intensity estimates obtained using the standard Dvorak method. Current intensity values derived operationally were obtained and converted to MSLP in order to provide an independent comparison dataset. The estimates were obtained from three TACs: the Tropical Analysis and Forecast Branch (TAFB) located at the National

TABLE 5. Evaluation of an objective satellite technique to estimate Atlantic TC intensity (MSLP). ODT is the modified Objective Dvorak Technique and TAC is the tropical analysis center's operational estimates based on the standard Dvorak method. The TAC value represents all available reports from the three TACs identified in the text. The comparison represents 346 matches when an ODT estimate and at least one TAC estimate are coincident (within 1 h) with a reconnaissance aircraft report. The bias and rmse are in hPa, and the positive bias indicates that the satellite estimates are weaker than the coincident reconnaissance aircraft validation.

MSLP estimate	Bias	Rmse
TAC (average)	5.91	10.61
ODT	0.33	8.34

Oceanic and Atmospheric Administration/National Centers for Environmental Prediction (NOAA/NCEP) Tropical Prediction Center, the NOAA/National Environmental Satellite, Data and Information Service (NESDIS) Satellite Analysis Branch (SAB), and the U.S. Air Force Global Weather Center (AFGWC).

Direct comparisons between the modified ODT and TAC-derived MSLP estimates are presented in Table 5. As before, the bias and rmse are calculated for the ensemble of cases from 10 storms, using reconnaissance aircraft MSLP reports as validation. Times that have an ODT estimate and at least one TAC estimate coincident (within 1 h) with a reconnaissance report are defined as matches and used in the calculation of the statistics shown in Table 5. In some cases, more than one TAC estimate was available at a given match time, in which case those values are averaged (if different). The statistical analysis includes 346 total matches from the 10 identified storm cases.

The results show that the ODT estimates are slightly superior to the average of the TAC estimates of MSLP in terms of estimate variance (rmse). The operational estimates tend to underestimate MSLP, and the ODT is effective in significantly reducing this bias. The performance is broken down into comparisons between the ODT and the individual TAC in Table 6. It is interesting to note that only the TAFB estimates exhibit a competitive bias compared with the ODT estimates. It is unclear whether the routine availability of reconnais-

TABLE 6. Comparison of the ODT performance relative to individual TAC estimates of Atlantic TC intensity (MSLP). Each comparison is a homogeneous sample, and coincident (within 1 h) reconnaissance aircraft reports of MSLP are used for validation. Bias and rmse are in hPa.

MSLP estimate	Bias	Rmse	No. of matches
TAFB	2.73	9.52	158
ODT	0.67	8.04	158
SAB	6.16	10.73	274
ODT	0.46	8.45	274
AFGWC	8.24	12.87	119
ODT	-0.45	8.99	119

TABLE 7. Comparison of TAC estimates of MSLP when reports from all three TACs were available at the same time. The homogeneous sample represents 33 matches. Coincident (within 1 h) reconnaissance aircraft reports are used as validation. Bias and rmse are in hPa.

MSLP estimate	Bias	Rmse
TAFB	3.12	11.96
SAB	8.00	13.80
AFGWC	9.33	14.09
ODT	0.07	11.45

sance aircraft reports in real time at the collocated Tropical Prediction Center may have influenced the TAFB operational estimates.

A further comparison indicates the degree of subjectivity in the application of the standard Dvorak technique by the TAC. Table 7 shows the statistics for a homogeneous sample when all three TAC estimates were available and coincident with ODT and reconnaissance reports. The sample size is small (33 com-

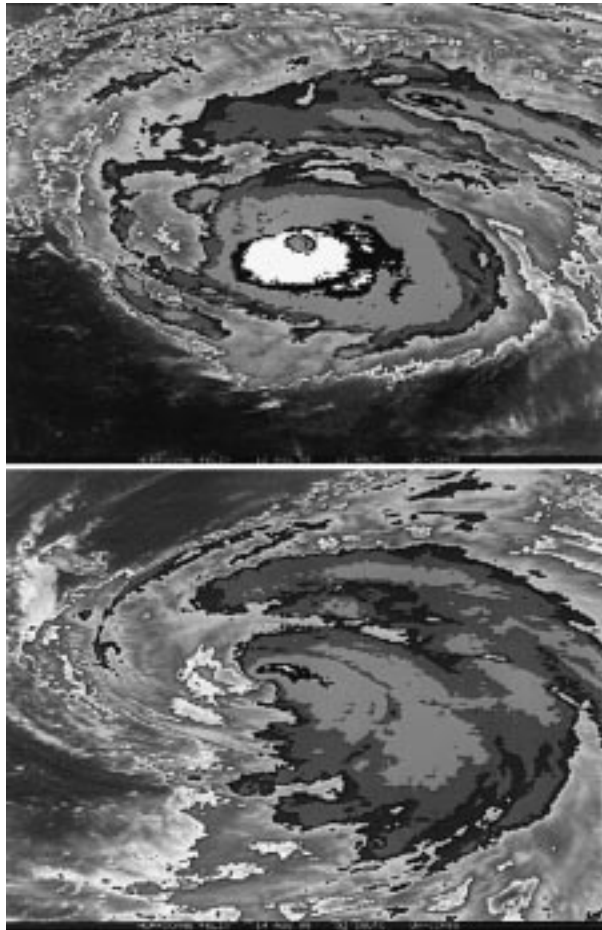


FIG. 1. GOES-8 IR imagery during Hurricane Felix. (top) Good eye pattern at 1200 UTC 12 August 1995; (bottom) shear pattern at 0300 UTC 14 August 1995. The Dvorak enhancement curve (BD) has been applied.

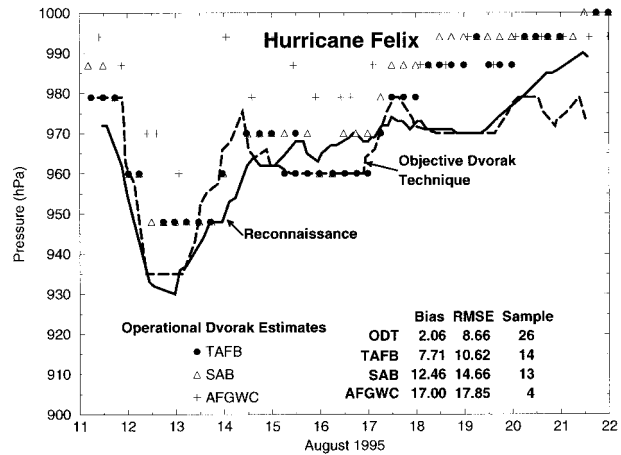


FIG. 2. Performance of the Objective Dvorak Technique (ODT) algorithm during Hurricane Felix in August 1995. Minimum sea level pressure estimates are graphed by interpolating ODT values (usually at 1–3-h intervals). Reconnaissance aircraft measurements are drawn in a similar manner for comparison. Operational Dvorak estimates are plotted, with the symbols indicating the tropical analysis center responsible for the estimate. The performance statistics for the storm (relative to the aircraft validation) are indicated on the figure, in hPa. “Sample” refers to those estimates from the ODT and TAC that were considered for the statistics (aircraft report within ± 1 h).

parisons) but the subjectivity in the standard Dvorak method is evidenced by the range in the statistics between individual TACs. Further examples of this subjectivity will be presented in the individual storm cases discussed below.

c. Individual storms

The performance of the ODT algorithm in certain situations can be characterized by examining estimate tendencies during the individual Atlantic storms considered in our study. The 10 storms in our sample from 1995 to 1996 represent a wide range of intensities, trends, and environmental conditions. For each storm, the ODT intensity estimates are compared to reconnaissance aircraft reports and trends, as well as the TAC operational estimates produced from the standard Dvorak method. In the graphs provided, note the frequent disagreement between estimates from the three TACs. A summary of the identified ODT performance characteristics is given in section 6.

1) HURRICANE FELIX

During the period of investigation, Felix initially possesses a well-defined eye that rapidly degrades as the storm encounters a strong shear environment (Fig. 1). As shown in Fig. 2, the ODT provides an accurate intensity estimate the majority of the time but weakens Felix too rapidly as the center is sheared (13–14 August). A significant portion of the statistical error with the ODT method in Felix can be accounted for during

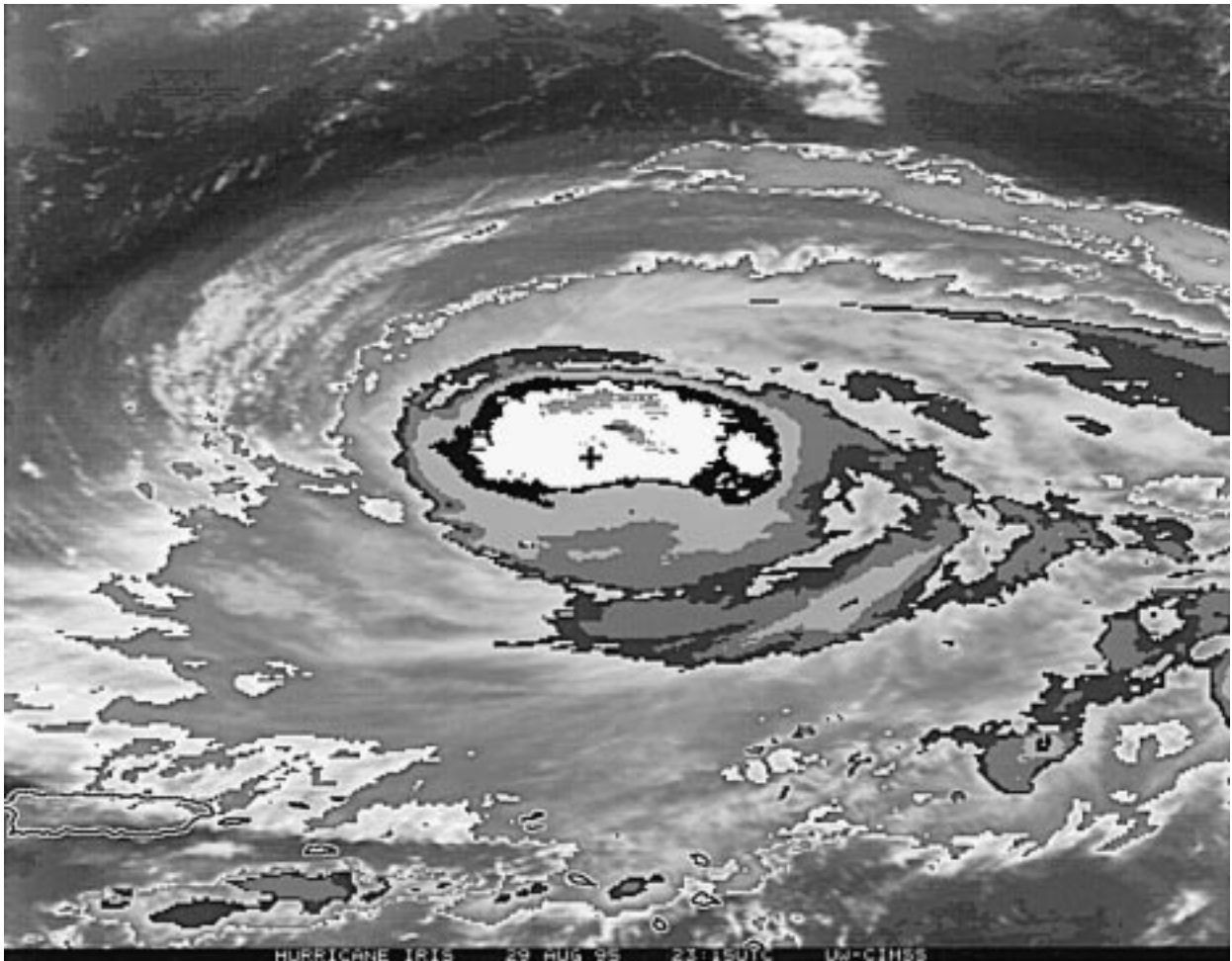


FIG. 3. GOES-8 enhanced (BD curve) IR image during Hurricane Iris at 2300 UTC 29 August 1995. The “+” indicates the storm center in the central dense overcast (CDO) as located by reconnaissance aircraft.

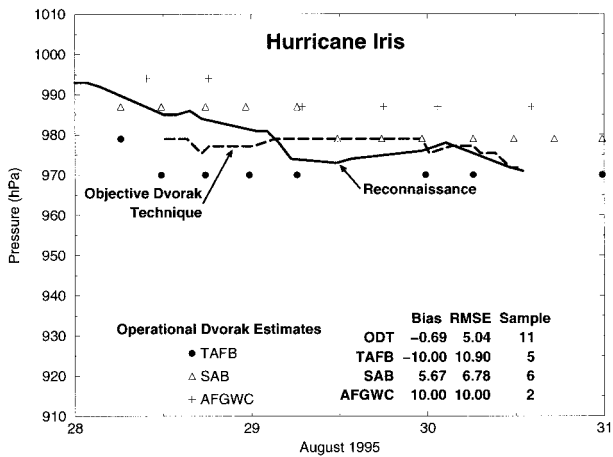


FIG. 4. Same as Fig. 2 except for Hurricane Iris in August 1995.

this shear-type pattern. The TACs generally underestimate the intensity of Felix, and over the latter part of the period, the ODT estimates are remarkably superior. In addition, the ODT provides the only estimates close to the reconnaissance reports during Felix’s maximum intensity on 12 August. There is fairly good agreement between the estimates from TAFB and SAB in the first half of the period but some disagreement thereafter. The estimates from AFGWC are consistently much too weak.

2) HURRICANE IRIS

Reconnaissance aircraft reports were collected during a period when Iris had weakened considerably from an earlier intense state. During this period, Iris is dominated by a CDO shown in Fig. 3. In these situations, the ODT algorithm identifies the CDO pattern and implements the appropriate approximation to the standard Dvorak rules for this condition. As indicated in Fig. 4, the ODT intensity estimates closely match the reconnaissance air-

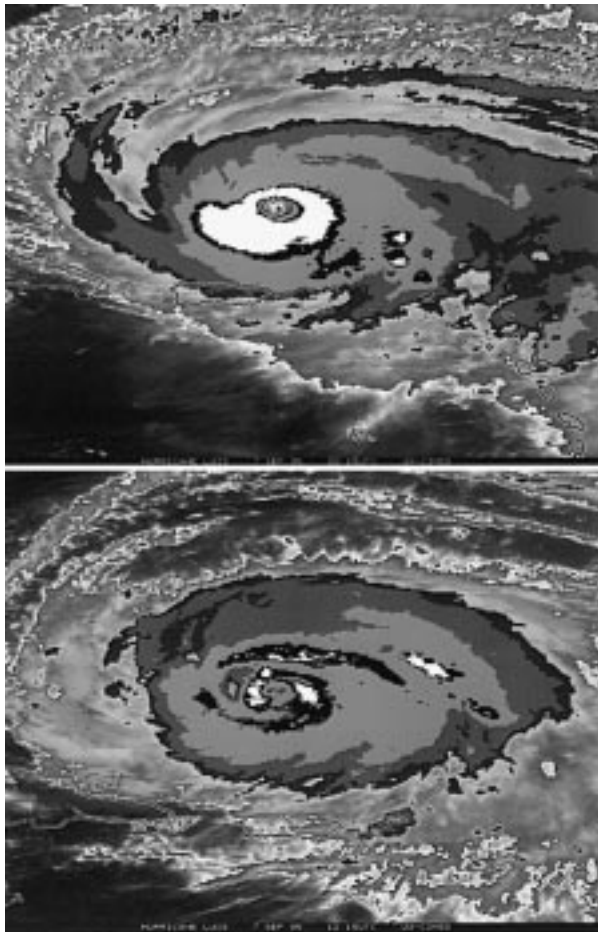


FIG. 5. GOES-8 enhanced (BD curve) IR imagery during Hurricane Luis on 7 September 1995. (top) Good eye pattern at 0000 UTC; (bottom) rapidly deteriorating structure at 1200 UTC.

craft MSLP, except for a tendency to slightly overestimate early in the period. Note the discrepancies between the operational estimates from the TAC. During the first half of the period, TAC intensity estimates are as much as 1.5 T numbers apart (25 hPa). The ODT tends to split the difference in this case, and the result is a superior performance relative to the TAC.

3) HURRICANE LUIS

Hurricane Luis begins the period of investigation with a very large, well-defined eye surrounded by strong (cold) convection. This signature rapidly deteriorates on 7 September (Fig. 5). The ODT estimates respond to the convective collapse by decreasing the intensity after this time (Fig. 6). This represents an intriguing case, since the cause of the rapid collapse of the surrounding convective signature is unclear. This signature is common with landfalling storms; however, Luis was not near any major landmass at the time of the collapse. Special Sensor Microwave/Imager (SSM/I) images indicate that a possible concentric eye structure was present prior to

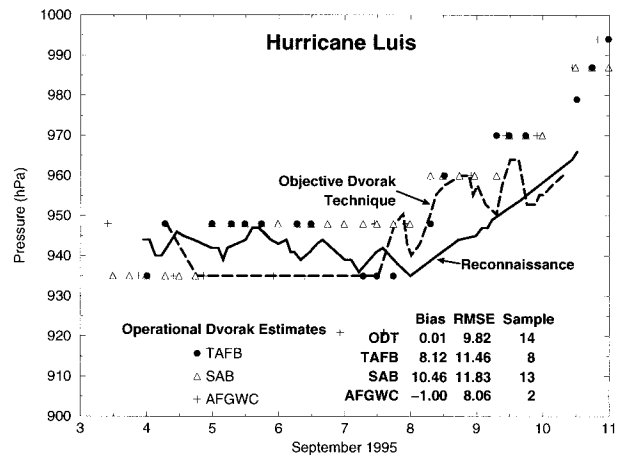


FIG. 6. Same as Fig. 2 except for Hurricane Luis in September 1995.

the collapse, but the implications of this feature are uncertain at this time.

The relatively slow decrease in intensity measured by aircraft reports following the rapid convective collapse violates one of the fundamental principles on which the ODT is based: the rigor of the surrounding convection is related to intensity. The ODT algorithm attempts to account for this phenomena by including the Dvorak rule described previously, which limits the decrease in CI number during weakening stages (step 9). Without such a constraint, the ODT underestimates would be much greater than shown in Fig. 6.

The SAB and TAFB estimates are generally too weak during the entire period, while the AFGWC bias is negligible. However, AFGWC incorrectly estimates Luis at 920 hPa on 7 September. The ODT exhibits a flat intensity estimation trace from 5 to 7 September, in which the intensity values are held down by the step 9 constraint invoked on 4 September after an earlier period of deepening (not shown). The SAB and TAFB estimates are also constant during this period, although most of the estimates are a half of a T number lower than the ODT.

4) HURRICANE MARILYN

The evaluation of the ODT during Hurricane Marilyn covers a period of steady intensification followed by steady weakening (Fig. 7). The ODT estimates are quite close to reconnaissance aircraft reports during the period when Marilyn is characterized by a well-defined eye (Fig. 8). A majority of the ODT statistical error can be accounted for during the weakening period after the eye has filled. In this particular case, the application of the Dvorak step 9 results in the ODT overestimating the storm intensity during this period. Overall, the TAC estimates using the standard Dvorak method are exceptionally good (Fig. 7). However, only AFGWC accu-

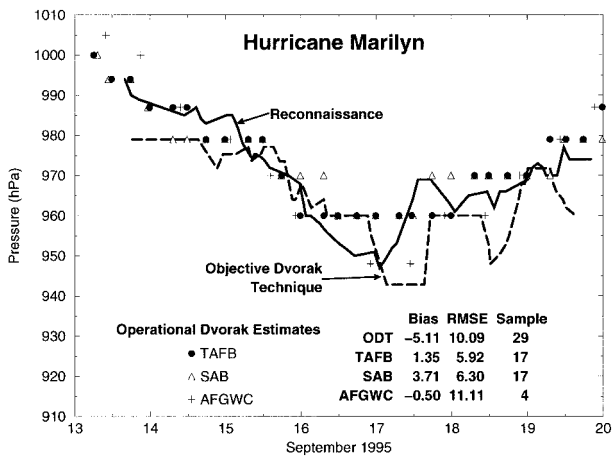


FIG. 7. Same as Fig. 2 except for Hurricane Marilyn in September 1995.

rately estimates the 948-hPa minimum pressure at 0000 UTC 17 September.

5) HURRICANE OPAL

Hurricane Opal is an example of dramatic development. During the period of rapid intensification, reconnaissance aircraft reports indicate an MSLP drop of 35 hPa in only 6 h. A small “pinhole eye” can be observed through the CDO in the GOES satellite IR imagery at the time of rapid deepening (warm spot in Fig. 9), but this eye signature is not large or warm enough to allow the ODT to properly estimate the intensity. Figure 10 shows that both the ODT and TAC intensity estimates are considerably weaker than reconnaissance aircraft measurements during this period.

The curve in Fig. 10 clearly shows the MSLP estimates by the ODT algorithm during Opal’s peak intensity are too weak. One factor contributing to this is the lack of imagery during the time of rapid intensification on 4 October (0400–0800 UTC). This data void is due

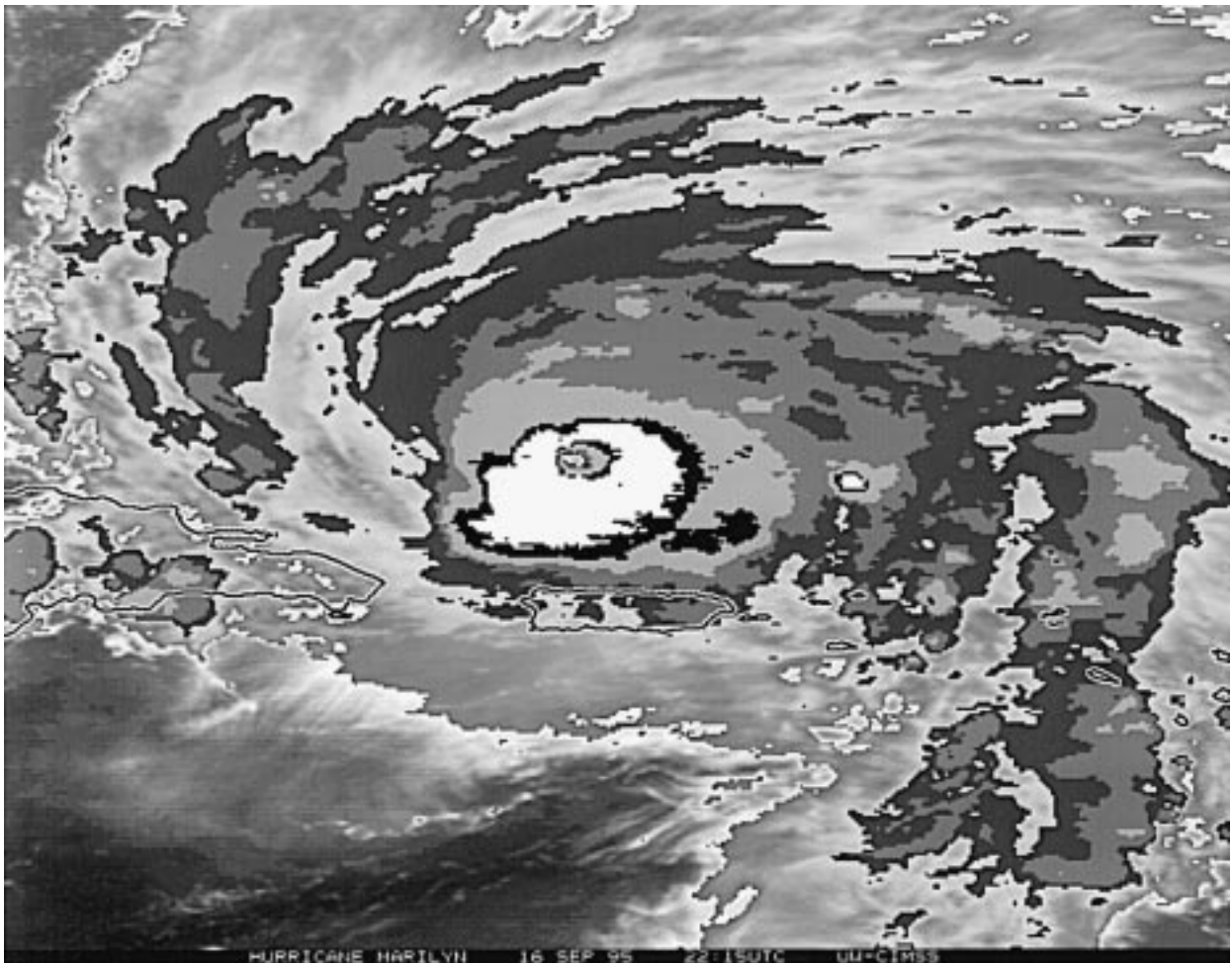


FIG. 8. GOES-8 enhanced (BD curve) IR image during Hurricane Marilyn at 2200 UTC 16 September 1995.

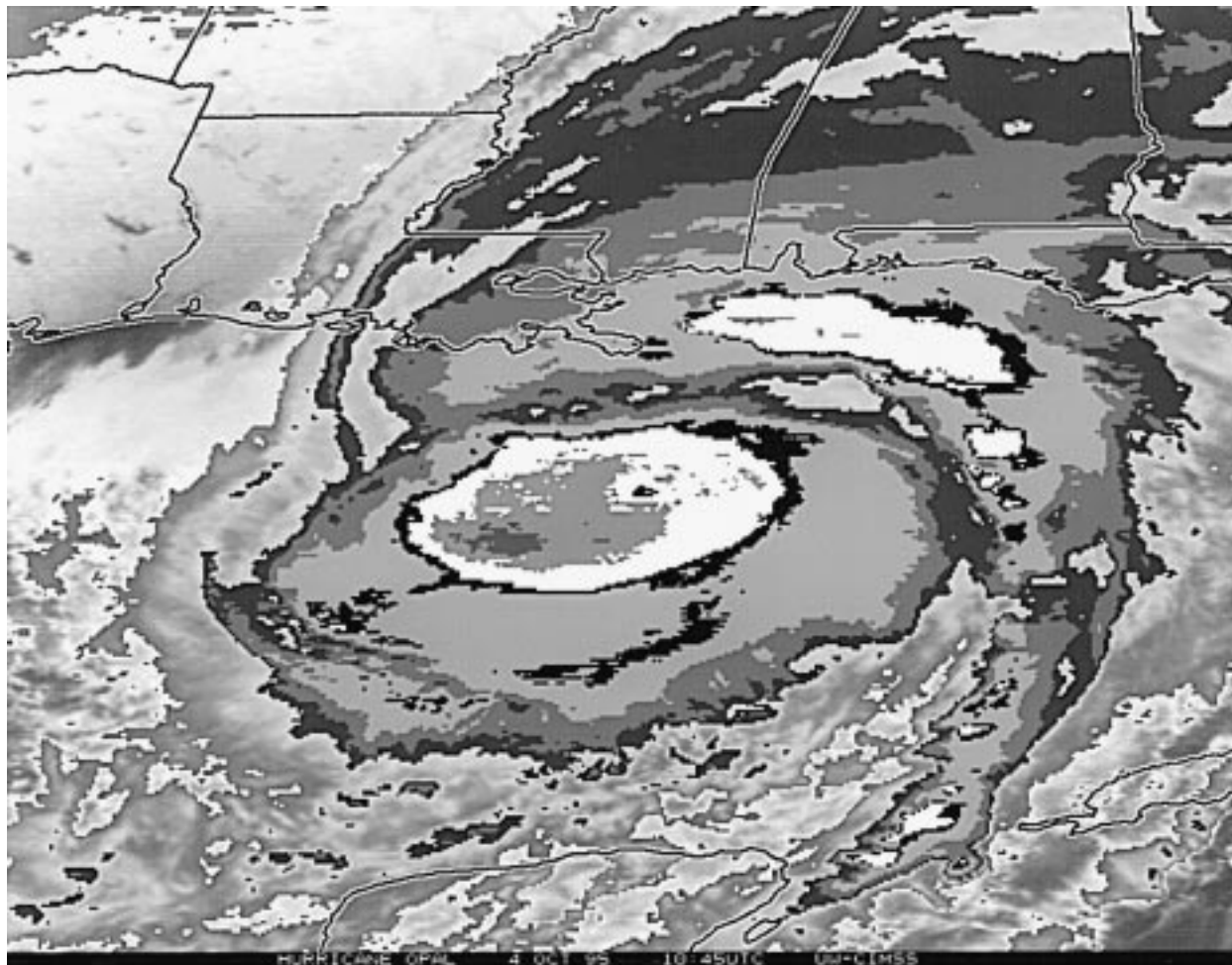


FIG. 9. *GOES-8* enhanced (BD curve) IR image during Hurricane Opal at 1100 UTC 4 October 1995. The extremely small “pinhole eye” is indicated by the black spot near the middle of the cold (white) overcast.

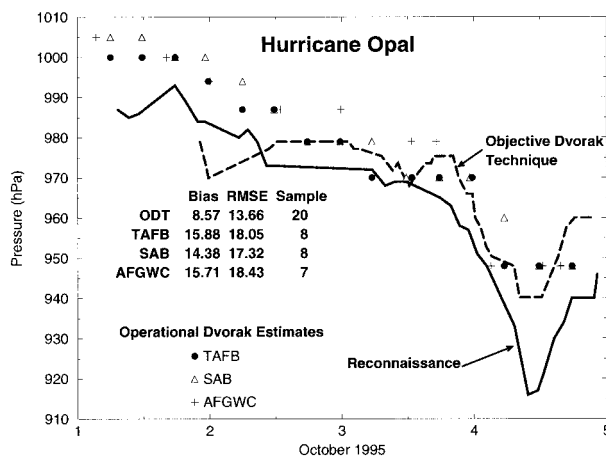


FIG. 10. Same as Fig. 2 except for Hurricane Opal in October 1995.

to the fact that *GOES-8* entered a satellite eclipse period in which no data can be taken/transmitted.

Outside of the eclipse period, the estimates are limited by the inability to resolve the pinhole eye (reported as small as 8 km in diameter by aircraft). This limitation is due to a combination of pixel horizontal resolution (4 km) and scanning geometry. The satellite-measured eye temperature is too cold given the scan angle and the small size of the eye, which collectively prohibits a clear view to the surface. Instead, the radiative signal likely includes contributions from the inner eyewall. Since the highest possible *GOES-8* pixel resolution was used in this study, such cases will be difficult to resolve unless the ODT scheme is further modified to lessen the dependence on the eye temperature parameter.

The time-averaging scheme employed to adjust the final ODT estimates also contributes to the underestimation during the rapid deepening. Our experience with the ODT estimates indicate that some form of time averaging is necessary. As mentioned in section 4, a modification has been introduced to curtail the time aver-

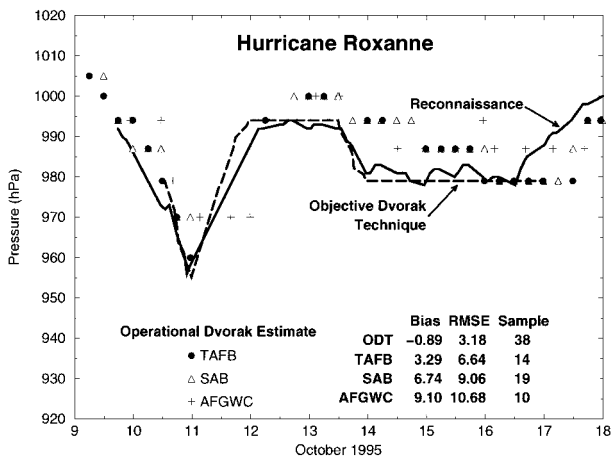


FIG. 11. Same as Fig. 2 except for Hurricane Roxanne in October 1995.

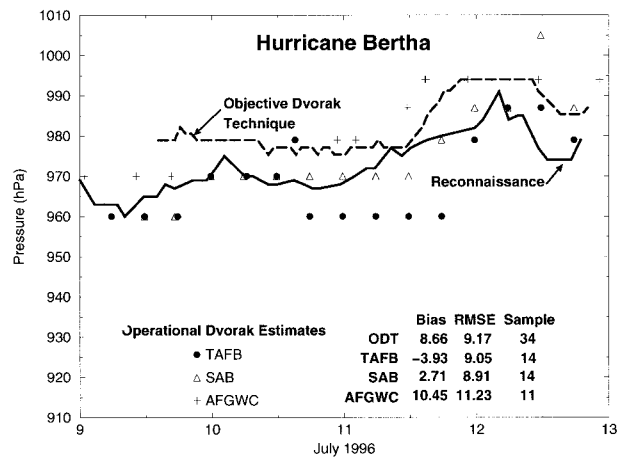


FIG. 12. Same as Fig. 2 except for Hurricane Bertha in July 1996.

aging interval to 6 h for cases like Opal in which rapid deepening is suggested in the satellite temperature measurements (section 2). However, even this modification may not be sufficient in extreme events such as Opal, and this will be an area of future research.

Despite the weak bias during Opal's peak intensity, the ODT does outperform the TAC estimates by a considerable margin during Opal.

6) HURRICANE ROXANNE

Hurricane Roxanne intensified rapidly as it approached the Yucatan Peninsula, then quickly weakened as it passed over land. After reemerging over the Gulf of Mexico, Roxanne reintensified slightly before eventually dissipating. Overall, the ODT accurately estimates the intensity of Roxanne throughout the investigated period (Fig. 11).

The TAC estimates in general match the observed intensity fluctuation trends throughout the investigation period. However, as characterized in many other storms investigated in this study, they generally underestimate the strength of the storm.

7) HURRICANE BERTHA

Analysis of Hurricane Bertha begins during the period of eye degeneration after the storm's initial strengthening period. Note the disparity (up to 34 hPa) between TAC estimates for this case (Fig. 12). Intensity estimates by the ODT generally underestimate the strength of the storm, particularly during 11–12 July as Bertha encounters a shear environment (Fig. 13). This characteristic is consistent with the analysis of Hurricane Felix described earlier. It is clear that the current methodology must be improved to handle the shear cases, as the Dvorak rules implemented into the ODT allow only for very limited analysis/adjustment in these situations.

8) HURRICANE EDOUARD

Distinct intensity fluctuations characterize Hurricane Edouard during the period of investigation. Overall, the ODT performs well throughout the analysis period (Fig. 14). An exception occurs on 27–28 August during a period of weakening. The ODT captures the general intensity trend but overestimates the actual values. This overestimate can be primarily attributed to the application of step 9. In this particular case, the adjustment is excessive due to the reemergence of an eye (and hence higher T numbers) during the period. Once the eye fills late on 28 August, the ODT intensity estimates return to more comparable values with reconnaissance reports.

TAC intensity estimates are again too weak. Particularly during the weakening stage of Hurricane Edouard from 31 August to 2 September, the TAC estimates run as much as 25 hPa too high.

9) HURRICANE FRAN

The early portion of the period of investigation during Hurricane Fran is dominated by a CDO environment (Fig. 15). Intensity values obtained with the ODT during this period are relatively constant despite a slow intensification reported by reconnaissance aircraft (Fig. 16). The onset of Fran's significant strengthening on 3 September is clearly captured by the ODT, as is the intensity trend for the next 2 days. However, there is a notable lag in the ODT curve that may be partially attributed to the time averaging. In this case the temperature data do not clearly indicate a rapid deepening signature (as in Opal). Therefore the time-averaging interval was kept at 12 h.

Intensity estimates from SAB are exceptional for Fran. However, both SAB and AFGWC (TAFB estimates were not available) do not capture the full strength of Fran on 4–5 September. Differences between the ODT and SAB performance can be primarily attributed to the period of storm organization on 30–31 August.

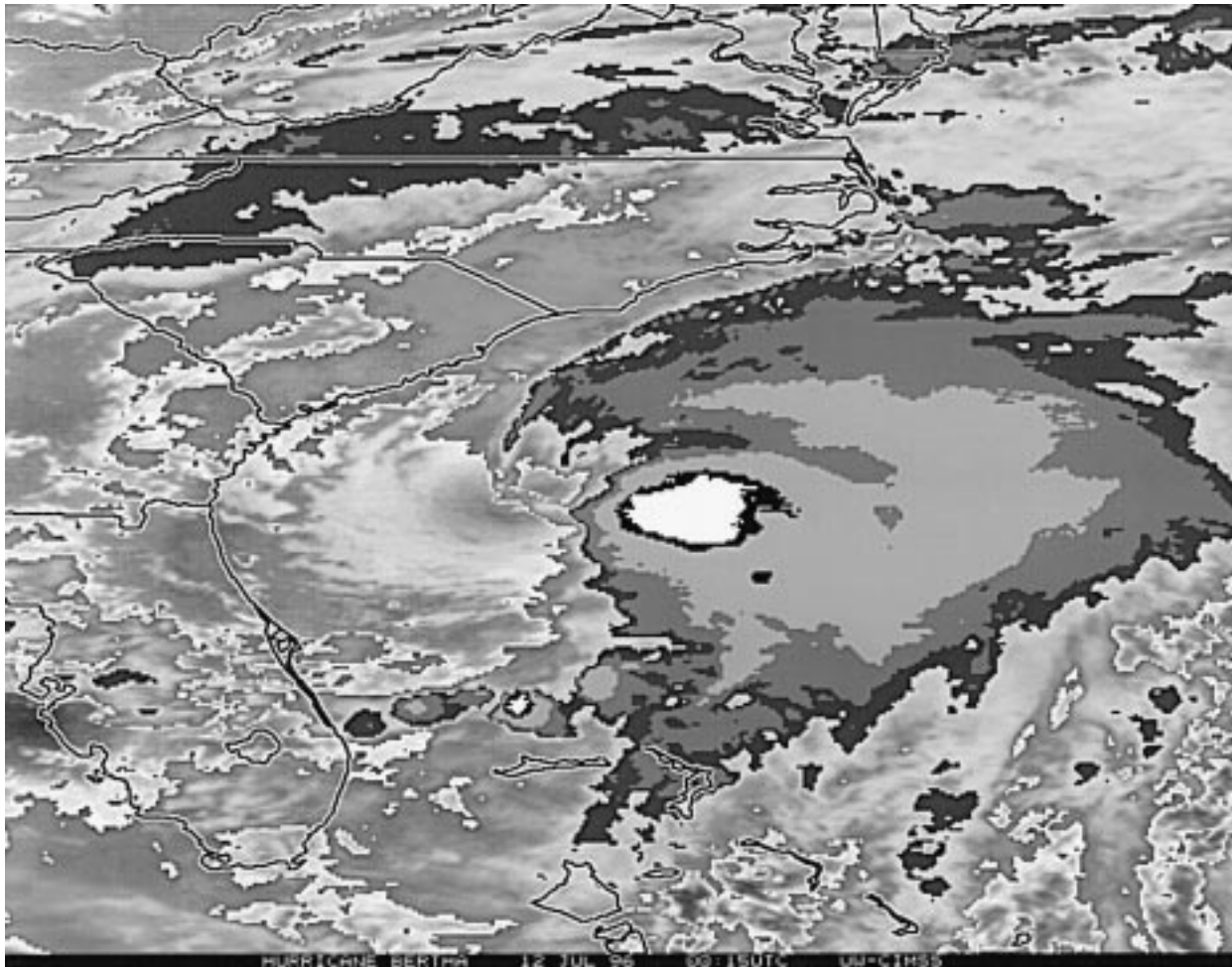


FIG. 13. GOES-8 enhanced (BD curve) IR image during Hurricane Bertha at 0000 UTC 12 July 1996.

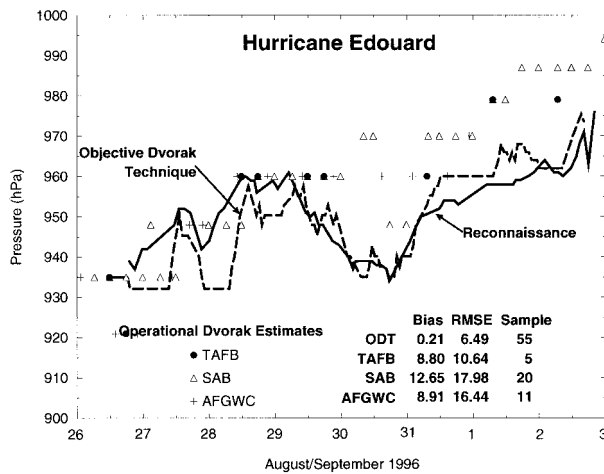


FIG. 14. Same as Fig. 2 except for Hurricane Edouard in August/September 1996.

During this period, the SAB estimates are generally in agreement with the reconnaissance values, while the ODT estimates are too strong. As mentioned earlier, Fran was identified as a CDO pattern storm at this time. The tendency for the ODT to overestimate intensity in these conditions, also characterized in other cases, is an important limitation that must be resolved in future research.

10) HURRICANE HORTENSE

ODT intensity estimates during the intensification and subsequent weakening periods of Hurricane Hortense are exceptionally close to those recorded by the reconnaissance aircraft reports (Fig. 17). However, the bulk of the ODT error can be accounted for during the period of storm organization (8–11 September). As in previous cases, a CDO pattern is identified throughout this period, and the ODT consistently overestimates the intensity. The TAC estimates are far superior in resolving the intensity during this period and, in general, perform well during Hortense.

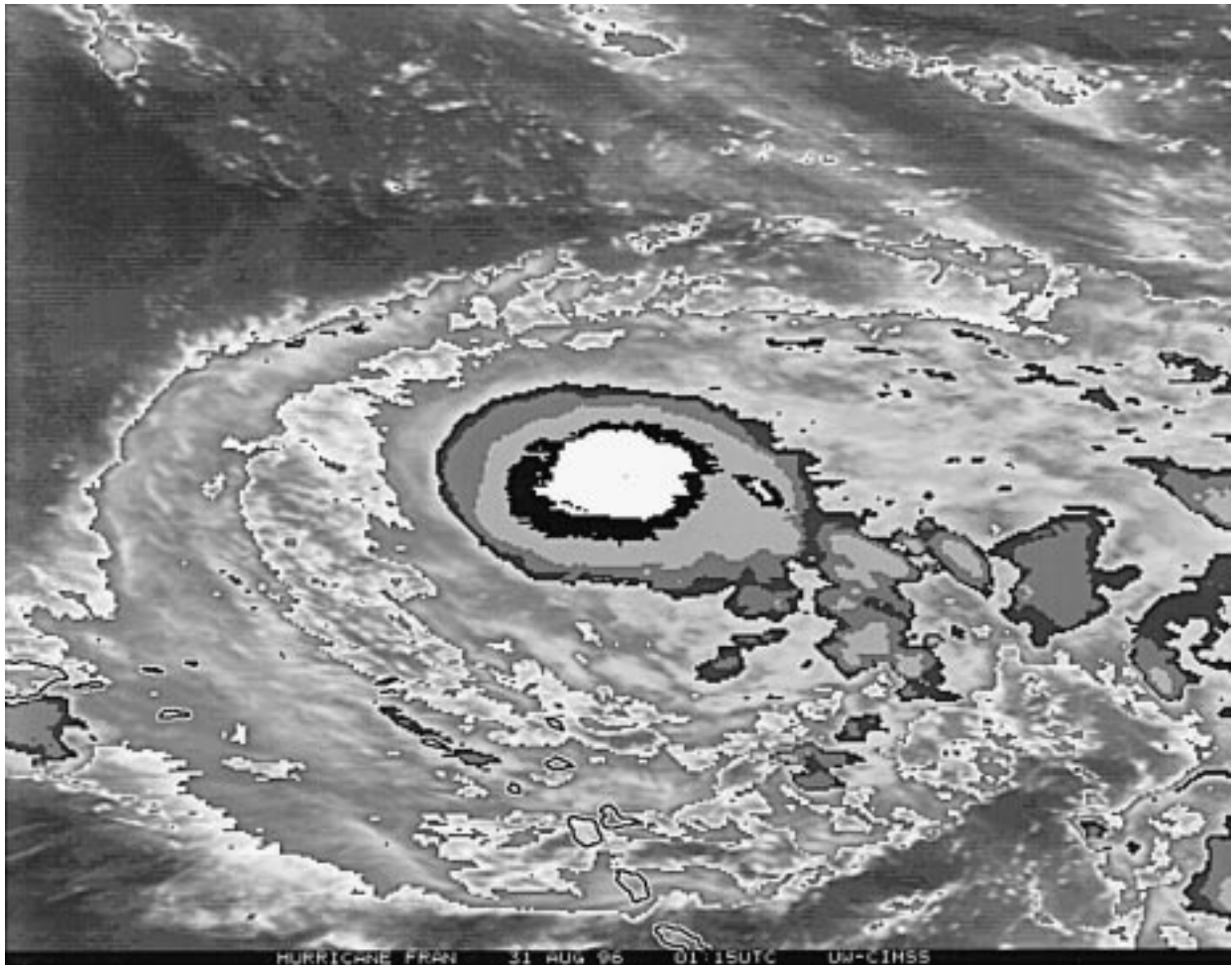


FIG. 15. GOES-8 enhanced (BD curve) IR image for Hurricane Fran at 0100 UTC 31 August 1996.

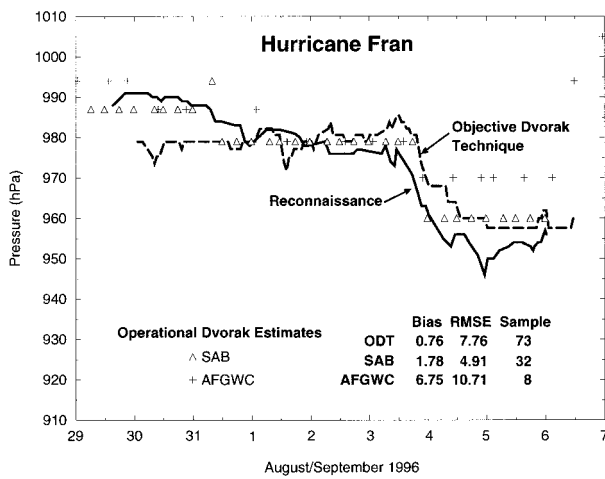


FIG. 16. Same as Fig. 2 except for Hurricane Fran in August/September 1996.

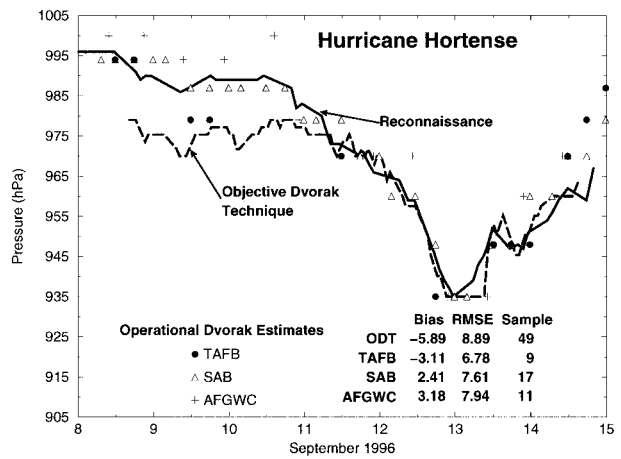


FIG. 17. Same as Fig. 2 except for Hurricane Hortense in September 1996.

6. Summary

A computer-based objective Dvorak technique designed to estimate tropical cyclone intensity from satellite IR observations was developed in order to eliminate subjectivity resulting from analyst interpretation of the standard Dvorak methodology. An original version of the ODT algorithm, primarily developed by the third author, was modified in this study to incorporate more of the rules and adjustments from the basic Dvorak method. In addition, the modified algorithm includes several new constraints and time averaging of consecutive estimates. When evaluated against reconnaissance aircraft reports of intensity (MSLP), it is found that the modifications result in a significant improvement to the ODT performance.

The modified ODT was evaluated on 10 Atlantic tropical cyclones during 1995–96 and determined to perform well under most conditions (the ODT is not applicable to tropical depressions or weak tropical storms). Overall, for a sample of 346 estimates of MSLP evaluated against reconnaissance aircraft reports, the ODT exhibits a negligible bias of 0.33 hPa and an rmse of 8.34 hPa. Coincident operational estimates by tropical analysis centers using the standard Dvorak method (taken as an average of estimates from the three TAC during the same 346 cases) overall are weaker than the ODT estimates with a slightly higher variance.

The specific findings of this paper are summarized as follows.

- 1) There can be considerable variability (subjectivity) between the operational intensity estimates from different tropical analysis centers that employ the standard Dvorak method.
- 2) The ODT is competitive with or slightly superior to the operational standard Dvorak method estimates of tropical cyclone intensity (MSLP) in terms of overall mean error (bias) and variance (rmse).
- 3) ODT-estimated intensities of tropical cyclones exhibiting a well-defined eye and surrounding eyewall structure are typically accurate (within ± 5 hPa).
- 4) The ODT performs well in most cases, but is less reliable in certain identifiable situations:
 - Estimates are generally too strong in central dense overcast (CDO) situations.
 - Estimates are too weak in strong shear and pinhole eye situations.
 - Some uncertainty in the application of Dvorak step 9 during weakening stages.
 - During rapid intensity fluctuations, ODT estimate trends may be damped somewhat due to the introduction of time averaging.

The primary purpose of this article was to evaluate and document the performance of the modified ODT and assess the potential for operational use. The results indicate that the initial goal of objectively simulating the standard Dvorak technique has been met. The pre-

liminary findings are encouraging, but additional cases need to be examined. At the time of writing, an operational trial was planned for the 1997 Atlantic hurricane season (in collaboration with TAFB and SAB).

Further modifications will be necessary in order to correct for the deficiencies that still exist in the ODT estimates. Directions of future research will include the introduction of a symmetry term into the ODT determination of the surrounding convective cloud parameter. Principle component analysis of image scenes will also be investigated as a potential pattern identification advancement (to address the CDO and shear pattern problems). Can we extend the ODT applications to weaker storms with T numbers < 3.5 ? Could artificial intelligence methods (such as neural networks) be used to better identify scene patterns, especially before an eye/eyewall has been established?

Further modification of the ODT algorithm will occur through empirical adjustments to situations of eye obscuration or rapid structure deterioration. Decreasing the dependence of the intensity estimate on the eye temperature may address the pinhole eye and viewing angle problems. Other future directions include the following.

- 1) Further investigation of rapid deepening events toward improving the ODT analysis (i.e., data signatures, optimization/elimination of time averaging).
- 2) Satellite data fusion: For example, uncertainties in eye position or storm structure in some cases may be reduced by incorporation of SSM/I microwave information (Velden et al. 1989). Also, utilization of other available geostationary satellite data in conjunction with the current IR analysis (i.e., visible and water vapor channel information) will be investigated.
- 3) Development of an objective storm center location routine to fully automate the ODT.
- 4) Investigation of modifications necessary for subtropical systems or hurricanes undergoing extratropical transition. Also, applications of the ODT to tropical cyclones in other basins (can the ODT be universally applied or are empirical adjustments necessary in each TC basin?).

5) Introduction of an objective TC intensity forecast routine into the ODT algorithm to provide intensity forecasts at various intervals out to 24 h. This will be designed to primarily follow the standard Dvorak forecast formulas (Dvorak 1995) but will incorporate additional predictors as determined through future research.

In regard to point 4, it should be emphasized that the current version of the ODT was empirically tuned on Atlantic cases. The performance evaluation documented in this article is valid only for Atlantic tropical cyclones. Applications to other tropical cyclone basins (i.e., western North Pacific) is being investigated.

The original version of the ODT algorithm is mechanically quite simple, and the additions/modifications outlined in this article have produced significant improvements. The ODT has been shown to be competitive with, and in some cases superior to, the more subjective

Dvorak method currently applied at operational tropical analysis centers. The future research directives will examine more cases and address some of the documented limitations that will hopefully lead to further gains in ODT performance. The reconnaissance aircraft data were critical to the development and evaluation of this satellite-based technique. The ODT should not be viewed as a replacement for the valuable in situ data collected by these reconnaissance missions. The goal is to provide consistently reliable satellite-based intensity estimates that can be used as objective guidance by tropical analysis centers and augment in situ reports when they are available.

Acknowledgments. The authors would like to acknowledge the contributions of Deb Molenaar (NOAA/NESDIS/RAMMB) toward the coding of the original ODT algorithm. Thanks go to Brian Maher, Steve Lyons, and Richard Pasch of NCEP/TPC for providing the aircraft and TAC data, and Jeff Hawkins (NRL/MRY) for input to the project, which is being supported by NRL Contract N00014-95-C-6017 (ONR PE 0603207N and SPAWAR PMW-185 PE 060320N). Appreciation is

extended to the U.S. Air Force and the NOAA AOML/HRD for providing the critical recon information needed to evaluate the technique described.

REFERENCES

- Dvorak, V., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, 420–430.
- , 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 47 pp. [Available from NOAA/NESDIS, 5200 Auth Rd., Washington, DC 20233.]
- , 1995: Tropical clouds and cloud systems observed in satellite imagery: Tropical cyclones. Workbook Vol. 2. [Available from NOAA/NESDIS, 5200 Auth Rd., Washington, DC 20233.]
- Santek, D., T. Whittaker, J. T. Young, and W. Hibbard, 1991: The implementation plan for McIDAS-AIX. Preprints, *Seventh Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, New Orleans, LA., Amer. Meteor. Soc., 177–179.
- Velden, C. S., W. S. Olson, and B. A. Roth, 1989: Tropical cyclone center-fixing using DMSP SSM/I data. Preprints, *Fourth Conf. on Satellite Meteorology*, San Diego, CA, Amer. Meteor. Soc., J36–J39.
- Zehr, R., 1989: Improving objective satellite estimates of tropical cyclone intensity. *Extended abstracts, 18th Conf. on Hurricanes and Tropical Meteorology*, San Diego, CA, Amer. Meteor. Soc., J25–J28.