

**NOAA NESDIS
CENTER for SATELLITE APPLICATIONS and
RESEARCH**

**GOES-R Advanced Baseline Imager
(ABI) Algorithm Theoretical Basis
Document
For
Hurricane Intensity**

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Version 2.0
September 15, 2010

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LIST OF ACRONYMS

ABI	- Advanced Baseline Imager
ADRS	- Ancillary Data Relay System
ADT	- Advanced Dvorak Technique
AIT	- Algorithm Implementation Team
AODT	- Advanced Objective Dvorak Technique
ASCII	- American Standard Code for Information Interchange
ATBD	- Algorithm Theoretical Basis Document
ATCF	- Automated Tropical Cyclone Forecasting system
AVHRR	- Advanced Very High Resolution Radiometer
AWG	- Algorithm Working Group
BD	- Basic Dvorak
CDO	- Central Dense Overcast
CDR	- Critical Design Review
CI	- Current Intensity
CIMSS	- Cooperative Institute for Meteorological Satellite Studies
CIRA	- Cooperative Institute for Research in the Atmosphere
CPHC	- Central Pacific Hurricane Center
CRT	- Cloud Region Temperature
CWRN	- Coldest-Warmest Ring Number
EIR	- Enhanced Infrared
ERT	- Eye Region Temperature
F&PS	- Functional and Performance Specifications
FFT	- Fast Fourier Transform
GEOCAT	- Geostationary Cloud Algorithm Testbed
GNU	- GNU's Not UNIX
GOES	- Geostationary Operational Environmental Satellite
GS	- Ground Segment
HIE	- Hurricane Intensity Estimation
JTWC	- Joint Typhoon Warning Center
MODIS	- Moderate Resolution Imaging Spectroradiometer
MRD	- Mission Requirements Document
MSG	- Meteosat Second Generation
MSLP	- Mean Sea Level Pressure
NHC	- National Hurricane Center
NOAA	- National Oceanic and Atmospheric Administration
ODT	- Objective Dvorak Technique
PORD	- Performance and Operational Requirements Document
RF	- Ring Fitting
RMSE	- Root Mean Squared Error
RMW	- Radius of Maximum Wind
RSMC	- Regional Specialized Meteorological Center
SABI	- Simulate ABI
SC	- Spiral Centering
SDT	- Subjective Dvorak Technique

SEVIRI	- Spinning Enhanced Visible and Infrared Imager
STAR	- Center for Satellite Applications and Research
TC	- Tropical Cyclone
TCFC	- Tropical Cyclone Forecast Center
TRR	- Test Readiness Review
USGS	- United States Geological Survey
UTC	- Universal Time Coordinates
UW	- University of Wisconsin
VAGL	- Vendor Allocated Ground Latency
WMO	- World Meteorological Organization

Abstract

This document is the Algorithm Theoretical Basis Document (ATBD) for the Hurricane Intensity Estimation (HIE) algorithm. It provides a description and the physical basis for the estimation of tropical cyclone intensity using infrared (IR) temperature values measured by the Advanced Baseline Imager (ABI) to be flown on the next generation of Geostationary Operational Environmental Satellite (GOES-R). The HIE has its origins with the Advanced Dvorak Technique (ADT) algorithm that is currently utilized operationally at several tropical cyclone forecast centers worldwide. This document contains a description of the algorithm, including scientific aspects and practical considerations.

1 INTRODUCTION

1.1 Purpose of This Document

The Hurricane Intensity Estimation (HIE) Algorithm Theoretical Basis Document (ATBD) provides detailed information regarding the Advanced Dvorak Technique (ADT), an algorithm that will derive estimates of tropical cyclone (TC) intensity using satellite imagery from the Advanced Baseline Imager (ABI) flown on the GOES-R series of NOAA geostationary meteorological satellites. This document summarizes the HIE/ADT algorithm methodology (through version 4.0) and usage of the application.

The central purpose of this ATBD is to facilitate development of operational Product Generation software for the HIE product which is implemented within the GOES-R Ground Segment product generation subsystem.

1.2 Who Should Use This Document

This document should be referenced by users who wish to operate the ADT, understand the internal workings of the algorithm, and learn how to interpret the analysis output.

1.3 Inside Each Section

This document is broken down into the following main sections.

- **Algorithm Overview:** Describes the development and theory basis for the ADT. This is covered in Section 2.
- **Algorithm Usage:** Provides a detailed description of the algorithm operation, the required input files and control parameters, and the program output. These are covered in Sections 3, 4, and 5.

- **Algorithm Limitations:** Discusses the current limitations of the algorithm and potential paths for future research to improve the ADT. This is covered in Section 6.

1.4 Related Documents

The ADT can utilize input and output data files in Automated Tropical Cyclone Forecasting System (ATCF) format. A complete document related to this formatting style can be found online at the following address:

http://www.nrlmry.navy.mil/atcf_web/

1.5 Revision History

Version 0.1 of this document was created by Timothy Olander of the University of Wisconsin-Madison/Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS). Version 0.2 was also written by Tim Olander at UW-CIMSS after review by Jaime Daniels of NOAA/STAR. Version 0.3 and 1.0 were completed after review and acceptance from AIT for the “Draft Version” document delivery. The HIE ATBD Version 1.0, was amended by Tim Olander at UW-CIMSS in order to update the guide for the “80% Version” document delivery after several significant milestones were achieved with the HIE algorithm, including the Algorithm Version 3 release to AIT, the Critical Design Review (CDR), and Test Readiness Review (TRR). Jaime Daniels supplied substantial review of ATBD Version 1.0 prior to Version 1.1 update, with Chris Velden (UW-CIMSS) providing a significant review of the updated Version 1.0 and 1.1 documents prior to release. Version 1.4 was modified/released to update the HIE ATBD in order to conform to AIT ATBD format standards. Version 1.5, updated the document to include new information, update validation studies, and address questions by Harris reviewers. This document, Version 2.0, addresses all comments from the System Engineering 80% review and final AIT ATBD review prior to the release of the HIE ATBD (100% delivery) Version 2.0

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|---------------|--|----------------|
| • Version 0.1 | Initial CIMSS release | March 2008 |
| • Version 0.2 | Modifications/Jaime Daniels review | May 2008 |
| • Version 0.3 | Modifications/AIT (Larisa Koval) review | June 2008 |
| • Version 1.0 | AIT release (80% delivery) | September 2008 |
| • Version 1.1 | Update/Chris Velden review | May 2009 |
| • Version 1.2 | AIT release/Larisa Koval review | June 2009 |
| • Version 1.3 | Modifications/CIMSS review | July 2009 |
| • Version 1.4 | Modifications/Jaime Daniels review | September 2009 |
| • Version 1.5 | Modifications/Jaime Daniels review | June 2010 |
| • Version 2.0 | Modifications/AIT review (100% delivery) | September 2010 |

2 OBSERVING SYSTEM OVERVIEW

2.1 Products Generated

The ADT algorithm generates real-time tropical cyclone (TC) intensity estimates using infrared window channel satellite imagery. The primary products generated by the ADT include the current intensity estimate analysis, in terms of wind speed, mean sea level pressure, and Current Intensity number (CI#), from the satellite image being interrogated as well as additional time-averaged and other time-dependent estimate values utilizing specific rules to limit the growth/decay of the intensity estimates over time. Graphical and textual listings of the historical ADT TC estimates can be viewed, saved, and distributed. It must be noted that the wind speed estimate is the only value output by the HIE algorithm which must meet the F&PS reproducibility requirements. Table 1 outlines the specifications for the hurricane intensity product GOES-R as defined in the latest version of the GOES-R Ground Segment Project Functional and Performance Specification (F&PS) requirements document.

Hurricane Intensity	Specification
Geographic Coverage	Full Disk
Vertical Resolution	N/A
Horizontal Resolution	2 km
Mapping Accuracy	1 km
Measurement Range	Dvorak hurricane intensity scale values of 1.5 – 8 or leading to wind speeds of 12.8 m/s (25 knots) to 87.5 m/s (170 knots)
Measurement Accuracy	6.0 m/s over the ocean
Refresh Rate/Coverage Time (Mode 3)	30 minutes
Refresh Rate (Mode 4)	30 minutes
VAGL (Mode 3 or 4)	806s
Measurement Precision	8.0 m/s over the ocean
Product Qualifiers	
Temporal Coverage	Day and night
Product Extent	Quantitative out to at least 65 degrees LZA and qualitative beyond
Cloud Cover Conditions	Clear conditions down to feature of interest associated with threshold accuracy
Product Statistics	Over hurricane cases

Table 1: Requirements for Hurricane Intensity product

2.2 Instrument Characteristics

Table 2 below shows the ABI channels and the channel used by the ADT algorithm. The performance of the ADT can be sensitive to imagery artifacts or instrument noise. Calibrated observations are critical because the ADT relies upon measured brightness temperature measurements to determine the TC intensity estimates. Properly navigated imagery is also essential, especially if run in a completely automated fashion using interpolated operational TC forecast positions as a first guess for the storm center determination schemes. The ABI channel specifications are given in the Mission Requirements Document (MRD) section 3.4.2.1.4.0 and it is assumed that the ABI performance will meet these specifications.

<i>Channel Number</i>	<i>Wavelength (μm)</i>	<i>Used in ADT</i>
1	0.47	
2	0.64	
3	0.86	
4	1.38	
5	1.61	
6	2.26	
7	3.9	
8	6.15	
9	7.0	
10	7.4	
11	8.5	
12	9.7	
13	10.35	✓
14	11.2	
15	12.3	
16	13.3	

Table 2: Channel numbers and wavelengths for the ABI and those used by the ADT.

3 ALGORITHM DESCRIPTION

The Advanced Dvorak Technique (ADT) algorithm (Olander and Velden, 2007) is a computer-based technique, developed at the University of Wisconsin-Madison/Cooperative Institute for Meteorological Satellite Studies (UW/CIMSS), to objectively determine tropical cyclone (TC) intensity using geostationary satellite infrared imagery. The ADT can be used to classify storm intensity from storm formation, through development and maturation, to dissipation.

The ADT is patterned after the Subjective Dvorak Enhanced Infrared ‘EIR’ Technique (SDT) (Dvorak, 1975, 1984) which made use of various pattern identification schemes and rules to determine TC intensity. The ADT was originally developed to closely mimic the SDT methodology in terms of intensity determination protocol and the incorporation of various rules and analysis methods. Some of the original SDT rules have subsequently been modified in the ADT as determined by in-depth statistical analysis of ADT performance during application. In addition, selected intensity determination modules within the ADT have adopted regression based methods, further advancing the ADT beyond the scope of the original SDT procedures and capabilities, as well as previous versions of the ADT; the Objective Dvorak Technique (ODT) (Velden et al., 1998), and Advanced Objective Dvorak Technique (AODT) (Olander et al., 2004 and 2002) at UW-CIMSS.

The significant modifications and additions made to the ADT results in an algorithm that bears little if any resemblance to its forerunners in terms of methodology, functionality, and content. The primary modifications from previous objective Dvorak-based methods include the addition of a history file (containing previous intensity estimates obtained during a storm lifecycle), utilization of a time-weighted averaging scheme for the final intensity, new definitions and determinations of environmental cloud-top temperature values used to determine scene type and intensity, the implementation and adjustment of SDT rules governing the variability of the intensity estimates, and the modification of the basic relationships governing the intensity estimates away from the pattern recognition-type SDT methodologies towards the use of regression-based equations utilizing objectively analyzed environmental parameters. These changes have led to more stable and statistically sound estimates of intensity by the objective ADT scheme.

3.1 Algorithm Overview

The ADT algorithm can perform an intensity analysis of any active global TC with an intensity of Tropical Depression status and a maximum wind of >25kts. Identification of storm systems for which to initialize and utilize the ADT algorithm are determined by official WMO Tropical Cyclone Forecast Center (TCFC) bulletins. For each TC, the ADT algorithm is intended to execute in an automated fashion, through the use of UNIX shell scripts via an automated command scheduler or other similar system setup, over the entire life cycle of the TC until the TCFC bulletins are discontinued by the issuing

forecast center. The processing logic used to determine an “active TC” is conducted prior to and external from the actual execution of the ADT itself, so this process is not described in this document. It is left to the implementing organization/group of the ADT to implement the actual process of determining an “active TC”. The ADT will assume that the image being examined contains an active TC of some valid intensity.

The primary advantage the ADT presents to TC forecasters is the ability to objectively determine TC intensity and storm center location without human subjectivity issues, or any manual intervention unless specifically requested. Initial TC storm center positioning is primarily determined via a polynomial interpolation of a short-term TC position forecast provided by the responsible TCFCs worldwide. Once determined, the infrared satellite image is interrogated by a series of algorithms to search for a potentially more accurate TC storm center based upon analysis of the cloud top temperature field.

Once the TC storm center has been determined, the “scene type” is automatically selected using a series of cloud top temperature statistical analysis routines. The scene type governs the subsequent regression schemes to be employed by the ADT to estimate intensity, and is based on cloud pattern recognition. Having established the scene type, the current TC intensity estimate is then derived for the image being investigated. The storm intensity estimate is output as maximum sustained 1-minute surface winds (Kts), and mean sea level pressure (MSLP) at the center (hPa). Various rules governing the intensity change rate, along with a time-averaging routine (using previous intensity estimates stored in an external storm file), are applied during individual stages of the intensity determination process, and are designed to limit/smooth the evolution of the TC intensity over time. The maximum wind and MSLP values are determined from an empirical relationship between the final calculated “current intensity” (CI#) estimate and the intensity parameters, and is TC basin dependent. A final minor adjustment to the MSLP is based upon the current latitude of the storm (Kossin and Velden 2005).

All of the critical parameters utilized in the determination of the intensity estimate values within the ADT operation are saved to an external file called the ADT “History File”. These values, stored for all previous analyses, are used by the ADT algorithm for various internal logic procedures as well as in the determination of specific parameters critical to the intensity estimation process. They can also be accessed by an analyst seeking specific information on past estimates.

3.2 Processing Outline

The top level flowchart describing the ADT processing is presented in Figure 1. Many of the functions displayed in Figure 1 are discussed in greater detail in the various Mathematical Description discussions in Section 3.4.2.

The automated derivation of the ADT intensity estimates follows the path indicated in Figure 1 below, with various branches governing non-intensity derivation branches controlled via input values entered at the start of the algorithm processing. These non-intensity derivation inputs allow various functions such as listing, graphing, or editing the

ADT history file (otherwise known as “tailored products”). The execution of the ADT will be performed in a completely automated fashion from a scheduled command on the computer where the ADT is installed and executed without any human interaction.

During the operation of the ADT algorithm, the program will need to automatically determine the correct position of the storm center (Section 3.4.2.1). Once this position is obtained, the derivation of the cloud pattern “scene type” will be performed (Section 3.4.2.2). The derivation of the scene type will in turn determine the method for determining the intensity estimate (Section 3.4.2.4) for the scene being interrogated. The derived intensity estimate will then be output to the user (Section 3.4.3) and saved to the ADT history file (Section 3.3.2.1).

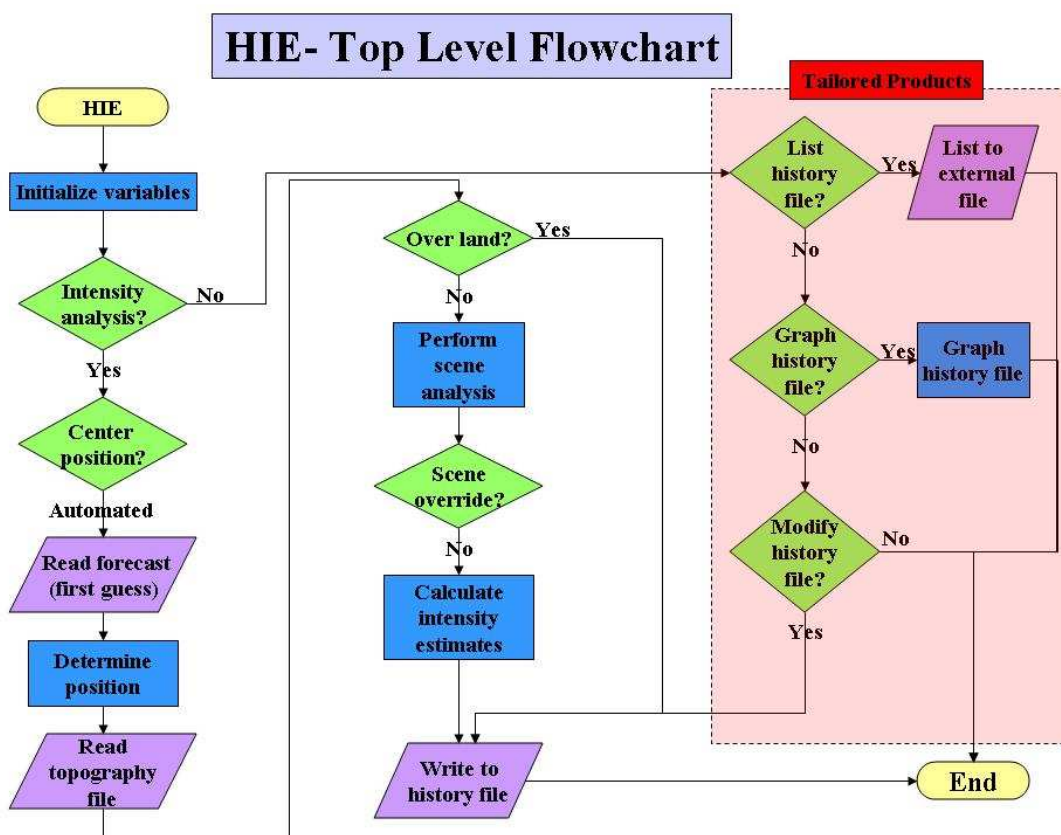


Figure 1: ADT Top-Level processing flowchart.

To utilize the ADT, the first step involves an initialization to set up the file and directory structures needed for I/O, storage, and ancillary data access. The details of this process are beyond the scope of this document, but the needed elements will be posted in a User’s Guide. Inputs consist of various keywords and parameter entries from a command line which control the Top Level path to be followed (green diamonds). These inputs can be automated via external scripts set up by the user in a fully automated system. If an intensity estimation is to be calculated through a fully automated procedure, the ADT must perform three main tasks; 1. Determine the TC center position, 2. Perform an analysis to select the proper scene type, and 3. Calculate the intensity estimate for the

selected scene type. These processes are described in the following sections. Non-intensity related tasks can also be automated to perform task such as listing of the history file or producing other output files (e.g. ATCF listings).

Input and output data requirements (purple trapezoids) will be discussed in the final subsection following the intensity estimate discussion.

3.3 Algorithm Input

Filename	Format	Originates	Contents
User determined	ASCII	Internal	History file (ADT analysis parameters)
Variable	Binary	NOAA	Infrared (longwave IR) Satellite Image
User determined	ASCII	Many	Tropical cyclone forecast
Digelev_hires_le.map	Binary	NOAA	.1° resolution topography flags
Variable	ASCII	NESDIS	Passive Microwave “Eye Score” value
Variable	ASCII	Many	Knaff/Zehr wind-pressure TC environment values

Table 3: Input data files for ADT algorithm.

3.3.1 Primary Sensor Data

The ADT currently utilizes longwave infrared window (approximately 10.7 μ m central wavelength channel; band 4 on the current GOES platforms) imagery from any of the operational geostationary satellite platforms, or from the MODIS instrument on the polar-orbiting NOAA Aqua or Terra satellites. The imagery can be in native satellite projection or remapped Mercator projection however they must contain proper navigation and calibration information. For GOES-R, Band 13 (10.35 μ m) data will be supplied to the HIE from the AIT framework which obtains the data via the Level 1B Processing System. AIT software library routines will interface directly with the HIE algorithm to transfer the necessary satellite data information to the intensity estimation routine as needed.

It is assumed that the entire storm and TC analysis region (TCFOV, defined below) will be within the field of view of the satellite image being examined, centered at the automated storm center position, and will also contain a limited number of bad scan lines and pixels per line. Typical temperature ranges for the IR pixels should be between approximately -100°C and +30°C. The HIE will check for bad pixels and lines in the TCFOV and replace them as necessary with either the adjoining (western) pixel values or adjoining (previous) line values. A bad pixel is defined as a temperature value greater than or equal to 320°K or less than 150°K. If 10 or more pixels on each line within the TCFOV are replaced the line is flagged as bad. If 10 or more bad lines are found in the TCFOV, the TCFOV is deemed to be too corrupted for use and the HIE algorithm will end. An error message and flag value (Section 5.4) will be output to indicate that this has occurred.

The imagery can contain data over ocean and land surfaces. The TCFOV in the HIE algorithm for the scene type and intensity derivation routines is a circle of radius 136km, so a box of size 136 X 136 contains the TCFOV (assuming a spatial resolution of 2km in the infrared window channel with GOES-R ABI data). The analysis region for the automated storm centering routines within the HIE algorithm package a bit larger than the scene type/intensity analysis domain at 190km plus 5 extra pixels on each side of the IR data array box. The size of the TCFOV array box containing the IR data for the automated storm center determination processing and scene type/intensity determination schemes are dependent upon the line and element resolution of the data in the IR image. For example, for a 2km image, the line minima/maxima are defined:

$$\text{Min/Max Line} = \text{Center_Line} \pm (\text{Analysis_Radius}/\text{Line_Resolution}) + 5 \text{ pixels}$$

If the minimum or maximum lines or elements go beyond the extent of the IR image being examined, the analysis region will be adjusted/shifted to contain IR image data (not read off the edge of the image), if possible. For example, if the analysis region extends 20 pixels past the maximum line value of the IR image being examined, the maximum value will be set to last line value available and the minimum value will be reduced by 20 pixels to accommodate the shift in the analysis region. If the analysis IR image is too small to accommodate this shift, an error will be returned and terminate the execution of the HIE.

3.3.2 Ancillary Data

3.3.2.1 ADT History File

The ADT history file is an ASCII format file containing ADT intensity estimates, locations, and other specific information for each image analysis. The ADT algorithm utilizes records in the history file in the determination of the intensity estimate values as well as the application of various rules utilized within the algorithm. This file will be 'initialized' the first time the ADT is activated on a target TC, either automatically (with the T# intensity value that the ADT determines for the first image), with a user defined input T# value for intensity (most likely the T# corresponding to the estimated wind speed from the TCFC forecast/discussion file, as shown in Section 3.3.2.2), or a default T# value of 1.0, dependent upon however the program is set up to be executed automatically. Each analysis stored in the history file will contain the following values shown in Table 4:

Value	History File Parameter
1	Date (YYYYMMDD format YYYY=year, MMM= 3-letter month ID, DD=day)
2	Time (hhmmss format)
3	Julian day and partial day
4	Raw T# unadjusted
5	Raw T# adjusted by Rule 8 rules
6	Final T# value (3-hour average)
7	Final CI# value
8	Eye region temperature (°C)
9	Mean cloud region temperature (°C) – movable annulus
10	Mean cloud region temperature (°C) – set region (old method)
11	“Coldest-warmest” cloud region temperature (°C)
12	Storm center latitude
13	Storm center longitude
14	Eye diameter, CDO size, or shear distance (in km)
15	Eye region temperature standard deviation value
16	Cloud region symmetry value
17	Satellite ID value
18	Eye region scene type (original value) 0=Clear Eye, 1=Pinhole Eye, 2=Large Eye, 3=No Eye
19	Cloud region scene type (original value) 0=CDO, 1=Embedded Center, 2=Irregular CDO, 3=Curved Band, 4=Shear
20	Eye region scene type Original value if user override performed, -1 if no override
21	Cloud region scene type Original value if user override performed, -1 if no override
22	Dvorak Weakening (Dvorak EIR Rule 9) flag 0=Off, 1=On; 2=On (initialized at >=T# 6.0
23	Dvorak Constraint Limits (Dvorak EIR Rule 8) flag 0’s=Shear Scene, 10’s=Eye Scenes, 20’s=Curved Band/CDO/EmbC/IrrCDO Scenes 0=No Constraint, 1=T#4.0 0.5/6hr, 2=6hr rule, 3=12hr rule, 4=18hr rule, 5=24hr rule 6=None, 7=None, 8=0.2/hr (1 st six hours only), 9=0.5/hr 30’s MW Adjustments : 30=12-hr Interp., 31=Initial, 32=On, 33=Hold, 34=Off
24	Latitude bias application flag 0=Off, 1=Merging, 2=On
25	Rapid dissipation flag (east pacific only) 0=Off, 1=On)
26	Land/ocean flag 1=Over Land, 2=Over Ocean
27	Eye region FFT value
28	Cloud region FFT value
29	Curved band analysis – BD curve gray scale value
30	Curved band analysis – convection curvature amount (out of 25)
31	Distance from center to “coldest-warmest” temperature value
32	Automated center determination flag (0=manual, 1=forecast interpolation, 4=spiral, 5=combo, 6=extrapolation
33	MSLP latitude bias adjustment value
34	Radius of maximum wind (in km)
35	External passive microwave (PMW) “eye score” value
36	Input 34 knot wind/gale radius value (for K/Z relationship; in km)
37	Input environmental pressure value (for K/Z relationship, in mb)
38	User comment – if available

Table 4: HIE history file parameter values.

3.3.2.2 Tropical Cyclone Forecast Product Formats

The ADT automated storm center location algorithm approximates TC position using three methods: polynomial interpolation of TCFC forecasts, linear extrapolation of the history file positions or with an advanced dual methodology examining the TC cloud top spiral features and circular feature (ring) search discussed in Section 3.4.2.1. Ancillary data, such as the operational forecast products described here, will be supplied to the HIE algorithm via the AIT Framework, which will obtain the data via the Ancillary Data Relay System (ADRS). Internal HIE software will obtain and read the input satellite data served by the AIT framework.

As a first guess, the forecast positions from TCFC forecast, with its file name and directory location passed to the HIE algorithm via algorithm inputs (command line, GUI values, or environmental variables, depending on the implantation of the algorithm), are read within the HIE algorithm to obtain the current position using a polynomial interpolation routine. This interpolation routine uses three forecast positions (current, 12 hour, and 24 hour positions) defined in the forecast file to interpolate the current position defined by the time of the image being examined. If the image time falls within the time period defined within the forecast file positions/times, a valid interpolated forecast position will be used within the algorithm, otherwise an extrapolation of the previous history file positions will be used. The five types of acceptable input file formats are:

- ATCF Forecast Record file
- NHC Discussion/Warning files
(WMO headers: “WTNT4? KNHC” or “WTPZ4? KNHC”)
- JTWC Tropical Cyclone Warning files
(WMO header: “WTPN3? PGTW”)
- Other Regional Specialized Meteorological Center (RSMC) Formats
 - ICAO format files from:
 - RSMC Nadi (Fiji): FKPS01-02 NFFN
 - RSMC New Delhi (India): FKIN20 VIDP
 - RSMC Tokyo (Japan): FKPQ30-34 RJTD
 - Tropical Cyclone Warning Centers (TCFC) Technical Bulletins: Australia
 - TCWC Perth: AXAU01-02 APRF
 - TCWC Darwin: AXAU01-02 ADRM
 - TCWC Brisbane: AXAU21 ABRF
 - RSMC La Reunion, MeteoFrance Warning files
(WMO header: WTIO30 FMEE)
- Generic Entry file

Depending on where the TC being investigated is located, some of the five formats may not be valid or available (ATCF are typically only available for storms monitored by US interests (NHC, CPHC) JTWC may not make available their ATCF files publically available and RSMC forecasts may be less reliable due to transmission issues from their originating locations. The order above is a general guideline for accessing the TCFC

forecast information, but again these can vary depending on TC location, method of accessing the forecast information, and transmission by the specific TCFCs listed above. Examples of each valid forecast file format are provided below.

3.3.2.2.1 ATCF Forecast Record Format

The ADT will skip redundant forecast positions (for each critical radii report).

AL, 13, 2002092400, 03, OFCL, 0, 127N, 620W, 50, 1006, TS, 34, AAA, 0, 0, 0, 0, 0, 0, 0, 60, 0, , 0, BRJ, 275, 16,
AL, 13, 2002092400, 03, OFCL, 3, 127N, 627W, 50, 1006, TS, 34, NEQ, 90, 30, 50, 90, 0, 0, 0, 60, 0, , 0, BRJ, 275, 15,
AL, 13, 2002092400, 03, OFCL, 3, 127N, 627W, 50, 1006, TS, 50, NEQ, 20, 0, 0, 20, 0, 0, 0, 60, 0, , 0, BRJ, 275, 15,
AL, 13, 2002092400, 03, OFCL, 12, 138N, 648W, 55, 1006, TS, 34, NEQ, 100, 30, 50, 100, 0, 0, 0, 65, 0, , 0, BRJ, 300, 15,
AL, 13, 2002092400, 03, OFCL, 12, 138N, 648W, 55, 1006, TS, 50, NEQ, 20, 0, 0, 20, 0, 0, 0, 65, 0, , 0, BRJ, 300, 15,
AL, 13, 2002092400, 03, OFCL, 24, 150N, 671W, 60, 1006, TS, 34, NEQ, 100, 50, 50, 100, 0, 0, 0, 75, 0, , 0, BRJ, 300, 13,
AL, 13, 2002092400, 03, OFCL, 24, 150N, 671W, 60, 1006, TS, 50, NEQ, 30, 20, 20, 30, 0, 0, 0, 75, 0, , 0, BRJ, 300, 13,
AL, 13, 2002092400, 03, OFCL, 36, 161N, 690W, 70, 1006, TS, 34, NEQ, 100, 60, 60, 100, 0, 0, 0, 85, 0, , 0, BRJ, 300, 11,
AL, 13, 2002092400, 03, OFCL, 36, 161N, 690W, 70, 1006, TS, 50, NEQ, 50, 30, 30, 50, 0, 0, 0, 85, 0, , 0, BRJ, 300, 11,
AL, 13, 2002092400, 03, OFCL, 36, 161N, 690W, 70, 1006, TS, 64, NEQ, 30, 20, 20, 30, 0, 0, 0, 85, 0, , 0, BRJ, 300, 11,
AL, 13, 2002092400, 03, OFCL, 48, 170N, 705W, 75, 1006, TS, 34, NEQ, 120, 80, 80, 120, 0, 0, 0, 90, 0, , 0, BRJ, 300, 8,
AL, 13, 2002092400, 03, OFCL, 48, 170N, 705W, 75, 1006, TS, 50, NEQ, 50, 30, 30, 50, 0, 0, 0, 90, 0, , 0, BRJ, 300, 8,
AL, 13, 2002092400, 03, OFCL, 72, 190N, 730W, 70, 1006, TS, 34, NEQ, 100, 60, 60, 100, 0, 0, 0, 85, 0, , 0, BRJ, 310, 8,
AL, 13, 2002092400, 03, OFCL, 72, 190N, 730W, 70, 1006, TS, 50, NEQ, 50, 30, 30, 50, 0, 0, 0, 85, 0, , 0, BRJ, 310, 8,

3.3.2.2.3 JTWC Tropical Cyclone Warning Record Format

As with NHC Bulletins, these forecasts can be readily obtained from the internet, and will have a separate WMO header for each storm and each basin covered by the Joint Typhoon Warning Center.

```
WTPN32 PGTW 291500                2004242 1417
MSGID/GENADMIN/NAVPACMETOCEN PEARL HARBOR HI/JTWC//
SUBJ/TROPICAL CYCLONE WARNING//
RMKS/
1. TYPHOON 19W (CHABA) WARNING NR 044
02 ACTIVE TROPICAL CYCLONES IN NORTHWESTPAC
MAX SUSTAINED WINDS BASED ON ONE-MINUTE AVERAGE
---
WARNING POSITION:
291200Z4 --- NEAR 29.4N5 130.0E4
MOVEMENT PAST SIX HOURS - 325 DEGREES AT 07 KTS
POSITION ACCURATE TO WITHIN 040 NM
POSITION BASED ON CENTER LOCATED BY A COMBINATION OF
SATELLITE AND RADAR
PRESENT WIND DISTRIBUTION:
MAX SUSTAINED WINDS - 095 KT, GUSTS 115 KT
RADIUS OF 064 KT WINDS - 050 NM NORTHEAST QUADRANT
050 NM SOUTHEAST QUADRANT
050 NM SOUTHWEST QUADRANT
050 NM NORTHWEST QUADRANT
RADIUS OF 050 KT WINDS - 080 NM NORTHEAST QUADRANT
080 NM SOUTHEAST QUADRANT
080 NM SOUTHWEST QUADRANT
080 NM NORTHWEST QUADRANT
RADIUS OF 034 KT WINDS - 200 NM NORTHEAST QUADRANT
OVER WATER
180 NM SOUTHEAST QUADRANT
180 NM SOUTHWEST QUADRANT
180 NM NORTHWEST QUADRANT
REPEAT POSIT: 29.4N5 130.0E4
---
FORECASTS:
12 HRS, VALID AT:
300000Z3 --- 31.6N0 130.3E7
MAX SUSTAINED WINDS - 080 KT, GUSTS 100 KT
RADIUS OF 064 KT WINDS - 050 NM OVER WATER
RADIUS OF 050 KT WINDS - 080 NM OVER WATER
RADIUS OF 034 KT WINDS - 200 NM NORTHEAST QUADRANT
OVER WATER
180 NM SOUTHEAST QUADRANT
OVER WATER
180 NM SOUTHWEST QUADRANT
170 NM NORTHWEST QUADRANT
OVER WATER
VECTOR TO 24 HR POSIT: 030 DEG/ 19 KTS
---
24 HRS, VALID AT:
301200Z6 --- 34.9N6 132.7E3
MAX SUSTAINED WINDS - 060 KT, GUSTS 075 KT
---
REMARKS:
291500Z7 POSITION NEAR 30.0N3 130.1E5.
TYPHOON (TY) 19W (CHABA), LOCATED APPROXIMATELY 215 NM SOUTH
OF SASEBO, JAPAN, HAS TRACKED NORTHWESTWARD AT 07 KNOTS OVER
THE PAST 06 HOURS. THE WARNING POSITION IS BASED ON 291130Z6
ENHANCED IR SATELLITE IMAGERY.
```

3.3.2.2.4 RMSC Record Formats

The WMO RSMC sites produce forecast products in several formats for an individual storm. The HIE algorithm can read most of these formats; however, subtle differences between site formats may lead to errors. If one forecast format fails, another format may be available from the RSMC providing the forecast. The formats listed below are the suggested forecast product formats to use for the different RSMC sites.

ICAO Format: Unfortunately the ICAO format is not uniform across all RSMC forecast centers. The ADT, however, attempts to account for the current differences and should successfully read all ICAO format forecasts unless they change.

```
FKPS01 NFFN 060300                2008037 0307
TC ADVISORY
DTG: 20080206/0300Z
TCAC: DARWIN
TC: GENE
NR: 35
PSN: S2854 W17748
MOV: ESE 15KT
C: 972HPA
MAX WIND: 65KT
FCST PSN +12HR: 11/1200 S3042 W17418
FCST MAX WIND +12HR: 55KT
FCST PSN +18HR: 12/0000 S3118 W17230
FCST MAX WIND +18HR: 50KT
FCST PSN +24HR: 12/1200 S3200 W17030
FCST MAX WIND +24HR: 45KT
NXT MSG: 20080206/0800Z
```

Australian TCFC Format: This warning format is produced by the Australian TCFCs and is utilized over the ICAO format due to the inclusion of the Identifier tag in the forecast body, allowing for greater ease in automated processing for obtaining and parsing the product information.

```
AXAU01 APRF 260705
IDW27600
TROPICAL CYCLONE TECHNICAL BULLETIN: AUSTRALIA - WESTERN REGION
Issued by PERTH TROPICAL CYCLONE WARNING CENTRE
at: 0704 UTC 26/01/2009
Name: Tropical Cyclone Dominic
Identifier: 12U
Data At: 0600 UTC
Latitude: 20.1S
Longitude: 115.6E
Location Accuracy: within 25 nm [46 km]
Movement Towards: south southwest [207 deg]
Speed of Movement: 8 knots [15 km/h]
Maximum 10-Minute Wind: 45 knots [85 km/h]
Maximum 3-Second Wind Gust: 65 knots [120 km/h]
Central Pressure: 987 hPa
Radius of 34-knot winds NE quadrant: 60 nm [110 km]
Radius of 34-knot winds SE quadrant: 60 nm [110 km]
Radius of 34-knot winds SW quadrant: 60 nm [110 km]
Radius of 34-knot winds NW quadrant: 60 nm [110 km]
Radius of 48-knot winds NE quadrant:
Radius of 48-knot winds SE quadrant:
Radius of 48-knot winds SW quadrant:
Radius of 48-knot winds NW quadrant:
Radius of 64-knot winds:
```

Radius of Maximum Winds:
Dvorak Intensity Code: T3.0/3.0/D1.0/24HRS
Pressure of outermost isobar: 1002 hPa
Radius of outermost closed isobar: 75 nm [140 km]
Storm Depth: Deep

FORECAST DATA

Date/Time : Location : Loc. Accuracy: Max Wind : Central Pressure
[UTC] : degrees : nm [km]: knots[km/h]: hPa
+12: 26/1800: 21.4S 115.3E: 055 [100]: 050 [095]: 982
+24: 27/0600: 22.8S 115.6E: 085 [155]: 030 [055]: 996
+36: 27/1800: 24.2S 116.4E: 120 [220]: 025 [045]: 999
+48: 28/0600: 25.4S 117.6E: 160 [295]: 025 [045]: 998
+60: 28/1800: 26.7S 118.6E: 210 [390]: 020 [035]: 1000
+72: 29/0600: 28.2S 119.7E: 250 [465]: 020 [035]: 1000

REMARKS:

TC Dominic was named at 03Z.

WTIO30 FMEE Format: This format is primarily used from the MeteoFrance site at La Reunion Island in the Southern Indian Ocean.

WTIO30 FMEE 071800

2008038 1802

RSMC / TROPICAL CYCLONE CENTRE / LA REUNION
TROPICAL CYCLONE FORECAST WARNING (SOUTH-WEST INDIAN OCEAN)
0.A WARNING NUMBER : 15/10/20072008
1.A VERY INTENSE TROPICAL CYCLONE 10 (HONDO)
2.A POSITION 2008/02/05 AT 1800 UTC :
15.0S / 82.9E
(FIFTEEN DECIMAL ZERO DEGREES SOUTH AND EIGHTY TWO DECIMAL NINE DEGREES EAST)
3.A DVORAK ANALYSIS : 6.5/7.0 /D 1.0/18 H
4.A CENTRAL PRESSURE : 906 HPA
5.A MAX AVERAGE WIND SPEED (10 MN) : 120 KT
6.A EXTENSION OF WINDS BY QUADRANTS (KM):
30 KT NE: 160 SE: 160 SO: 260 NO: 200
50 KT NE: 060 SE: 040 SO: 080 NO: 080
7.A FIRST CLOSED ISOBARE (PRESSURE / AVERAGE DIAM): 1004 HPA / 800 KM
8.A VERTICAL EXTENSION OF CYCLONE CIRCULATION: DEEP
1.B FORECASTS:
12H: 2008/02/06 06 UTC: 15.3S/83.3E, MAX WIND=110KT, INTENSE TROP. CYCL..
24H: 2008/02/06 18 UTC: 15.6S/83.7E, MAX WIND=100KT, INTENSE TROP. CYCL..
36H: 2008/02/07 06 UTC: 16.4S/84.6E, MAX WIND=090KT, INTENSE TROP. CYCL..
48H: 2008/02/07 18 UTC: 17.6S/85.5E, MAX WIND=080KT, TROPICAL CYCLONE.
60H: 2008/02/08 06 UTC: 18.9S/86.2E, MAX WIND=060KT, SEVERE TROP. STORM.
72H: 2008/02/08 18 UTC: 20.1S/86.4E, MAX WIND=050KT, SEVERE TROP. STORM.
2.B OTHER INFORMATION:
T=6.5+, CI=7.0
HONDO SHOWS AN ANNULAR PATTERN (YET SLIGHTLY ERODED IN THE SOUTHEASTERN PART). THE ENVIRONMENT IS FAVORABLE ; LOW LEVELS INFLOWS ARE WELL ESTABLISHED, WINDSHEAR IS WEAK AND UPPER LEVEL DIVERGENCE RATHER GOOD.

3.3.2.2.5 Generic Format

Each line in the Generic Entry file contains either the initial/current position of the storm or a forecast position at 12-hours or 24-hours, and is formatted as follows:

dd mm yyyy tttt aa.a bbb.b		
<u>parameter</u>	<u>value</u>	<u>format</u>
dd	date	two digit integer
mm	month	two digit integer
yyyy	year	four digit integer
tttt	UTC time	HHMM format : HH-hour MM-minute
aa.a	latitude	floating point (+/- : north/south)
bbb.b	longitude	floating point (+/- : west/east)

An example file for Hurricane Floyd using the 12 September 1999/03:00UTC forecast product:

```
12 09 1999 0300 22.7 64.5
12 09 1999 1200 22.9 66.0
13 09 1999 0000 23.2 68.3
```

The first line contains the “initial” position, with the second and third lines containing the 12-hour and 24-hour forecast positions. Use of a forecast file older than 24 hours from the initial time of the forecast file will result in a failure with the forecast interpolation routine since the image being examined will fall outside of the time range being read by the HIE algorithm (which only uses the initial position/time, the 12 hour forecast position, and the 24 hour position). If the time of the image being examined by the HIE falls within the current and 24 hour times defined in the forecast file being used, a valid forecast position will be determined. In addition, if the time of the image being examined falls before the initial time within the forecast file (as can happen if the TCFC releases the forecast file prior to the initial time within the forecast file), the interpolation routine will also fail since the time being interpolated to falls outside of the three positions defined in the forecast file. A failure to properly interpolate the forecast position will result in an extrapolation of the history file (if utilized, as described in Section 3.4.2.1), or termination of the ADT algorithm if an extrapolation cannot be performed.

3.3.2.3 Topography File Format

TC land interaction will be determined utilizing the high-resolution digital elevation map `digilev_hires_le.map` provided in the HIE package. The current file supplied with the HIE package uses an 8-km surface elevation map, adopted from the GEOCAT library, which was originally derived from the USGS GTOPO30 dataset available on the USGS website at:

<http://edcdaac.usgs.gov/gtopo30/gtopo30.html>.

The algorithm used to read this topography file was supplied by AIT programmers and converted from FORTRAN90 to C for insertion into the HIE algorithm.

To determine if a storm is over land, the following logic is utilized. If a 10 X 10 pixel grid box, centered at the current storm location, possesses 85% or more (85 out of 100 pixels) of its area as a land feature, the land flag will be triggered. If the land flag is triggered, no intensity estimate will be produced. The history file will still include an entry for any intensity estimate attempted while over land. Typically the automated HIE will continue to attempt intensity estimates while the storm is over land until either the official TCFC forecasts are discontinued or the TC reemerges over open ocean again and has not dissipated while over the land surface. The date and time(s), latitude, longitude, land flag, internal HIE satellite ID, and automated centering method values will contain their assigned values, however the values for the intensity estimates and the remaining parameters will be assigned a “missing value”. All values will contain zero for their missing values except the four temperature values (99.50), the radius of maximum wind value (-99.5), and microwave eye score value (-99.5). Calculation of both Final T# values and the CI# value will exclude all “over land” entries once the storm resumes movement over open water (non-land grid points). It is assumed that the entire 10 X 10 grid box will fall within the image being examined (as defined in Section 3.3.1).

3.3.2.4 Passive Microwave Eye Score File

The external passive microwave “eye score” algorithm, described in Section 3.4.2.12, will provide the ancillary date, time, and score value for the HIE when available. This information is currently scheduled to be derived and supplied by NOAA/NESDIS/SAB for the HIE algorithm via the AIT Framework, which will obtain the data via the Ancillary Data Relay System (ADRS). Internal HIE software will obtain and read the input satellite data served by the AIT framework. The score value should be a floating point value, while the date and time formats should be consistent with the corresponding data value (Value 1 and 2) formats in the ADT history file, described in Section 3.3.2.1.

3.3.2.5 Knaff/Zehr Wind-Pressure Relationship Parameters

A new relationship between the TC wind and MSLP values has been implemented into the ADT using the methodology outlined in Knaff and Zehr, 2007. This technique

utilizes several environmental TC parameters to convert the T# value obtained by the ADT to wind speed (using the relationship shown in Table 6) to an estimate of MSLP.

The environmental parameters needed by the ADT to calculate the MSLP estimate are the environmental MSLP and the gale radius (the 34 knot wind radius) of the TC being examined. The environmental MSLP value can be obtained by determining the outermost closed isobar and adding 2 hPa, while the gale radius can be derived by averaging all available quadrant 34 knot wind radii estimate values. These values are obtained from the ATCF Best Track/Objective Aid/Wind Radii format files using the observational comprehensive archive (CARQ) record values. The ATCF homepage is provided in Section 1.4. The environmental MSLP/last closed isobar value is the "RADP" value, while the 34 knot radii values (value of 34 in the RAD column) will be stored in the RAD1 through RAD4 values.

3.4 Theoretical Description

3.4.1 Physics of the Problem

The HIE algorithm is based upon the simple premise that various cloud patterns and cloud top temperatures values/fields are related to the current tropical cyclone intensity. Tropical cloud regions that are less organized possess isolated and short-lived convective regions. As these regions become more organized, the convection becomes stronger and more widespread. The released latent heat from the convection supplies further energy to the convective region to increase the duration and vigor of the convection, leading to stronger wind speeds as the pressure within the organizing tropical system decreases related to the surrounding environmental pressure. The process continues to feed upon itself, with stronger convection releasing greater amounts of latent heat and a further reduction in the storm central pressure, which increased the geostrophic and ageostrophic wind speed wind around the storm.

As the convection continues to organize and intensify the satellite-observed cloud top temperature values decrease as the tops of the storms reach higher into the troposphere. Further increase in storm organization enhances the TC secondary circulation, leading to a more symmetrical convective appearance and the development of an eye feature at the center of the storm system. Various environmental factors, such as wind shear, sea surface temperature changes, and land/weather system interactions will limit the maximum intensity of the storm and/or lead to a decrease in the storm intensity through a disruption the convective processes driving the storm development.

Monitoring the changes in convective cloud patterns and cloud-top temperature values from satellite platforms over time can provide vital information about the organization and strength of the storm being observed. Relating these patterns and values to storm intensity is the objective of the HIE. Utilization of infrared imagery from geostationary satellites provides the ideal data to perform this function.

3.4.2 Mathematical Description

The designation of the current image scene type, the derivation of the hurricane intensity estimates, and the determination of the automated storm center position estimate all involve complex mathematical processes. These processes will be discussed in the following sections.

3.4.2.1 Automated Storm Center Determination

The ADT automated storm center determination process utilizes an interpolation of an official TCFC short-term track forecast as a first guess for the storm center position. Official forecasts can be obtained from various World Meteorological Organization (WMO) sanctioned Regional Specialized Meteorological Center (RSMC), such as the

NOAA National Hurricane Center (NHC) for the Atlantic Ocean, Caribbean Sea, and Eastern Pacific Ocean and the Central Pacific Hurricane Center (CPHC) for the Central Pacific Ocean (to dateline). A list and examples of all RSMC valid forecast products is provided in Section 3.3.2.2. Forecasts are typically provided from NHC and CPHC every six hours for active TCs at or above Tropical Depression classification. These forecast positions are given every 12 hours, and the ADT normally uses the initial position and the first 12-hour forecast point for its interpolated values to the current analysis time.

The ADT will interpolate the provided TC position forecast to the current satellite image time using a polynomial interpolation of the storm forecast positions. If the forecast interpolation fails for any reason, a linear extrapolation of storm positions from the previous 12 hours (stored in the history file) is attempted. Once a valid interpolated forecast or extrapolated history file position is obtained, the Final T# intensity estimate (explained later in the document) of the record immediately preceding the current analysis time in the history file is found. If this value is less than 3.5, the interpolated/extrapolated point is used as the final automated storm position. However, if this value is greater or equal to 3.5, a thorough analysis of the image is conducted to determine if a potentially better storm center location can be employed.

Two techniques are used in the auto-centering scheme (Wimmers and Velden, 2004). These methods are quite computationally intensive and may take a significant amount of time to complete, since the routines require the satellite image being investigated to be remapped into a rectilinear projection before proceeding. The computation issue has been somewhat alleviated with the introduction of several mathematical shortcuts within the routine and with the implementation of the HIE algorithm on more state-of-the-art computers possessing greater computational power. Both processes are always performed during the auto-centering process.

The remapping to rectilinear projection process involves transforming satellite data, most likely in the original satellite projection (but it could be in any other non-linearly displayed projection such as Mercator), into a grid layout with equal spacing between the different grid points in both latitude and longitude locations. In order to do this, each point on the rectilinear projected grid must be interpolated from the original data points in the satellite image being analyzed. In order to speed up this process, a spline-fitting routine can be used to estimate certain values instead of interpolating each point directly from the satellite data. This process involves directly interpolating only a set number of points in the rectilinear projected grid (defined within the program) and then it will fit a cubic spline between the interpolated points to estimate the values between the interpolated points. The HIE will directly interpolate every third point on the rectilinear grid and then fit the two remaining points between each grid point (in the x and y direction). This process can drastically speed up the performance of the remapping process but will result in a remapped file that is very similar to the one that would be produced by a direct interpolation of each point. The routines that perform the cubic spline interpolation process were originally provided by Dave Santek of the Space Science and Engineering Center in Madison, WI, and were converted from the original FORTRAN code to C for the HIE algorithm.

The first technique, the Spiral Centering (SC) routine, determines a center point in the image where there is a maximum alignment between the image cloud top temperature gradient and the 5-degree log spiral vector emanating from the center point within each different analysis region (at different points within the remapped rectilinear grid, as described below). The equation for the 5-degree log spiral is:

$$R(\Theta) = A * e^{(B * \Theta)}$$

$R(\Theta)$ = radial distance from origin (center point of SC analysis regions)

A = starting position distance of spiral from origin

B = angle between spiral tangent and radial line at point (R, Θ) (5° in this case)

Θ = angle from the x-axis

The log spiral must be converted to Cartesian coordinates in order to determine the vector at each point within the cloud top temperature grid field. If the origin of the analysis grid is center location located at $(0,0)$, any point on the log spiral can be defined as:

$$X(\Theta) = R(\Theta) * \cos(\Theta)$$

$$Y(\Theta) = R(\Theta) * \sin(\Theta)$$

In the northern hemisphere, the X axis would increase positive moving east and the Y axis would increase positive moving north. In the southern hemisphere, the X axis would be the same, but the Y axis would increase positive moving south. This will assure the log spiral will spiral outwards in the correct direction for each hemisphere to match the cyclonic curvature of the storm rotation.

This analysis is a two step procedure consisting of two analysis processes. The size and resolution of the different analysis grids are hardcoded within the HIE algorithm, with a fine-resolution analysis grid embedded within a course-resolution grid. The first step is a “course-resolution” analysis, where the temperature gradient and log spiral analysis vectors are calculated at individual grid points (the origin point $R(\Theta)$ in the log spiral equation) within a 1.75° -radius circular analysis region at a “course” resolution of 0.2° . Once an intermediate maximum alignment center position is determined using the cross-product analysis, a second “fine resolution” analysis is performed in a rectangular region surrounding the initial center position at a 0.1° “fine scale” resolution to find the final spiral center determined position.

The resolutions of the course and fine scale analysis grids were chosen in order to try and optimize the computation time of the SC routine versus the ability of the routine to capture the rotational features of the image being examined. Since the routine is processing the image over an image of size $N \times N$ at each point within the analysis region at different analysis resolutions, any increase in analysis resolution will result in an increase in processing for each pixel on the order of N^4 . As computing power improves, an increase of the analysis resolutions can be considered (to eventually match the resolutions of the imagery being investigated), but currently the values utilized are optimized to allow for efficient and accurate processing.

The alignment is calculated by summing the cross-products of the image temperature gradient vector with an overlaid spiral unit vector field (Figure 2). The equation for the cross product is:

$$\mathbf{a} \times \mathbf{b} = a * b * \sin\Theta * \mathbf{n}$$

where:

a and b = magnitudes of vectors **a** and **b**

Θ = smaller angle between vectors **a** and **b**

n = unit vector perpendicular to the plane containing vectors **a** and **b**

As can be seen, the cross product value between the temperature gradient vector and the spiral vector will be maximized where the angle between the vectors is 90°. The vectors **a** and **b** can be defined as either the temperature gradient or the spiral vector field, but for this discussion, **a** is assigned to the temperature gradient vector and **b** is the spiral vector.

The initial SC analysis field normally takes shape as a “bull’s eye” pattern around the TC’s center of rotation. An additional “distance penalty function” field (a weak “bull’s eye” pattern centered on the first guess forecast position) is added to the initial spiral center analysis field to guide the storm center determination process away from the edges of the spiral center analysis region. The final “enhanced” spiral analysis field results. This approach has the advantage of using the composition of the whole image instead of just the orientation of the spiral bands. Also, by using only the curvature of the image, the algorithm is not drawn to high-temperature “moats”, but rather uses their curved shape as a guide to the optimal center. The technique closely mimics the method used by experienced meteorologists to determine a center of rotation because it naturally assigns appropriate weights to the rotation-induced gradients of all sizes. However, the algorithm can be quite sensitive to the effects of upper-level shear in IR imagery, leading to center estimates driven by patterns in the asymmetric cirrus clouds rather than low-level clouds defining the center.

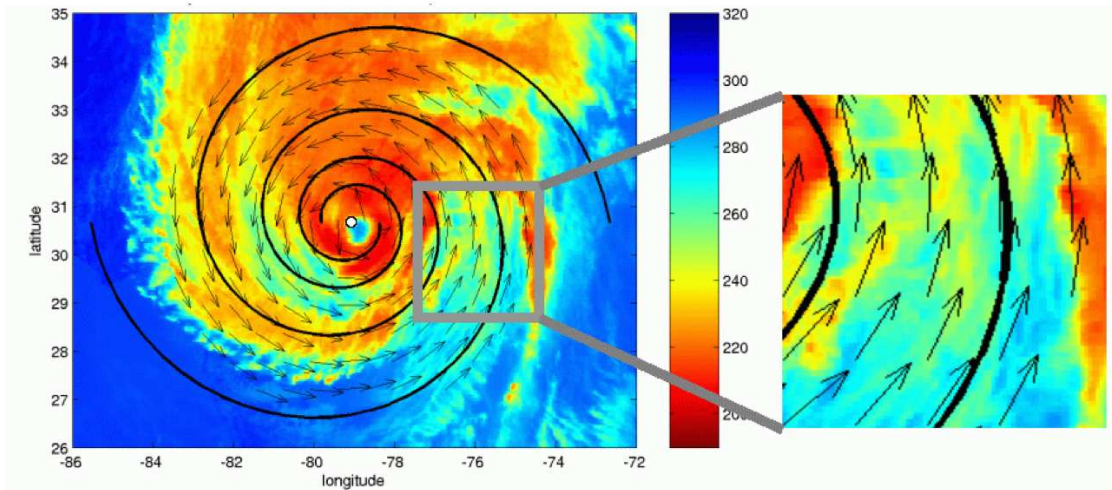


Figure 2: Example of a 5-degree log spiral field vector field. Black lines represent two spirals emanating from test center point (white dot). Arrows represent vector of log spiral at various points in analysis region.

Further calculation beyond the SC method is needed to resolve the exact center of rotation in storms which possess a well-defined eye (if one is present in the image being analyzed). Although finding the eye of a storm is a simple task for the meteorologist to perform subjectively, it is made objectively and computationally difficult by partial obscurations and nearby, oddly shaped high-temperature moats. To address this issue, the second technique is attempted at the completion of the SC process. The Eye Ring Fitting (RF) analysis method performs a search around the enhanced spiral analysis center point for the most intense gradients in a small ring-shaped area defining the storm eyewall. The dot product of the gradient field is summed for each point on each individual ring and center point, with the maximum value indicating the determined center point and TC eyewall size (Figure 3). The dot product equation is the following:

$$\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}| * |\mathbf{b}| * \cos\Theta$$

where:

Θ = angle between a and b vectors

In the RF routine, \mathbf{a} would be the temperature gradient vector at a specific point on the ring and \mathbf{b} would be the “position” unit vector from the center point to the ring at the point being analyzed.. When the vectors are in the same direction, the angle will be near zero, maximizing the product of the vector magnitudes. This process is performed over a circle of radius 0.75° from the center position corresponding to the spiral analysis center point determined in the SC routine. The resulting field is the final RF analysis score field.

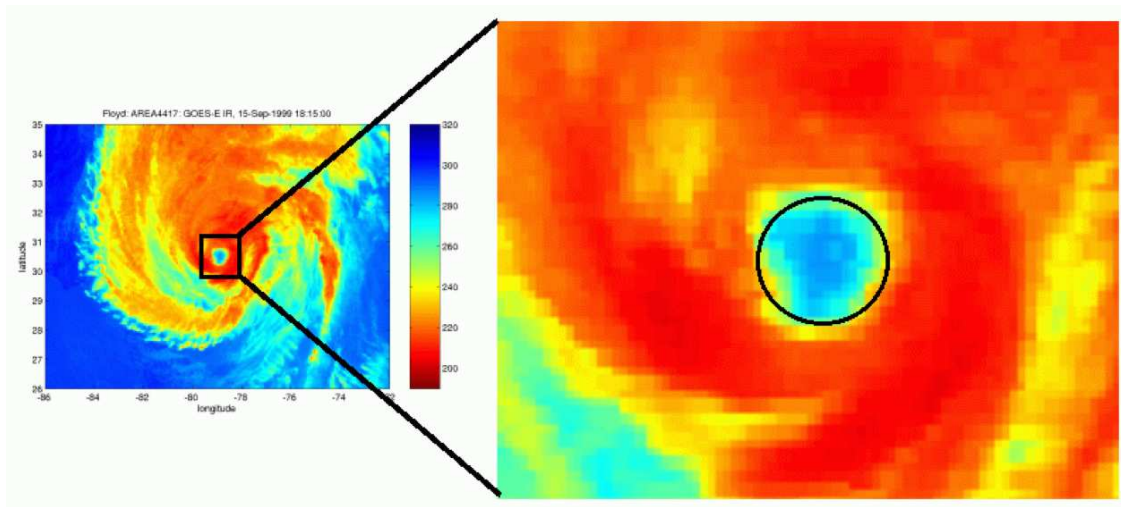


Figure 3: Example of eye ring analysis (black circle) which best matches temperature gradients of the eyewall feature in the tropical cyclone.

Once both analyses techniques have successfully completed, their derived center points and corresponding confidence factors are used to determine the “best” storm position for the scene being analyzed. The confidence factors score derivation process is performed in two steps. For each point an Enhanced Spiral Part (ESP) confidence score is derived by determining the minimum value of the sum of two weighted spiral values, as shown in the following equation:

$$\begin{aligned} \text{ESP score} &= \text{Distance Penalty (DP)} + \text{Spiral Part score (SP)} \\ \text{DP} &= \text{constant} * \text{distance of point from First Guess position} \\ \text{SP} &= 10 * (\text{spiral score at point} - \text{maximum spiral score}) \end{aligned}$$

Where “spiral score at point” is equal to the spiral score (from the SC routine process described previously) at each point in the analysis and “region maximum spiral score” is the maximum spiral score value within the analysis region. Basically this value is just the difference between the spiral score value at each individual point in the analysis region from the maximum spiral score value within the entire region.

If the position of the maximum ESP value (least negative) is outside of a set radii distance threshold (the maximum allowable displacement value of 1.15°) from the first guess position (forecast interpolation position), the ESP confidence factor will only be derived and the position of the ESP maximum will be used as the storm center position by the HIE algorithm. This will result in the “Spiral Centering” automated storm centering method type being used (ID value of 4 for parameter 32 in the history file listed in Section 3.3.2.1) and identified as “SPRL” in the History File Listing shown in Section 3.4.3.2.

If the position of the maximum ESP value (least negative) is within the set radius threshold of 1.15° , however, a second “distance weighted” Enhanced Spiral Part (ESPd) confidence score will be derived, adding the “Distance Bonus (DB)” value to the initial

ESP value. The DB value is a constant value (equal to 4.5) which will further weight all ESP score values within 0.25° of the derived Spiral Center position derived previously. This is done to further weight the scores in the calculation described next towards the previously calculated Spiral Center position.

A third confidence factor will be also be derived utilizing the RF routine analysis values. This value is simply a sum of the ESPd value and the ring fit analysis score value at the position being analyzed. This value is called the Combined Confidence (CC) factor value. If the maximum CC factor value is greater than an empirically determined value, the position of the maximum CC factor will be used as the final automatically-derived storm center position. This will result in the “Combination Ring/Spiral” automated storm centering method type being used (ID value of 5 for parameter 32 in the history file listed in Section 3.3.2.1) and identified as “COMBO” in the History File Listing shown in Section 3.4.3.2.

An example of an actual TC storm center selection process is shown in Figure 4. If the previous Final T# intensity was between 3.5 and 4.5, the Spiral Centering and Eye Ring Analysis positions will be used if three or more eye or embedded center scene types have been identified for previous intensity estimates prior to the current analysis date/time. This will ensure that the storm organization is sufficient for the different techniques to work properly and correctly estimate the storm center location. If less than three eye/embedded center scenes have been found, the forecast interpolation position will only be utilized. Once the Final T# value has exceeded 4.5, both auto-centering techniques will be attempted.

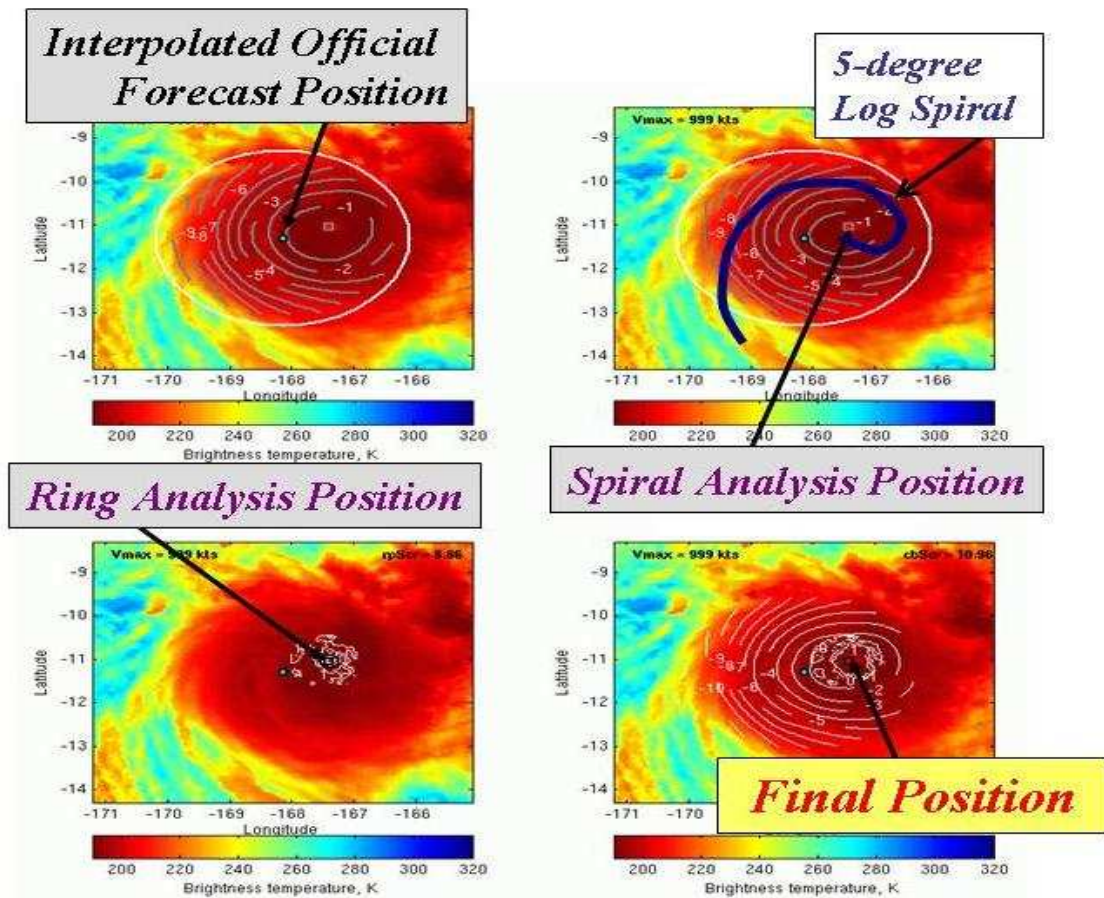


Figure 4: Four-panel image showing various steps, and resultant analysis for each step, in the automated storm centering routine. Upper two images show the initial and enhanced Spiral Centering (SC) contour analyses fields. The white oval represents the computation boundary of the SC analysis. Upper left is initial spiral analysis gradient field, with the enhanced SC in upper right (an example 5-degree log spiral is shown with blue line). Lower left shows contour field associated with Ring Fitting (RF) analysis. Lower right is combined SC and RF analysis contour field. Initial forecast position (blue dot) and subsequent intermediate and final center positions (red dots) are indicated.

3.4.2.2 Scene Type Determination

The ADT scene type determination process flowchart is shown in Figure 5.

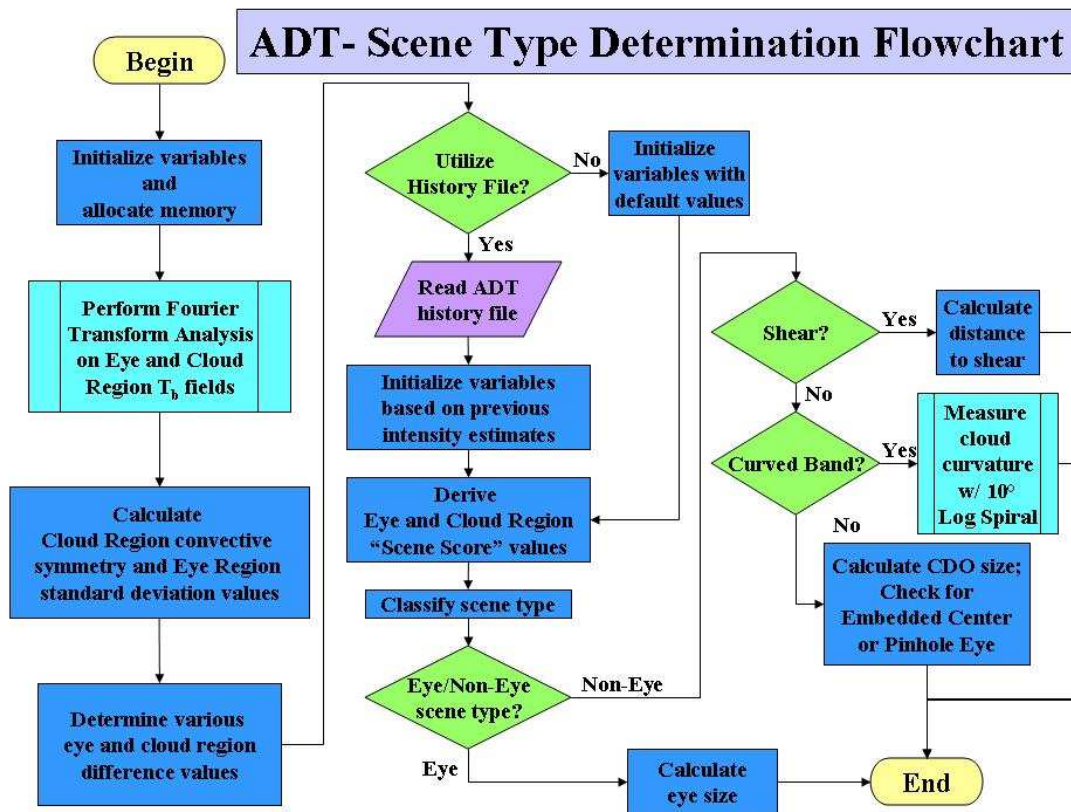


Figure 5: Scene Type determination flowchart.

3.4.2.2.1 Eye and Cloud Region Scene Score Determination

The original “decision tree” methodology of scene type determination patterned after the subjective Dvorak Technique has been replaced with a “scene score” determination scheme. This methodology helps alleviate the occasional rapid and unrealistic scene type variability in the ADT output between consecutive image analyses by replacing the “branches” in the decision tree methodology with natural threshold divisions (scores).

The scene score is a sum of selected environmental parameters measured from the satellite imagery for both the eye (when an eye is present, 0-24 km from the determined center position) and cloud region (24-136km from the center position) of the TC. These scores are used to objectively determine the storm scene type. Each parameter in the scene score derivation was originally a “branch” in the initial decision-tree methodology and is weighted by an empirically-determined value, shown in the equations listed below,

chosen to closely mirror the influence of the parameter in the original determination methodology.

The eye region scene score is derived with the following equation:

$$\text{Eye score} = \text{FFT}_{\text{Eye}} + \text{BD}_{\text{Eye}} + \text{PrevEye} + \Delta\text{T}_{\text{Eye-Cloud}} + \text{Adj}_{\text{T-12hr}}$$

FFT_{Eye} : Number of harmonics in eye region Fast Fourier Transform
 $1.0 - ((\text{EyeHarmonicValue} - 2) * 0.1)$

BD_{Eye} : BD-enhancement category of eye region temperature
 $-1.0 * (\text{EyeBDCat} * 0.5)$

PrevEye : Adjustment for previous record eye scene
 $+0.25$

$\Delta\text{T}_{\text{Eye-Cloud}}$: Difference between eye and cloud region BD-enh. categories
 $(0.25 * (\text{CloudBDCat} - \text{EyeBDCat})) +$
 $(0.50 * (\text{CloudCWBDcat} - \text{EyeBDCat}))$

$\text{Adj}_{\text{T-12hr}}$: Adjustment for 12-hour previous record T# strength
 $\text{MAX}(-1.0, \text{T\#Value}_{\text{T-12hrs}} - 4.5)$

The cloud region scene score is derived with the following equation:

$$\text{Cloud score} = \text{BD}_{\text{CloudCW}} + \text{BD}_{\text{Cloud}} + \text{FFT}_{\text{Cloud}} + \text{PrevScene} + \text{Adj}_{\text{T-12hr}}$$

$\text{BD}_{\text{CloudCW}}$: BD-enh. category of “coldest-warmest” cloud region temp.
 $\text{CloudCWBDcat} * 0.25$

BD_{Cloud} : BD-enhancement category of eye region temperature
 $\text{CloudBDCat} * 0.25$

$\text{FFT}_{\text{Cloud}}$: Adj. based on harmonics in cloud region Fast Fourier Trans.
 $\text{If}(\text{CloudHarmonicValue} \leq 2) \text{value} = \text{MIN}(1.5, \text{BD}_{\text{CloudCW}} * 0.25)$

PrevScene : Adjustment for previous record cloud scene
 -0.50 if curved band or shear scene

$\text{Adj}_{\text{T-12hr}}$: Adjustment for 12-hour previous record T# strength
 $\text{MIN}(1.0, \text{T\#Value}_{\text{T-12hrs}} - 2.5)$

More specific definitions and measurement details of utilized temperature categories and values, such as the “coldest-warmest” cloud region temperature value and BD enhancement category, are discussed here and in the following sections of this document.

- EyeHarmonicValue: Count of the number of times the harmonic values in the Fast Fourier Transform analysis increases over the previous value. Each harmonic value corresponds to a single cosine wave, at different frequencies, used to approximate the temperature histogram for the image region being investigated. More changes in the values indicate more harmonics and a less uniform temperature scene in the eye region.
- CloudHarmonicValue: Same as EyeHarmonicValue, but with cloud region.
- EyeBDCat: Gray scale category within the BD-curve enhancement of the eye region temperature value. The BD-curve enhancement is shown in Figure 7, with Table 5 listing the temperature breakdown values for each gray scale range..
- CloudBDCat: Same as EyeBDCat, but with cloud region temperature value.
- CloudCWBDcat: Same as EyeBDCat, but with cloud region “coldest warmest” temperature value.
- T#Value_{T-12hrs}: Final T# value at time 12 hours previous of current time.

The Fast Fourier Transform (FFT) analysis is a well established and documented mathematical function to determine the variability of a “signal” over its range of values. In this case, the signal is the temperature histogram over a set temperature range. The FFT attempts to approximate this signal using a combination of a number of cosine waves with different frequency. A histogram with containing a large number of values in a small number of bins can be estimated with a low frequency cosine wave, while more chaotic histograms with more temperature value bins containing data can be approximated by the combination of several cosine waves at different frequencies.

Additional environmental variables are used in several specific checks to further refine eye and cloud scene types after the individual scene score values have been derived, such as the cloud symmetry value (discussed in Section 3.4.2.4.2) to help determine an ‘Irregular CDO’ scene, or eye radius size to define a ‘Large Eye’ scene.

3.4.2.2.2 Eye and Cloud Region Scene Types

The three eye region scene types and five cloud region scene types are described below:

<u>Eye Region Scene Type</u>	<u>Description</u>
EYE	Any eye type (clear, ragged, and obscured)
PINHOLE	Very small eye/pronounced warm spot
LARGE	Clear, well-defined eye with radius ≥ 38 km
<u>Cloud Region Scene Type</u>	<u>Description</u>
UNIFORM CDO	Overcast cloud region with uniform temperature structure
EMBEDDED CENTER	Arc of convection within central overcast cloud region
IRREGULAR CDO	Cloud region over storm center, but large shift in coverage

CURVED BAND
SHEAR

Curved cloud region surrounding circulation center
Displaced convection and exposed circulation center

Examples of ADT Eye Region Scene Types

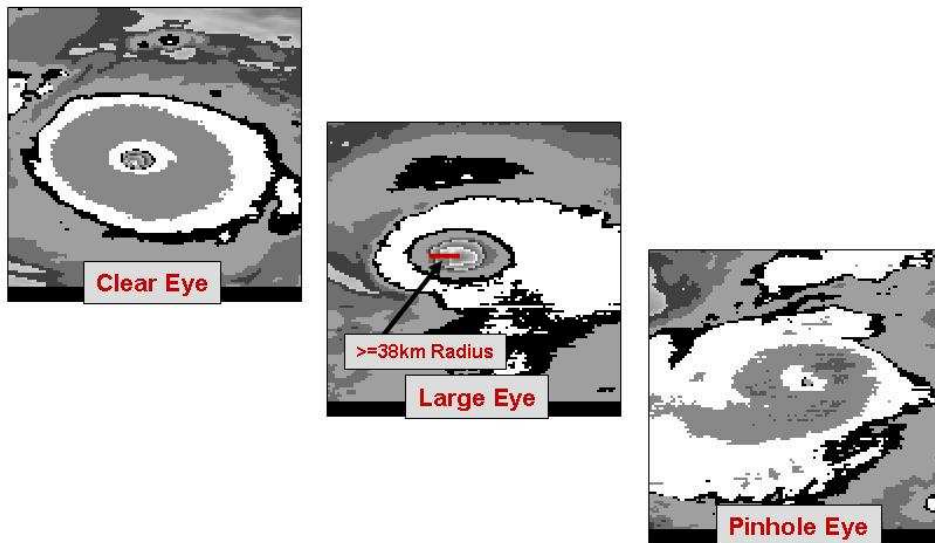


Figure 6: Examples of three ADT Eye Region scene types.

Examples of the three eye scene types are shown in Figure 6. Eye size is derived by measuring the distance across the eye between BD-curve “Dark Gray” temperature range edges (Figure 7). Table 5 lists the temperature ranges and the corresponding “gray scale” color values. Distances are measured at 90° angles outward from the auto-selected center location and are averaged to give an approximate eye size.

Temperature Range	Gray Scale Category/Comment	Value
> +9°C	No enhancement – Low clouds	0
+9°C to -30°C	Off White – Cirrus Outflow Pattern	1
-30°C to -42°C	Dark Gray	2
-42°C to -54°C	Medium Gray	3
-54°C to -64°C	Light Gray	4
-64°C to -70°C	Black	5
-70°C to -76°C	White	6
-76°C to -80°C	Top Medium Gray	7
< -80°C	Top Dark Gray	8

Table 5: BD-curve enhancement temperature and corresponding gray scale values.

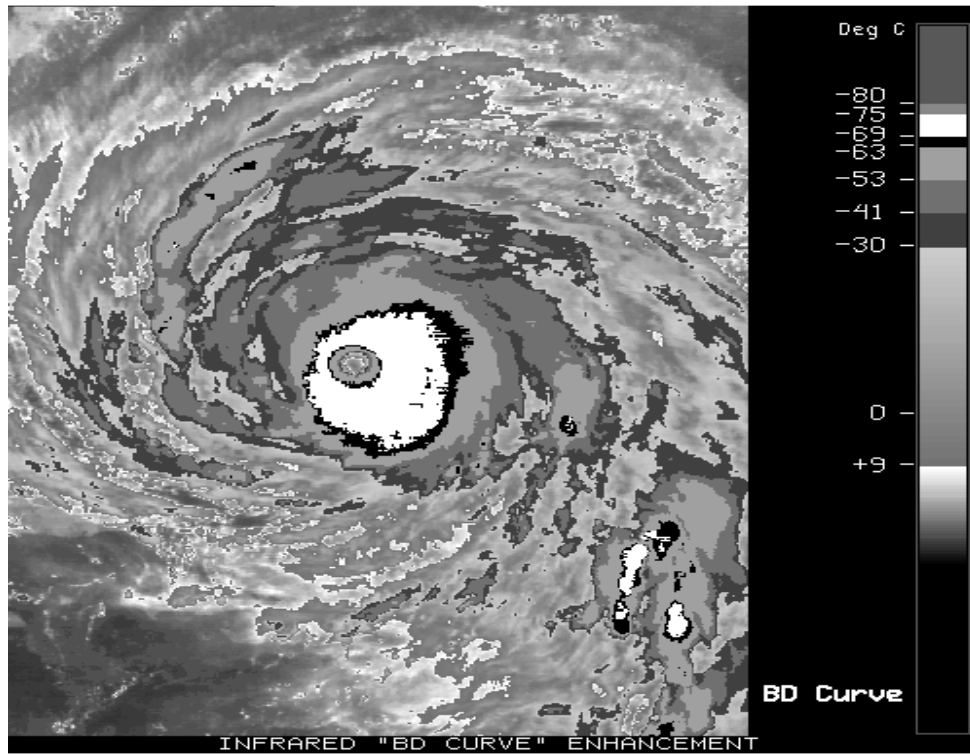


Figure 7: BD-curve Enhancement displayed on a longwave window channel infrared image.

Examples of ADT Cloud Region Scene Types

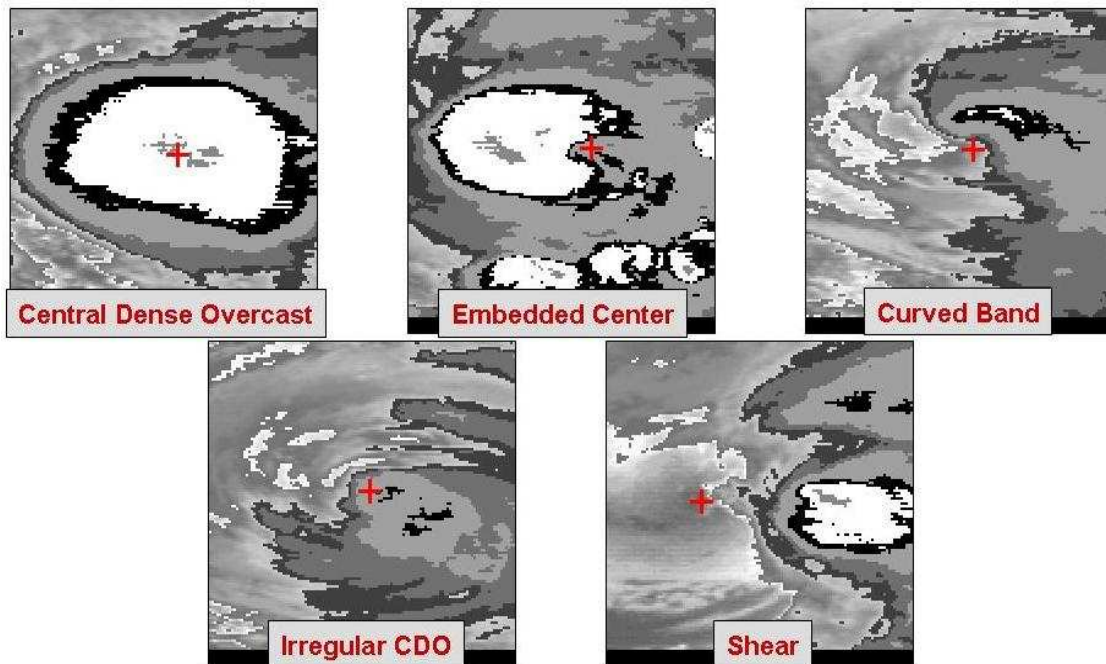


Figure 8: Examples of the five ADT Cloud Region scene types.

Examples of the five cloud region scene types are shown in Figure 8. If the cloud scene is determined to be a “Curved Band” type scene, a 10° Log Spiral analysis will be performed to determine the curvature extent of the convective cloud region around the selected center position (described in greater detail in Section 3.4.2.4.3). The amount of curvature depends on the BD-Curve Gray Scale (Table 5) being used. The algorithm will first target the “Light Gray” gray scale range to define the convective region of the curved band area. If this temperature region is devoid of significant activity or completely surrounds the selected storm center position in this gray scale range, analysis of warmer/colder ranges BD-curve temperature levels will be performed. Once a Curved Band gray scale and curvature amount at the provided storm center location is determined, an additional search will be performed to look for another possible storm center location that yields a greater amount of curvature in the cloud region, and thus a higher intensity estimate. This maximum curvature search value is supplied only as a reference to the HIE user and is not utilized in any way by the HIE algorithm or stored in the history file for future use/reference. It is supplied at the request of ADT users to help assess the accuracy of the curved band intensity calculation and to aid TCFC forecasters in the TC storm center determination process for possible storm center location adjustment. The location and associated amount of maximum cloud curvature can vary greatly from image to image, so interpretation of its value is left to the user to assess.

Once the scene type has been determined the intensity estimate for the derived scene type will be calculated using various environmental values such as the eye and surrounding cloud top temperatures, convective symmetry, eye and cloud region sizes, and other measured or derived values stored in the history file using various methods described in the following sections.

3.4.2.3 Eye and Surrounding Cloud Region Temperature Determination

Proper determination of the storm center position is paramount for an accurate storm intensity estimate since the eye and cloud region temperature value calculations are heavily dependent on this location.

Determination of the eye region temperature is relatively straightforward. This temperature is assigned the value of the warmest pixel within a 24 km radius from the user or automated storm center location. Since an incorrect eye temperature can lead to an incorrect intensity estimate, proper selection of the storm center location is essential. Note: The ‘eye’ terminology can be misleading, as this temperature is calculated even if a storm eye is not present. It basically represents a center, or core temperature, and is derived and utilized by the ADT even in non-eye scenes/situations.

The calculations of the two surrounding cloud region temperature values are a bit more complicated than for the eye temperature. The first cloud region temperature value computed uses the storm center location and lies between an annulus of 24 and 136 km from the center location. Pixel-width rings within this annulus are then analyzed (e.g.,

for a 4 km resolution infrared image, there will be $(136 - 24)/4 = 28$ rings). On each ring the warmest brightness temperature is found and stored. The coldest of these ‘warmest’ values is then selected, and referred to as the “coldest-warmest” temperature. It is used only in the determination process for the cloud region scene type. The ring number (CWRN) distance (in km from the storm center location) on which the “coldest-warmest” temperature value is located is used in the determination of the final “mean” cloud region temperature discussed below. For more information about this value, see Velden et al. (1998) and Zehr (1989).

The second temperature value computed is the “mean” cloud region temperature, and is the actual value that is assigned as the ADT’s final cloud region temperature used in subsequent intensity determinations. First, an 80km wide annulus region is determined around the storm center location, with the annulus midpoint centered on the CWRN distance explained above. Typically the minimum inner/maximum outer radius of the annulus will be the CWRN distance minus/plus 40 km. The minimum inner radius, however, is restricted to 24 km from the storm center location. There is no corresponding maximum limit on the outer radius distance. For example, if the CWRN distance is 48 km, the inner distance, if centered upon this point, would be at 8km. Since the minimum annulus radius cannot be less than the minimum value of 24 km (not 8 km), and the annulus will always be 80km wide, the outer distance will be 104km. Once the annulus is defined, it is divided into 24 arc regions (15° each) and the average temperature of each arc is calculated. The mean of the 24 average arc temperature values is computed and assigned as the final ADT cloud region temperature value.

The cloud region “coldest-warmest” (CloudCW) temperature value is a “historical” temperature value that mimics the cloud temperature value utilized in the original Dvorak EIR technique. The CloudCW value was utilized in older versions of the algorithm as the final cloud region temperature value, but it was replaced with the “mean” temperature value after a close examination of both values found that the CloudCW temperature value varied significantly more than the mean value. The intensity estimates computed using the coldest-warmest temperature values were also found to be inferior to the intensity estimates using the mean temperature values, thus the change was implemented. The CloudCW value is still utilized within the ADT scene selection process as described above, so the calculation of the value still remains within the ADT algorithm and the derived parameters are saved in the ADT history files.

3.4.2.4 Intensity Estimation Processing

The HIE/ADT hurricane intensity estimation processing scheme involves several steps, as shown in Figure 9. Many of the specific elements involved in the intensity estimation derivation process are discussed in detail in the following sections. Intensity constraint rules are discussed in detail in Section 3.4.2.6.

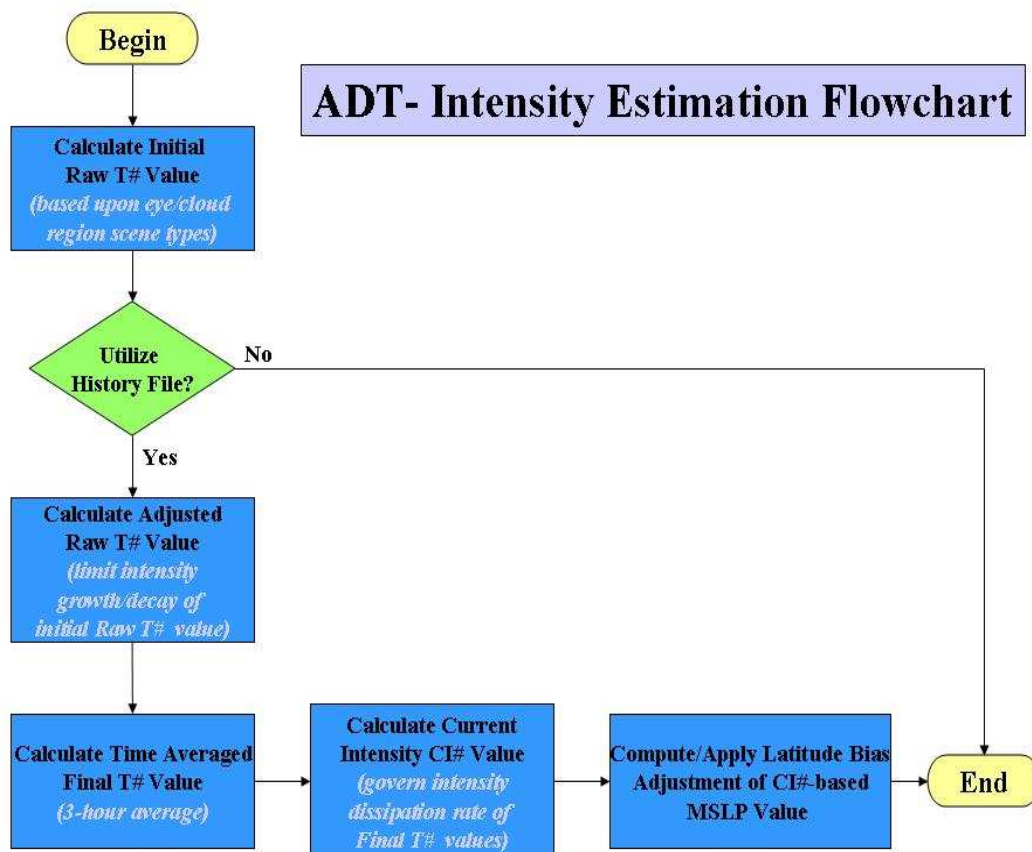


Figure 9: ADT Intensity Estimation flowchart.

3.4.2.4.1 Intensity Estimate Derivation Methods

As discussed in the Algorithm Overview in Section 3.1, the ADT is originally based upon the operationally-utilized Subjective Dvorak Enhanced Infrared 'EIR' Technique (SDT). Several deviations from the original SDT have been included into the ADT in order to improve upon the initial implementation of logic from the SDT into the ADT. The primary advancement involves the utilization of linear regression equations relating various cloud parameters to TC intensity. These equations were implemented for all eye scenes and several of the cloud scenes described in Section 3.4.2.4.2. The remaining

scene types not utilizing regression-based methods have also been improved to better correlate their specific cloud parameter measurements to TC intensity.

3.4.2.4.2 Regression-based Intensity Estimates

As mentioned previously, a regression-based analysis scheme was implemented in order to better correlate ADT eye and cloud region temperature measurement values with observed intensity. Measured values such as maximum eye region and minimum cloud region temperatures have been used historically in the SDT and early versions of the ADT to estimate TC intensity in all eye scene types as well as the CDO (and Irregular CDO) and Embedded Center cloud scene types. These parameters worked well in most cases, but additional methods were explored to better assess the TC intensity. Using linear regression analysis, additional parameters were found to aid significantly in the process of estimating TC intensity using infrared window imagery. A schematic representation of the regression-based parameters used in the ADT is provided in Figure 10.

The cloud symmetry value measures the temperature difference between opposing sides of the storm to assess the structure of the convection surrounding the eyewall region of the TC. Storms possessing a more symmetric convective structure (smaller temperature differences between opposing sections of the storm eyewall cloud region) are typically more intense than storms with asymmetric convection. This parameter is actually indirectly included in the SDT EIR technique via measurements of the width of the various BD-enhancement gray shades surrounding the storm center position as well in the “climatological” pattern-T# comparison diagrams. The cloud symmetry value is obtained by determining the average cloud top temperature value within the 24 sectors defined earlier (15-degree arcs, 80-km wide annulus from storm center with distance from eye pre-determined by warmest-coldest ring value). Opposing sector values (180-degree rotation) are differenced and summed around the storm center. These twelve values are then averaged to determine the final cloud symmetry value.

Another important parameter is the size of the central dense overcast, or CDO scene type, region in a non-eye situation. This parameter mimics the SDT which also makes use of a CDO size parameter to help assess the current strength of the storm. The impact of this value itself is not large, but it was found to be a significant contributor to estimating intensity in these situations when combined with the other parameters. The value is derived by simply averaging the diameter measurements of the storm CDO along four axes centered on the storm center position. The CDO edge is defined as the boundary between the Light Gray and Medium Gray shades in the BD-enhancement shown in Figure 7 and listed in Table 5.

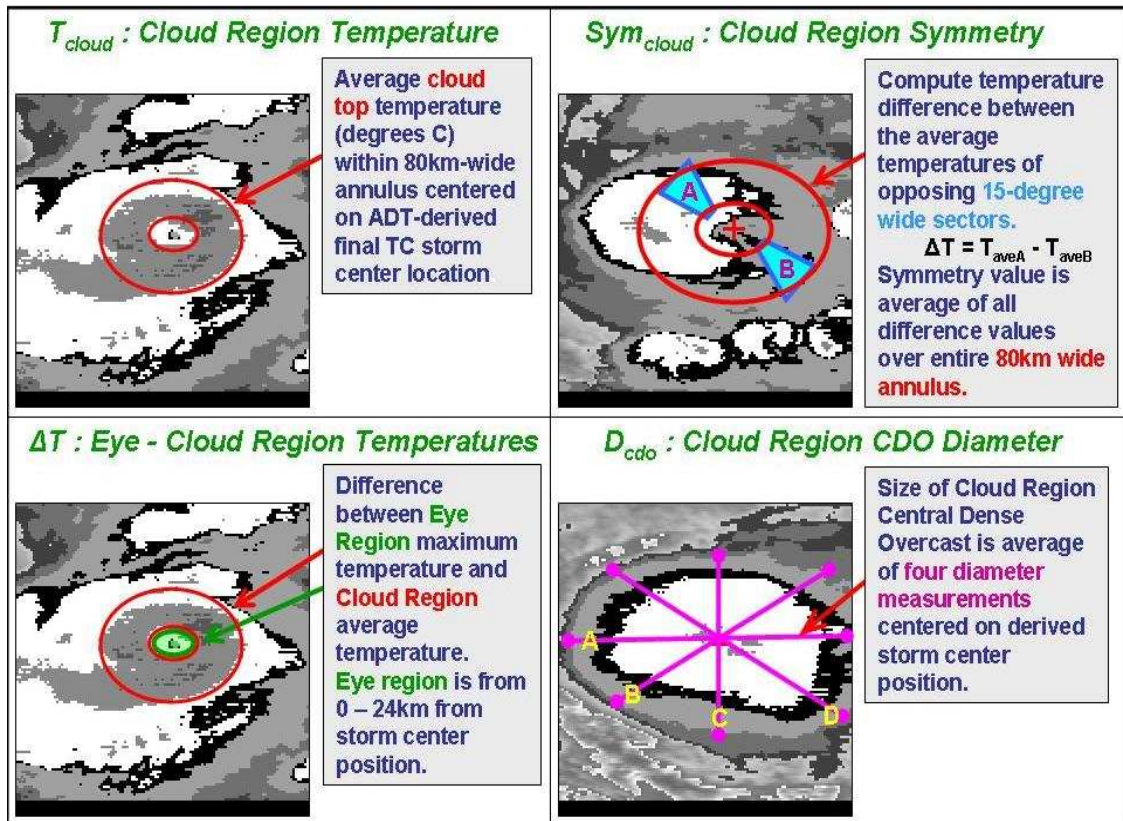


Figure 10: Schematic representation of the four regression equation parameters.

Two separate regression equations are used in the ADT; one equation for the eye scene types and one equation for the cloud scene types. The equations yield intensity estimates in terms of T# values which can be converted to MSLP or Maximum Wind Speed (as discussed in Section 3.4.2.5.:

$$\text{Eye Scenes: Intensity} = 1.10 - 0.070 * T_{cloud} + 0.011 * \Delta T - 0.015 * Sym_{cloud}$$

$$\text{Cloud Scenes: Intensity} = 2.60 - 0.020 * T_{cloud} + 0.002 * D_{cdo} - 0.030 * Sym_{cloud}$$

- T_{cloud} : Cloud region average temperature (deg C)
- ΔT : Eye (max) – cloud (ave) region temperatures (deg C)
- Sym_{cloud} : Cloud region temperature symmetry (deg C)
- D_{cdo} : Cloud region CDO size (km)

Significant correlation improvements between ADT intensity estimates and aircraft reconnaissance intensity observations were realized with the implementation of the new regression equations over the previous intensity estimation techniques. The cloud scene correlations improved from 0.28 to 0.50, while the eye scenes improved from 0.62 to 0.70. The improvement in the cloud scene correlation is most significant since the CDO scene type still remains the most troublesome area within the ADT algorithm and one that continues to merit research attention.

3.4.2.4.3 Non-Regression Intensity Estimates

The remaining cloud scene types that do not utilize a regression-based intensity estimation scheme are the Curved Band and Shear scenes. Intensity estimates for these two scenes rely on techniques based on the original SDT. The Shear scene type measures the distance between the determined storm center position (usually the interpolated forecast position) and the leading edge of the main convective region defined as the minimum distance to the “Dark Gray” BD-curve Gray Scale temperature range (Table 5). The value of this distance is then related to intensity; the greater the distance the weaker the storm intensity. A distance of 140km or greater will correspond to a T# intensity of 1.5, with an increase in intensity of 0.5 for every 30km distance reduction (except for the following two exceptions; 1.) At 80km, the intensity is 2.25; and 2.) Between 0 and 35km, the T# intensity is at its maximum value of 3.5). Subsequent modifications have improved the identification of the edge of the main cloud region, leading to superior intensity results for this scene type.

The Curved Band scene type utilizes a methodology similar to the one used in the automated storm center determination scheme described in Section 3.3.2. This technique utilizes a 10-degree log spiral to measure the amount of convection and determines the amount of curvature, in terms of 15° segments, in the cloud region surrounding the storm center. The technique to compute the curvature measures the cloud top temperature at each point on the log spiral in 15° steps along the spiral. The measured temperature must be colder than the specific threshold temperature value being checked to be classified as convective cloud. The specific threshold temperature values correspond to the maximum temperature values within each gray scale temperature range listed in Table 5. The gray scale ranges between the Dark Gray and White enhancement ranges, inclusive are utilized in this process. Each point on the log spiral arc are checked at 15° increments, with a count of “consecutive cloud segments” retained to find the maximum number of consecutive segments in each gray scale range, if available. Consecutive cloud segments are counted on this arc to determine the amount of curvature (24 segments would correspond to 360-degrees of curvature).

The Light Gray temperature range is checked first, with warmer ranges checked if the number of consecutive segments does not exceed seven segments. If a gray range is not found in these three ranges, the scene type is assumed to be a shear scene. If the Light Gray region is found to possess more than 25 consecutive segments, the routine will then check the curvature of the Black and White temperature ranges. If each number of consecutive segments in the Black and White ranges are also greater than 25, the scene type will be assigned a CDO/Embedded Center scene type, otherwise the scene will be assigned a Curved Band scene type. The amount of curvature is then related to a T# intensity value based upon the original Dvorak Technique (with an additional adjustment provided for curved bands measure from the Black and White temperature ranges). For less than 20% curvature the T# intensity will be equal to 1.5. Between 20% and 40% curvature, the T# range will increase from 1.5 to 2.5. Above 40% curvature the T# intensity will increase by 0.5, starting at 2.5 for 40% to 4.0 for 100% (and up to 4.5 for

120% curvature). T# values are interpolated to the nearest 0.1 increment between the curvature threshold values listed.

The storm center utilized for the Curved Band scene is primarily the interpolated official forecast since the storm strength is typically too low for the auto-centering techniques to be used. The 10-degree log spiral is rotated in 10-degree increments around the storm center to find the maximum cloud curvature amount at the selected center position. A search for the storm center position that yields the highest value is also conducted and output to the user for reference if it does not correspond to the original, interpolated forecast position.

3.4.2.5 Intensity Estimate Conversion: T#/CI# to MSLP/Maximum Wind

The ADT intensity estimates are derived in terms of T# and CI#, which are a holdover from the SDT, where higher values correspond to stronger, more intense tropical cyclones. The T# is short for “Tropical Number”, and is defined in the SDT in relation to storm strength categories of mean sea level pressure (MSLP) and maximum sustained surface wind speeds (Dvorak 1984). The T# represents the “current” intensity of the storm. There are three T# values derived by the HIE; the Raw T#, the Adjusted Raw T#, and the Final T# values. These are explained in the following section (Section 3.4.2.6).

The Current Intensity (CI#) is derived from the HIE Final T# value after a final set of time-based intensity constraint rules/adjustments are applied after the storm has stopped (temporarily?) strengthening, and represents the final intensity estimate output by the HIE. The three T# and CI# values can differ depending on the current intensity status of the storm and how it has changed over a given period of time (the constraint rules can vary over different time periods), but each value provides information about the current storm status and evolution.

The empirically-derived relationship between the CI# and storm intensity categories is given in Table 6 for the Atlantic TC basin (after Dvorak, 1984). The Northwest Pacific basin relationships (Shewchuck and Weir, 1980) differ slightly (not shown). Thus, proper identification of the correct relationship to use is essential for conversion of the CI# to intensity. The ADT can automatically determine the conversion method “basin” based upon the longitude value of the selected storm center location. A storm west of the international dateline (180° E/W) and east of the Prime Meridian (0° E/W) is designated as a Northwest Pacific storm (regardless of N/S hemisphere), with all other storms designated as Atlantic basin (in consultation with users).

It should be noted that for T#/CI# values greater than 8.0 or less than 2.0 in Table 6, the MSLP estimates were not provided by the original Dvorak study, and are thus extrapolated in the ADT by using MSLP gradients from preceding/following categories in the conversion table. These values include those found between 1.0 and 2.0 and between 8.0 and 8.5.

Classification (approx)	CI# Value	Wind Speed (kts)	MSLP (hPa)
	1.0	25.0	1014.0
	1.5	25.0	1012.0
	2.0	30.0	1009.0
Tropical Storm	2.5	35.0	1005.0
	3.0	45.0	1000.0
	3.5	55.0	994.0
Hurricane – Cat 1	4.0	65.0	987.0
	4.5	77.0	979.0
Hurricane – Cat. 2	4.7	82.2	975.4
	5.0	90.0	970.0
Hurricane – Cat 3	5.2	94.8	966.0
	5.5	102.0	960.0
Hurricane – Cat 4	6.0	115.0	948.0
	6.5	127.0	935.0
Hurricane – Cat 5	6.8	134.8	926.6
	7.0	140.0	921.0
	7.5	155.0	906.0
	8.0	170.0	890.0
	8.5	185.0	873.0

Table 6: Relationships between ADT-derived CI# values and TC maximum sustained surface wind speed and mean sea level pressure (MSLP) values for Atlantic basin storms.

3.4.2.6 Intensity Constraint Limits (Dvorak EIR Rule 8)

The ADT limits the magnitude of intensity change between estimates based on a modification to the SDT EIR Rule 8 which constrains the rate of increase or decrease of the Raw T# intensity estimate (value initially determined by the scene type and/or regression analyses, and before any rules or adjustments are applied) based upon specified rates of change over designated time periods. The rate of change checks are performed against the Final T# (after rule adjustments and time averaging described later) values stored in the history file for times prior to the current analysis time. The rate of change allowance is dependent upon the current intensity of the storm, as defined in the Dvorak EIR technique (Dvorak 1984). The Final T# value of the record immediately prior to the current analysis time is used as the current intensity estimate. When the intensity of the storm is less than T4.0, the current Raw T# rate of change cannot exceed ± 0.5 T# over 6 hours. If greater or equal to T4.0, the rate of change of the Raw T# value cannot exceed the following rates: 1.0 over 6 hours, 1.5 over 12 hours, 2.0 over 18 hours, and/or 2.5 over 24 hours.

The ADT also employs a modified version of this rule based upon the current scene type analyzed: The allowable rate of change is reduced by 0.5 during most non-Eye scene types (Curved Band, CDO, Embedded Center), so that the amount of change is limited to 0.5/1.0/1.5/2.0 T# over 6/12/18/24 hours. For Eye scenes the amount of allowed change

is increased by 0.5 to 1.5/2.0/2.5/3.0 T# over 6/12/18/24 hours. The latter modification allows the Final T#/CI# to increase at a quick enough and realistic rate during “rapid intensification” events. For Shear scenes, the rate of change rule is unmodified from the original SDT EIR Rule 8.

If one of the criteria is exceeded, the Adjusted Raw T# (value after all rules/adjustments, but before time-averaging) will be assigned the maximum/minimum value allowed by the above criteria, and will be used in the determination of the corresponding Final T# and CI# values. Note: The unadjusted Raw T# value is always stored in the history file for reference to the raw intensity estimates before any adjustments.

As a final “gross error check” for the Raw T# values derived by the ADT, a supplementary Rule 8 rule has been added to the constraint limits listed above. This additional rule will limit the growth of the Raw T# value by 0.5 over 1 hour. Implementation of this rule was found to be necessary due to the inherent variability of the ADT during “scene type transitions”, especially between eye and non-eye cases. Due to the completely objective nature of the scene determination scheme, and the discrete threshold values that are used to define the different scene types, changes between scene types can result in unrealistic jumps in Raw T# values from one intensity estimate to another. The addition of this rule produces estimates that are reasonable when these types of scene changes occur, but will not allow the Raw T# values to change at a rate greater than observed in nature.

Implementation of this modified rule has allowed for the Final T# calculation to be changed from a time-weighted 6-hour average to a 3-hour average (discussed in the next section). By utilizing the 3-hour scheme, the admissible rate of change of the Final T# value is greater than with the 6-hour scheme, making for more allowable rapid increases in intensity over short time periods that can be associated with storms undergoing rapid intensity changes.

3.4.2.7 Time Averaging Scheme

Time-averaging of ADT intensity outputs is employed to smooth the “noise” inherent in individual estimates, which as mentioned above can result from objectively changing scene types and crossing value thresholds in consecutive analysis times. The time-averaging scheme uses the current Raw T# and all available Raw T# values obtained within the last 3 hours. The time-average is a straight non-weighted mean of these estimates. The 3-hr time window for the averaging is based on empirical analysis noted above, and user preference input. The ADT Final T# at any current analysis time reflects this time-averaged value.

3.4.2.8 Weakening Flag (Dvorak EIR Rule 9)

The ADT Weakening Flag is modeled after the STD EIR Rule 9 (Dvorak, 1984), but also utilizes a modification to the original STD EIR Rule 9 that is applied at some operational TC forecasting centers. The “original” STD EIR Rule 9 rule is used in the determination of the CI# after a storm has reached its maximum intensity and is weakening during the dissipation stage of the TC lifecycle (e.g. extra-tropical transition, moving over cold waters, interacting with severe atmospheric shear, etc). The EIR Rule 9 will hold the CI# at values 0.5 to 1.0 higher in value than the current Final T# (Raw T# after adjustments and time-averaging). Subjective application of this rule (e.g. how and when to apply it) varies between forecasters and is the focal point of much debate. The value of 1.0 is utilized in the ADT since it provides the most statistically accurate estimates of storm intensity when compared with actual reconnaissance observations.

The “modified” Weakening Flag rule logic affects the calculation of the CI# during the formation/strengthening stage of the storm prior to maximum TC intensity (where the “original” Rule 9 rule will be invoked) as follows: “Always hold the CI# to the highest Final T# over the last 6 hours, but never greater than 1.0, in all cases”. This rule will hold the ADT CI# equal to the highest Final T# obtained during the previous 6 hours. For example, if the Final T# value had previously obtained a value of 5.2, but now is decreasing, the CI# value will be held at 5.2 for up to 6 hours or until the Final T# falls below 4.2. This rule is dis-invoked if the TC re-strengthens to the held CI# and greater intensity values.

3.4.2.9 Rapid Weakening Flag

It is commonly observed that TCs can dissipate at a very rapid rate as they move over colder waters. However, the Dvorak Technique Rule 8 and Rule 9 constrain the rate of dissipation and it is believed that these rules do not allow for the rapid dissipation rates commonly observed in the East Pacific region (and periodically noted in other oceanic regions).

In order to alleviate this limitation, the Dvorak EIR Weakening Rule 9 has been modified to allow the CI# intensity estimate to reflect this commonly observed phenomenon. The ADT Rapid Weakening Flag relaxes the application of the original Rule 9 intensity adjustment to the Final T# when determining the CI#. Normally, up to 1.0 T# is added to the current Final T# value to come up with the CI#. In cases where rapid weakening is determined, the additive value is modified to 0.5. To be identified as a possible rapid weakening event, the Adjusted Raw T# values over the previous six hours are evaluated. If the slope of these values is less than $-0.5/6$ hours the weakening flag is tripped and subsequently observed for an additional six hours. If over a second six hour period the slope does not increase over the threshold, the rapid weakening flag is turned on and the CI# additive constant is adjusted from 1.0 to 0.5. The rapid weakening flag is held on until the slope of the Adjusted T# values over six hours becomes greater than $-0.37/6$ hours. If this condition is exceeded for a continuous period of six hours, the rapid weakening flag is then turned off and the additive value returns to 1.0.

3.4.2.10 MSLP Latitude Bias Adjustment

If the Knaff/Zehr pressure/wind relationship is not utilized by the ADT (Section 3.3.2.5), the MSLP value output by the ADT will include an adjustment based on the latitude of the storm, designed to eliminate a bias noted by Kossin and Velden (2003) in the ADT-derived MSLP values and underlying Dvorak Technique. The equation used for this adjustment is:

$$CI\#_{adj} = CI\#_{orig} + (7.325 - (0.302)*ABS(latitude))$$

This equation requires the $CI\#_{orig}$ value to be entered in units of pressure (hPa). Since the ADT produces estimates in terms of T# values, the $CI\#_{orig}$ value must be converted to millibars before the adjustment equation is applied. The pressure adjustment value is stored in a history file.

The MSLP bias adjustment is only applied to scene types that utilize eye and cloud temperature values to determine the strength of the storm since the bias is related to corresponding temperatures associated with a higher/lower tropopause height. In order for the adjustment to be turned “on”, six hours of continuous “EIR-type” scenes must be present. These types of scenes are CDO, Embedded Center, and Eye scenes, while non-EIR scenes include Shear, Curved Band, and Irregular CDO. Once the scene criterion is met, the bias adjustment is blended into use over the next six hours using a time-weighted multiplication factor, ranging from 0.0 at the initial time to 1.0 at the six hour time period, with the determined latitude bias adjustment value.

For more specific information about the latitude bias adjustment, please refer to the following online document (Kossin and Velden, 2003) at:

http://www.ssec.wisc.edu/~kossin/articles/kossin_velden_MWR.pdf

3.4.2.11 Radius of Maximum Wind Estimate

The ADT invokes a subroutine after each intensity estimate to approximate the radius of maximum wind (RMW). This subroutine calculates the RMW using a regression equation derived from historical comparisons between IR imagery cloud top temperature fields and collocated in-situ reconnaissance aircraft radius of maximum wind measurements. If the derived ADT cloud region temperature (described in Section 3.4.2.3) is colder than -50°C , the distance from the storm center to the -45°C cloud top temperature isotherm is measured in four directions and averaged to produce a final distance measurement. The RMW location (in kilometers from the storm center position) is then determined from this distance using the equation:

$$RMW = 2.8068 + (0.8361*dist)$$

If the ADT derived cloud top temperature value is warmer than -50°C , the distance to the isotherm defined by the equation $(ERT + 2.0*CRT)/3.0$, where ERT is the eye (center)

temperature and CRT is the cloud region temperature, is used in the above equation to determine the RMW value.

3.4.2.12 Passive Microwave (PMW) Eye Score

In order to try and alleviate a long standing issue with obtaining accurate intensity estimates with the ADT during Central Dense Overcast (CDO) scene types, an external routine, using passive microwave (PMW) imagery, is used to derive an “eye score” value that the ADT can use to obtain a more accurate intensity estimate than can be obtained with the IRW imagery alone. The process of how the PMW eye score is derived will be detailed in a yet to be written document.

Once the eye score is derived, the score and the PMW scan date and time information is passed into the ADT algorithm. Typically the eye score information is delayed from the current IR analysis time by anywhere from one hour to longer delay periods. This does not pose a problem for the ADT.

Utilization of the PMW eye score value will only be allowed prior to three consecutive, automated “eye” scene type determinations by the ADT algorithm. Once three consecutive eye scene types have been found using the IR imagery alone, the PMW “eye score” information will be ignored no matter what its value may be.

Before the three eye scenes are found, the PMW eye score value will be used to determine the intensity of the storm at the time of the PMW eye score value (it will actually be assigned to the time record in the existing storm history file that exists immediately after the date/time of the PMW eye score record). There are two threshold eye score values that are utilized in the PMW eye score routine, each corresponding to a different T# intensity value to be assigned in the ADT algorithm for the intensity. If the eye score value is equal to or greater than 20.0, but less than 60.0, the ADT will reassign the Raw T# intensity score of the existing record in the ADT history file to be 4.3. If the eye score value is greater than or equal to 60.0, the Raw T# value for this record will be assigned to a 5.0. If no records exist in the ADT history file after the PMW eye score record time, the intensity estimate for the current IR image being analyzed will be modified to one of these two values.

In order to try and alleviate an artificial “jump” in the ADT history file records once the PMW eye score value exceeds one of the threshold values, all of the CI# values, as well as the adjusted Raw T# and Final T# values, in each record up to 12 hours prior to the PMW eye score record time will be adjusted linearly to a value between the “current” PMW eye score intensity value and the CI# value of the 12-hour previous record. The history file records will be physically changed within the history file, but the “historical” values (obtained prior to the application of the PMW eye score adjustment) will be kept in the history file comment section for each record.

For example, if the PMW eye score value of 26.2 occurred at 20:56UTC, the following record in the history file (most likely at 21:15UTC) will have its Adjusted Raw T#, Final T#, and CI# values all changed to 4.3. Looking back 12 hours from the 21:15UTC record shows the 9:15UTC record with an intensity value (CI#) of 3.4. Thus, all records between 9:15 and 21:15 will have their Adjusted Raw T#, Final T#, and CI# values changed to the corresponding linear interpretation value between 3.4 and 4.3 (depending on the time between the two end times). The original values will be stored for each of these times in their corresponding comment section in the history file.

The same adjustment 12 hour previous record adjustment will be applied if the PMW eye score values change from the first threshold range (between 20.0 and 59.9) to the second (60.0 and above). For example, if the MW eye score exceeds 60.0 at 14:45UTC, all records back to 2:45UTC will be linearly adjusted between the 5.0 value at 14:45 and the CI# value at 2:45UTC.

The PMW eye score adjustment will continue to be applied as long as two conditions are not met. The first, as mentioned previously, occurs when three consecutive, automatically determined scene types are determined from the IR imagery to be “eye” scene types. The second occurs when the PMW eye score value drops below the 20.0 threshold value for more than 12 hours. Once either of these situations occurs, the PMW eye score adjustment will be terminated. If the first situation occurs, the PMW eye score adjustment can never be applied during the remainder of the storm’s lifecycle. If the second situation occurs, the PMW adjustment can once again be applied if a PMW eye score value once again exceeds a threshold value.

During the application of the PMW eye score adjustment, the Rule 8 flag value in each history file record will be modified to store a descriptive value for each situation during the PMW eye score adjustment period. These values will be displayed in the History file Listing described in Section 3.3.2.1. The value will be “MW ON” when the eye score values are 20.0 and above, “MW Adj.” for the 12 hour period prior to the first eye score values exceeding 20.0, and “MW Off” for either of the two conditions where the eye score adjustment is turned off (the records 12 hours previous to the “MW Off” will be assigned “MW Hold” in the second condition described in the above paragraph). The records modified during the initial 12-hour adjustment periods (either with the first eye score value above 20.0 or with the transition between the 20.0 and 60.0 values) will all have their comment section appended with the information “MWinit=A.A/B.B/C.C”, where A.A, B.B, and C.C are the initial Adjusted Raw T#, Final T#, and CI# values, respectively (prior to the MW adjustment).

3.4.3 Algorithm Output

Filename	Format	Contents
User determined	ASCII/NetCDF	History file (ADT analysis parameters)
User determined	ASCII	ADT history file listing
User determined	ASCII	HIE output error and diagnostic codes

User determined	netCDF	HIE Metadata - Storm Name and Number w/ basin ID (e.g. 03L) - Storm Position (latitude and longitude) - Current Intensity - Difference between current and previous intensity - Number of Measurements during storm history
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Table 7: Output data file from ADT algorithm

The HIE algorithm has a 30 minute refresh rate, therefore it should be run once every half an hour. The primary product output for the HIE algorithm is the history file, which contains all of the important derived analysis information for each individual image analysis. These parameters are listed in Section 3.3.2.1, but they will be described in the tables in Section 3.4.3.1 in terms of product, quality, and diagnostic parameters.

HIE runtime error and diagnostic codes will be presented in Section 3.4.3.2. These codes will be presented in a bit/byte format for each of the different codes provided during runtime execution of the HIE algorithm. Error codes will provide information when the HIE is not able to execute to completion successfully (output an intensity estimate), while the diagnostic codes provide important information to the user during the intensity estimation process which do not result in termination of the algorithm.

HIE metadata, described in Section 3.4.3.3 are the required HIE output parameters to meet algorithm specifications which will be output to the framework netCDF file.

3.4.3.1 History File Output

The following parameters described in Tables 8, 9, and 10 will describe the Product, Quality Flag, and Diagnostic output parameters contained within the HIE history file output for each analysis during each storm lifecycle. The official F&PS HIE required output is wind speed. This value is not directly output in the HIE history file, but instead it is derived from the CI# value as described in Section 3.4.2.5 and listed in Table 6.

3.4.3.1.1 Product Output

Category	Description	Value
CI#	Current Intensity number (wind speed value derived from CI# using relationship in Table 6)	1.0 – 8.0

Table 8: HIE History File product output value

3.4.3.1.2 Quality Output

Category	Description	Value
Land/Ocean flag	Storm center position (latitude and longitude) over land or ocean	1=Over Land 2=Over Ocean

Table 9: HIE History File quality output value

3.4.3.1.3 Diagnostic Output

Category	Description	Value
Date	Image analysis date	YYMMMDD format (YYYY=year, MM=3 letter month ID, DD=day)
Time	Image analysis time (in UTC)	hhmmss format (hh=hour, mm=minutes, ss=seconds)
Julian date and partial date	Julian date and percentage of day at image analysis time	jjj.pppp (jjj=julian date, pppp=partial date %)
Raw T#	Raw T# value	1.0 – 8.0
Raw T# adjusted	Adjusted Raw T# value	1.0 – 8.0
Final T#	Final T# value (3 hour time average)	1.0 – 8.0
Eye Temperature	Warmest temperature value in eye region (0-24km from storm center)	In degrees Celsius
Cloud Temperature	Average cloud top temperature in 80km wide annulus centered at storm center (minimum radius=24km, maximum radius=136km)	In degrees Celsius
Cloud Temperature (old value)	Average cloud top temperature between 24 - 136km from storm center	In degrees Celsius
“Coldest-Warmest” Cloud Temperature	Warmest temperature on coldest 4km ring between 24 – 136 km from storm center	In degrees Celsius
Latitude	Storm center latitude	North = positive South = negative
Longitude	Storm center longitude	West = positive East = negative
Eye/CDO size or shear distance	Value containing either the radius of the storm eye feature, the size of the cloud CDO region, or the distance from the storm center to the cloud edge (dependent upon eye and cloud scene type values)	In kilometers
Eye StdDev	Standard deviation of the eye region temperature values	In degrees Celsius
Cloud Symmetry	Cloud region symmetry value (average difference between opposing cloud region slices in annulus)	In degrees Celsius
Satellite ID	Satellite ID value	n/a
Eye Scene Type	Eye region scene type	0 = Clear Eye 1 = Pinhole Eye

		2 = Large Eye 3 = No Eye
Cloud Scene Type	Cloud region scene tyoe	0 = CDO 1 = Embedded Center 2 = Irregular CDO 3 = Curved Band 4 = Shear
Rule 8 Flag	Dvorak EIR Rule 8 constraint limits	<u>Ten's designations</u> 0's=Shear Scene 10's=Eye Scenes 20's=Curved Band/CDO/EmbC/ IrrCDO Scenes 30's MW Adjustments : 30=12-hr Interpolation 31=Initial MW adjustment 32=MW adjustment On 33=Holding MW adjustment 34=MW adjustment Off <u>One's designations</u> 0=No Constraint 1=T#4.0 0.5/6hr 2=6hr rule 3=12hr rule 4=18hr rule 5=24hr rule 8=0.2/hr (1 st six hours only), 9=0.5/hr
Rule 9 Flag	Dvorak EIR Rule 9 weakening flag	0 = Off 1 = On 2 = On (Initialized at >-6.0)
Latitude Bias	Latitude Bias application flag	0 = Off 1 = Merging (12 hours) 2 = On
Rapid Dissipation	Rapid Dissipation flag (only applied in East Pacific ocean basin < 140W)	0 = Off 1 = On
Eye FFT	Eye region FFT harmonic value	0 – 13
Cloud FFT	Cloud region FFT harmonic value	0 – 13
Curved Band Gray Scale	BD enhancement Gray Scale value	See Table 5
Curved Band Curvature	Amount of curvature in Curved Band Gray Scale analysis region	X = 1 – 25 (curvature % = X-1/24)
Coldest Warmest Distance	Distance to “coldest-warmest” ring from storm center	In kilometers
Fix Method	Automated storm centering method	0 = manual 1 = forecast interpolation 4 = spiral analysis 5 = ring/spiral combination 6 = extrapolation

Latitude Bias Adjustment	Amount of latitude bias adjustment to MSLP value (from MSLP to T# relationship)	In millimeters
RMW	Derived radius of maximum wind from satellite imagery	In kilometers
PMW value	External PMW “eye score” value	n/a
Gale Radius	34 knot wind speed gale radius value (for use in Knaff/Zehr MSLP/Wind speed relationship)	In kilometers
Environmental Pressure	Environmental storm pressure value (for use in Knaff/Zehr MSLP/Wind Speed relationship)	In millibars

Table 10: HIE History File diagnostic output values

3.4.3.2 Output Error and Diagnostic Codes

The HIE performs validity checks for the various input products and internally determined values during the execution of the HIE. Various error and diagnostic messages are produced during the execution of the ADT and output at the end of the processing cycle. These messages can be used by the user to determine why a particular ADT run failed or how the ADT obtained a certain intensity estimate value. These error and diagnostic values are shown in Tables 11 and 12.

GOES-R HIE Error Codes

<i>Byte</i>	<i>Bit</i>	<i>HIE Code</i>	<i>Error Description</i>
0	0	-1	Error reading from existing history file
0	1	-2	Error creating history file
0	2	-3	Error writing to history file
0	3	-4	Error writing comment to history file (date error)
0	4	-151	PLOT option not available with this version of ADT
0	5	-152	Empty
0	6	-153	Empty
0	7		Empty
1	0	-11	Error reading image file
1	1	-12	Error accessing image file
1	2	-13	Bad navigation
1	3	-14	Line/Element mismatch
1	4	-15	Multiple bands
1	5	-16	Latitude/Longitude conversion error
1	6	-17	Data read off edge of image
1	7		Empty
2	0	-21	Invalid storm center location
2	1	-22	Error setting up navigation
2	2	-23	Bad navigation
2	3	-31	Error accessing topography file
2	4	-32	Error reading topography file
2	5	-41	Fourier Transform Analysis failure
2	6	-51	Error with eye and/or cloud region temperature value(s)
2	7	-61	Error with Start Date with DELETE keyword
3	0	-43	Error accessing forecast file; extrapolation failed
3	1	-44	Invalid forecast file; extrapolation failed
3	2	-45	Error reading forecast file; extrapolation failed
3	3	-46	Forecast interpolation failure; extrapolation failed
3	4	-71	Error writing output ASCII list file
3	5	-72	Empty
3	6	-81	Error determining ocean basin
3	7		Empty
4	0	-101	Error allocating memory for output wind field GRID
4	1	-102	Error opening output wind field GRID file
4	2	-103	Error creating output wind field GRID file
4	3	-104	Error writing to output wind field GRID file
4	4	-105	Error closing output wind field GRID file
4	5	-107	Error creating output ASCII grid file
4	6	-108	Error creating output ASCII grid position file
4	7		Empty

Table 11: HIE algorithm runtime error codes.

GOES-R HIE Diagnostic Codes

<i>Byte</i>	<i>Bit</i>	<i>HIE Code</i>	<i>Diagnostic Description</i>
0	0	1	Empty
0	1	2	Performing full ADT analysis
0	2	11	Utilizing history file
0	3	12	Utilizing image file
0	4	13	Writing output ASCII list file
0	5	14	Utilizing forecast file
0	6	15	Empty
0	7	16	Utilizing topography file
1	0	31	Empty
1	1	32	Empty
1	2	42	Forecast interpolation successful
1	3	43	Error accessing forecast file; extrapolation o.k.
1	4	44	Invalid forecast file; extrapolation o.k.
1	5	45	Error reading forecast file; extrapolation o.k.
1	6	46	Error with forecast interpolation; extrapolation o.k.
1	7	51	Will utilize position
2	0	61	Overwrote record in history file
2	1	62	Inserting record in history file
2	2	63	Added record to empty history file
2	3	64	Added record to end of history file
2	4	65	Modified record(s) in history file
2	5	66	Deleted record(s) in history file
2	6	67	Wrote record(s) to history file
2	7	68	Added comment to history file record
3	0	71	Tropical cyclone over land
3	1	72	Ocean basin automatically determined
3	2	73	Ocean basin manually selected
3	3	81	Empty
3	4	91	Warmest pixel temperature location
3	5	115	Empty
3	6	121	Simultaneous OVER and AUTO keyword usage
3	7		Empty
4	0	101	Successfully completed listing
4	1	102	Successfully completed graph
4	2	103	Successfully completed record deletion
4	3	104	Successfully completed ADT analysis
4	4	105	Empty
4	5	21	Empty
4	6	22	Using automatically selected storm center position
4	7		Empty

Table 12: HIE algorithm runtime diagnostic codes.

3.4.3.3 HIE Metadata

The HIE will be required to output a series of metadata values. These values will include the following parameters:

Storm Name and Number (including official basin ID value) Basin ID values: L=Atlantic, E=East Pacific (east of 140°W, C-Central Pacific (between 140°W dateline, W=West Pacific (west of dateline)
Storm location (latitude and longitude)
Current storm intensity (F&PS requirement is wind speed in m/s)
Difference between current and previous storm intensity (wind speed in m/s)
Number of intensity measurements for entire storm history

Table 13: HIE algorithm metadata values

These values will be provided to the user along with any other output values, such as error codes, and tailored products such as storm listings and current intensity bulletins.

4 TEST DATA SETS AND OUTPUTS

4.1 AVHRR and MODIS data validation study

4.1.1 Simulated Input Data Sets

The initial test of the HIE algorithm (Version 5) on GOES-R ABI-like data, a GOES-R proxy dataset consisting of 1km spatial resolution AVHRR and MODIS images was collected and archived by the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. This dataset consists of the following imagery sets:

- Polar satellite (AVHRR or MODIS) full resolution imagery
- Time-matched (as close as possible) full resolution GOES IR
- AVHRR or MODIS IR remapped to 1km (*P01*)
- Reduced resolution polar IR 2km (resembling the GOES-R footprint) (*P02*)
- Reduced resolution polar IR 4km (resembling the current GOES footprint) (*P04*)
- GOES IR remapped 4km (*G04*)

A full description of the datasets can be obtained from the *GOES-R AWG Winds Group Tropical Cyclone Proxy Data and Intensity Estimation Algorithm Documentation and Preliminary Results* report, which can be found at the CIRA AWG project website at the following address: <http://rammb.cira.colostate.edu/projects/awg>.

For ADT testing, only the full resolution Polar imagery and the GOES IR remapped 4km data is used. Eleven TCs were selected for testing consisting of a total of 357 individual scenes which occurred between 2002 and 2006 (Table 14). Each of the polar images uses the full resolution IR data from MODIS or AVHRR and remaps it to a TC-centered Mercator projection image with 1 km resolution.

Storm Name & Year	Scenes	Size (MB)
Lili 2002	21	150
Isabel 2003	66	469
Emily 2005	41	286
Katrina 2005	57	377
Rita 2005	43	303
Stan 2005	13	93
Wilma 2005	61	435
Alpha 2005	8	58
Beta 2005	9	66
Hilary 2005 (EP)	12	87
Ernesto 2006	26	187
Total	357	2511

Table 14: TC case study sample information used for testing the ADT on GOES-R proxy data.

ADT intensity estimates are processed using the collocated GOES-IR 4km spatial resolution data from the current GOES satellites and the GOES-R proxy data from the polar data in order to assess potential impact on the ADT intensity estimates from the improved ABI spatial resolution. ADT intensity estimates are only derived using the collocated images for each dataset (closest match temporally between the current GOES and polar/GOES-R proxy data sets).

Figure 11 illustrates the improvement realized with the simulated GOES-R ABI imagery over the current GOES-12 imagery for Hurricane Wilma on 19 October 2005. Wilma possessed an extremely small eye at this time. ADT intensity estimates using the GOES-12 infrared window (IRW) drastically underestimated the storm intensity at this time due to the inability to resolve the eye (and thus led to an incorrect ADT scene type determination). Using the simulated GOES-R ABI imagery, the ADT was able to identify the scene type correctly as an eye feature, resulting in a much more accurate intensity estimate for this individual image.

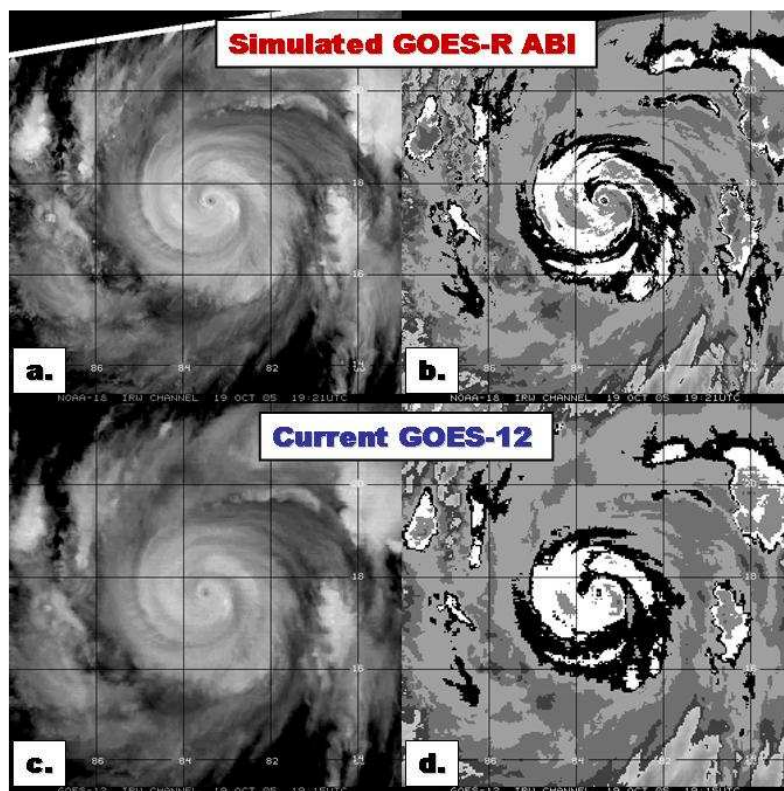


Figure 11: Simulated GOES-R ABI infrared window (IRW) imagery with a.) black/white contrast stretch and b.) “BD-curve” enhancement, and current GOES-12 IRW imagery with c.) black/white contrast stretch and d.) “BD-curve” enhancement, for Hurricane Wilma on 19 October 2005 (19:21 and 19:15UTC,

respectively). Contrast stretch/enhancement show improved capability to capture small eye feature with the ABI.

4.1.2 Output from Simulated Input Data Sets

As discussed in the previous section, the ability to discern smaller TC features, such as extremely small “pinhole” eyes using higher spatial resolution imagery, can lead to improved intensity estimates from the ADT algorithm. Examination of the ADT intensity estimates for Hurricane Wilma in 2005 over the entire storm lifetime illustrates the impact on numerous ADT intensity estimates, especially during the extremely small eye time period. Figure 12 shows the ADT Raw T# value differences derived from the current GOES and GOES-ABI, versus verifying aircraft reconnaissance. The intensity differences are most notable during the period from about 19 October/18:00UTC to about 20 October/12:00UTC. During this period the ADT had significant problems resolving/retaining an eye feature scene type when utilizing current GOES-12 IR imagery. When utilizing the GOES-R ABI data, the ADT was able to resolve and maintain an eye scene consistently during the same time period, resulting in intensity estimates more closely matching those obtained by aircraft reconnaissance.

Hurricane Wilma --- October 2005

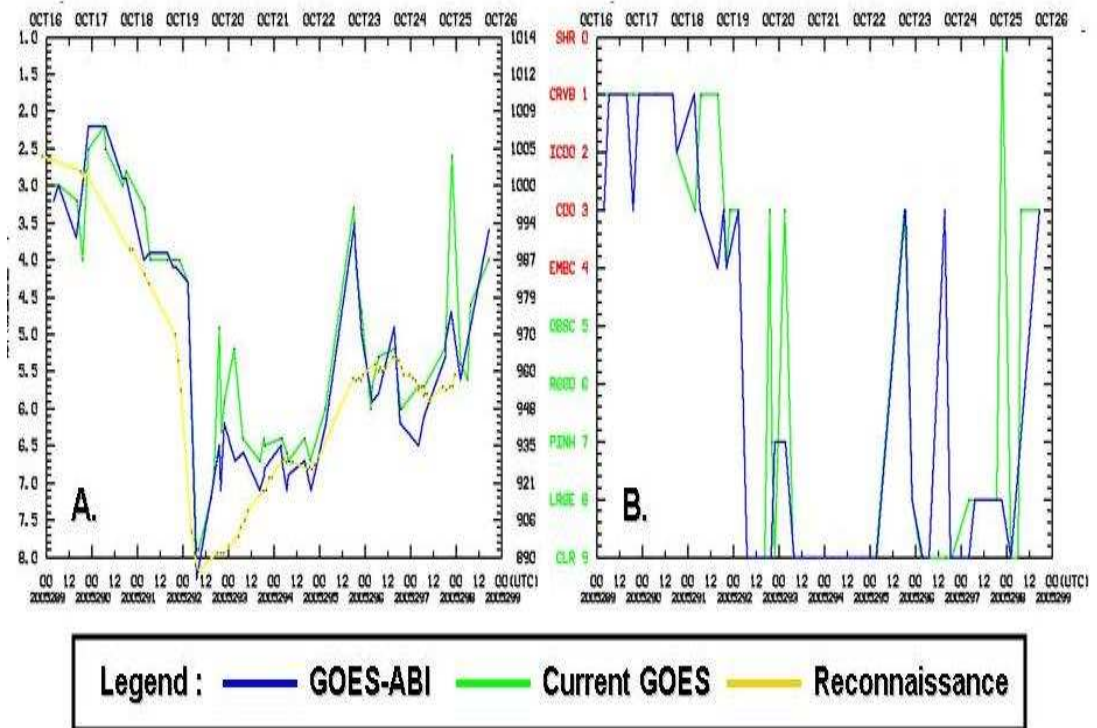


Figure 12: ADT Raw T# Intensity Estimates and B.) Scene type selection for Hurricane Wilma (2005). GOES-ABI (blue), current GOES (green), and aircraft reconnaissance (yellow) values are displayed.

4.1.3 Precision and Accuracy Estimates

Homogeneous ADT intensity estimates from the current and simulated GOES data sets are compared using a total sample of 39 estimates within one hour of a verifying reconnaissance wind speed measurement over 11 Atlantic basin storms between 2002 and 2006. Table 15 shows the statistical comparisons of the HIE intensity estimates for both the current and simulated GOES data sets using Version 5 of the HIE.

	GOES-ABI		GOES-Current	
Intensity	Accuracy (m/s)	Precision (m/s)	Accuracy (m/s)	Precision (m/s)
CI#	-3.56	7.57	-3.83	7.14
OpCen	-2.09	6.23	-2.09	6.23

Table 15: HIE and Operational Center (OpCen) Bias and StdDev wind speed estimate values, as validated against collocated aircraft reconnaissance measurements, for HIE intensity estimates using simulated GOES-ABI and current GOES imagery (in m/s).

Some tuning to the ADT scene type and intensity determination schemes may be necessary to account for the improved spatial resolution and resulting scene type samples (i.e. more eye scenes) once a greater sample of higher-temporal data is available (i.e. after GOES-R launch).. In addition, the increased temporal image frequency between the current GOES and GOES-ABI may require some modification to the time-averaging scheme and application of time-base rules. Improvements based upon this proxy data set could be attempted for future HIE algorithm deliveries prior to GOES-R launch, but a more complete proxy dataset analysis would be desired before any significant algorithm modifications are conducted in order to fully assess the impact of the GOES-R ABI data on the HIE algorithm.

4.2 MSG SEVIRI and Simulated GOES-R ABI data validation study

4.2.1 Simulated Input Data Sets

A second validation test of the HIE algorithm (Version 5) using simulated and GOES-R ABI-like data was conducted using data collected and distributed by CIRA. This data set consisted of collocated infrared window channel imagery from the Meteosat Second Generation (MSG) SEVIRI instrument (10.8 μm) and simulated GOES-R ABI (SABI) data (10.3 μm) derived from the MSG data using ABI channel coefficients supplied by the Joint Center for Data Assimilation. Both data sets were presented at 3 km spatial resolution at a 15 minute temporal resolution. Statistical comparisons regarding the spatial aspect of the data sets are expected to be minimal due to the equal resolution between the two data sets. Instead the study will focus on the impact of the improved 15-minute resolution with the ABI data over the 30-minute resolution available with the current GOES imagery.

Data was collected for a total of seven tropical cyclones, during the 2006 to 2008 tropical cyclone seasons, in the eastern and central North Atlantic Ocean basin within the viewing region of the MSG satellite, as listed in Table 16. A total of 5764 images were supplied by CIRA for the seven storms in the validation study after manual quality control measures were taken (visual inspection of each individual image in the data set).

Storm Name & Year	Scenes	Start Date/Time	End Date/Time
Gordon 2006	953	10 Sept / 1800 UTC	20 Sept / 1930 UTC
Helene 2006	1046	12 Sept / 1200 UTC	23 Sept / 1345 UTC
Dean 2006	452	13 Aug / 0600 UTC	17 Aug / 2345 UTC
Karen 2007	422	24 Sept / 0000 UTC	28 Sept / 1200 UTC
Ike 2008	845	30 Aug / 0600 UTC	8 Sept / 1200 UYC
Bertha 2008	1808	30 June / 0600 UTC	20 July / 0645 UTC
Omar 2008	238	16 Oct / 0000 UTC	18 Oct / 1200 UTC
Total	5764		

Table 16: 2006 – 2008 MSG/SABI TC validation case study sample information.

4.2.2 Output from Simulated Input Data Sets

The HIE estimates produced for each storm and data type were initialized using the NHC Best Track intensity information interpolated to the Start Date/Time for the storm being analyzed. Statistical comparisons were homogeneous between all data sets and image times available and were compared to the NHC Best Track wind speed estimates interpolated to the image times being compared (since aircraft reconnaissance data is either not available or severely limited for each storm in the data sample).

The NHC Best Track data was obtained for each storm from the NHC FTP site after a thorough post-storm analysis has been performed to derive the best 6-hour resolution intensity trend of each storm in the data sample. Wind speeds for the HIE estimates were derived from the CI# estimates using the conversion table listed in Table 6.

In general, more error is expected with this data sample due to the fact that many of the individual TC views obtained with the MSG satellite (and derived SABI data) at a high local zenith angle (50 or more degrees from nadir). High local zenith angles may limit the ability of the satellite to view the structure of the eye region properly, thus affecting the eye temperature value obtained in the imagery. This could affect the intensity estimates from the HIE during eye scene types since the eye temperature could be sampling the eye wall instead of the ocean surface. In addition, high local zenith angles will also affect various measurement values obtained by the HIE, such as the shear distance values, the amount of cloud curvature with the curved band scene types, and possibly the areal coverage of the CDO region being measured.

4.2.3 Precision and Accuracy Estimates

A total of 2453 homogeneous estimates were found between the 15 and 30 minute temporal resolution data samples for the MSG and SABI data sets. Table 17 displays the statistical measurements for accuracy and precision, absolute bias and standard deviation respectively, for the Version 5 HIE wind speed (in m/s) estimates derived from the CI# and compared to the interpolated NHC Best Track intensity estimate information.

Units m/s	Bias	Accuracy	Precision	Num
SABI – 30 min	1.46	1.46	8.93	2453
SABI – 15 min	1.89	1.89	8.97	2453
MSG – 30 min	1.05	1.05	8.67	2453
MSG – 15 min	1.48	1.48	8.66	2453

Table 17: Comparisons between SABI and MSG data samples for 15 and 30 minutes temporal resolution satellite data availability. Accuracy and Precision are provided by the absolute bias (ABias) and Standard Deviation (StdDev) for the total sample size (Num).

In general, the accuracy measurements were well under the 6.5 m/s threshold for the HIE algorithm, while the precision values were near the threshold 8.0 m/s threshold despite the poor viewing angles available for much of the data sample. Over 60% of the imagery sampled for the comparisons in Table 17 had local zenith angles greater than or equal to 50 degrees, and 17.6% had local zenith angles greater than 60 degrees.

Overall, MSG data demonstrates slightly better accuracy precision than the SABI data. This is consistent with the results obtained in section 4.1.3 comparing current satellite data (GOES) to simulated ABI data MODIS/AVHRR) even though that data sample was significantly smaller.

Comparing the different temporal resolution data sets, no improvement in either precision or accuracy was obtained with the 15-minute data over the 30-minute data for both the MSG and SABI data samples.

Again, it should be noted that the results from this experiment should not be highlighted despite the large number of data matches between the HIE estimates and the “ground truth” NHC Best Track data. Not only are there a large number of high local zenith angle cases, but in general the NHC Best Track estimates are typically on the conservative side, which could lead to larger errors and biases than would be obtained with in situ aircraft reconnaissance measurements of intensity.

4.3 Validation study using current GOES imagery

4.3.1 Input Comparison Data Sets

Ten tropical storms of varying intensity between 2004 and 2008 were analyzed using the HIE (Version 5) using current GOES infrared window (10.7 μ m) imagery. The ten storms in the data sample are listed by the year in which they occurred:

- 2004: Hurricane Alex, Hurricane Charley
- 2005: Tropical Storm Arlene, Hurricane Dennis, Hurricane Katrina, Hurricane Rita
- 2006: Hurricane Ernesto
- 2007: Hurricane Dean
- 2008: Hurricane Dolly, Hurricane Gustav

This study will serve as a baseline for the algorithm accuracy since only current goes imagery at 4 km spatial resolution and 30 minute temporal resolution is used without any MW eye score input.

4.3.2 Output from current GOES data sets

Aircraft reconnaissance in situ measurements of intensity will be used to validate the accuracy of the HIE intensity estimates. Measurements of TC central MSLP will be converted to wind speed (in m/s) and compared to the HIE estimates within one hours of the reconnaissance data. Statistical measurements of accuracy and precision will be compared for the intensity estimates derived from the Version 5 HIE algorithm and for the corresponding ensemble (of SAB and NHC estimates when both are available) Operational Center (OpCen) estimates (within 30 minutes of the HIE intensity estimate).

4.3.3 Precision and Accuracy Estimates

Table 18 displays the statistical comparisons between the HIE (Version 5 – 100% delivery) and the OpCen estimates of intensity in terms of the AWG definitions of accuracy (absolute bias (ABias)) and precision (standard deviation (StdDev)) along with the bias of each method for the 529 homogeneous sample comparisons.

As with the other studies listed in this document, intensity differences are given in terms of HIE intensity estimates or OpCen estimates minus aircraft reconnaissance, so a positive/negative bias indicates an over/underestimate of intensity by the HIE or OpCen in comparison to the aircraft reconnaissance in situ measurement.

Units m/s	Bias	Accuracy	Precision	Num
HIE Version 5 (100%)	-5.91	5.91	7.60	529
OpCen	-2.42	2.42	6.27	529

Table 18: Comparisons between the HIE (Version 5) and the Operational Forecast Center (OpCen) intensity estimates versus aircraft reconnaissance measurements of intensity for the 10 case validation TC sample.

4.4 Passive Microwave (PMW) Eye Score validation study

4.4.1 Input Data Sets

In order to determine the impact of use of the PMW Eye Score (described in Section 3.4.2.12) values on the HIE algorithm, a final validation data set was collected containing 40 storms between 2005 and 2008 where the PMW Eye Score values were available. This study will also assess the impact of all changes between Version 3, the 80% code delivery and version used in all previous validation tests, and Version 5, the 100% code delivery version. The inclusion of the PMW values within the HIE is the last major upgrade to the HIE algorithm prior to 100% delivery to AIT.

The scope of this study is to examine a large data set to properly assess the impact of the PMW Eye Score data on the HIE. Previous impact study data sets were either too small or had significant limitations, as discussed in the individual sections above, to properly implement and assess the use the PMW Eye Score values on the individual data sets. Utilization of current GOES data, available at the time of each TC in the study, will provide an upper boundary for the statistical validation of the HIE using a large data sample. Statistical improvements using the simulated ABI data from the previous validation studies can be implied to this data sample to estimate the statistical accuracy which could be obtained with the improved ABI imagery.

4.4.2 Output from PMW Eye Score validation study

Aircraft reconnaissance in situ measurements of intensity will be used to validate the accuracy of the HIE intensity estimates. Measurements of TC central MSLP will be converted to wind speed (in m/s) and compared to the HIE estimates within one hours of the reconnaissance data. Statistical measurements of accuracy and precision will be compared for the intensity estimates derived from the Version 3 and Version 5 HIE algorithms.

4.4.3 Precision and Accuracy Estimates

Table 19 displays the statistical comparisons between the two HIE versions used for this validation study in terms of the AWG definitions of accuracy (absolute bias (ABias)) and precision (standard deviation (StdDev)) along with the bias of each method for the 744 homogeneous sample comparisons.

As with the other studies listed in this document, intensity differences are given in terms of HIE intensity estimates minus aircraft reconnaissance, so a positive/negative bias indicates an over/underestimate of intensity by the HIE in comparison to the aircraft reconnaissance in situ measurement.

Units m/s	Bias	Accuracy	Precision	Num
HIE - Version 3	-2.48	2.48	7.22	744
HIE - Version 5	-2.45	2.45	6.75	744

Table 19: Comparisons between the Version 3 and Version 5 HIE algorithms versus aircraft reconnaissance measurements of intensity for the 40 case TC sample from 2005 to 2008.

4.5 Error Budget

As shown in the statistical results presented in the previous sections, the accuracy of the HIE algorithm (Versions 3 and 5 of the algorithm) using various current and simulated GOES-R ABI data sets are close to or exceeding the AWG measurement accuracy requirements of 6.5 m/s for accuracy and 8.0 m/s for precision. In general, the requirement for accuracy has been achieved for each validation study. The precision requirement was met in the studies presented in Section 4.1, 4.3, and 4.4, however it was not met in the study presented in Section 4.2. Taking into account the limitations presented in the Section 4.2 study with high local zenith angle issues and use of non-in situ “ground truth” data the HIE algorithm has met and exceeded the required specifications thresholds for accuracy and precision, and it is fully expected to meet and exceed the AWG specified levels of accuracy and precision required for the hurricane intensity algorithm.

The results from the validation study presented in Sections 4.3 and 4.4 provide the largest statistical data samples versus aircraft in situ measurements of intensity and show the impact of the differences between Version 3 (80% delivery) and Version 5 (100% delivery). The results from these validation studies not only demonstrates the improved accuracy of the HIE algorithm between the two versions, but also in the utilization of the PMW Eye Score data. These results clearly demonstrates the ability of the HIE algorithm to exceed the spec requirements for the HIE algorithm despite using current GOES imagery instead of simulated GOES-R ABI data. From these studies, it has been shown that the Version 5 HIE algorithm is ready for GOES-R launch.

5 PRACTICAL CONSIDERATIONS

5.1 Numerical Computation Considerations

The ADT is a self-contained algorithm which does not rely on any external processes to be completed prior to the start of the intensity estimation process. An external passive microwave eye score value (Section 3.4.2.12) can be derived and passed into the ADT upon initiation of the routine execution, but the ADT does not depend on this value in order to run successfully.

5.2 Programming and Procedural Considerations

The ADT has been checked for memory leaks and other programming errors using the open source software “Valgrind” which is freely available under the GNU General Public License by the Valgrind Developers Group at valgrind.org.

5.3 Quality Assessment and Diagnostics

The following procedures are recommended for diagnosing the performance of the ADT as the algorithm is being executed in real-time.

- Monitor the automated ADT output to check that the scene types are matching what the forecaster would expect to obtain if manually performing the SDT. For example, if the user expects to see an eye scene but obtains something other than an eye, the automated storm center position value should be investigated.
- Assess the accuracy of the automated storm center position determination process, especially when a forecast interpolation is being performed. If the center is not in the region where the HIE user would expect the storm center to be, make sure the forecast being utilized is the latest available. If it is not available, the use of an official forecast from another TCFC may be considered for use.
- If an individual temperature value is found to be inconsistent with surrounding values in the history file, check the image for data dropouts and/or bad pixels.
- Periodically cross-check the ADT intensity estimates with other available estimates (satellite or aircraft-based) from in-house sources.

5.4 Exception Handling

The HIE performs validity checks for the various input products and internally determined values during the execution of the HIE. Various error and diagnostic messages are produced during the execution of the ADT and output at the end of the processing cycle. These messages can be used by the user to determine why a particular ADT run failed or how the ADT obtained a certain intensity estimate value. See Section 3.4.3.4 for the tables that display the various HIE Error and Diagnostic codes in terms of

the internal HIE code values and the corresponding error values in a bit/byte format desired for the AIT Framework.

5.5 Algorithm Validation

Validation of the HIE tropical cyclone intensity estimates requires collocated measurements of reference (“ground truth”) tropical cyclone surface maximum wind speed. These measurements, as discussed in Section 4, are typically obtained from in situ reconnaissance aircraft using dropsondes to measure the at or near surface wind speeds within the tropical cyclone eyewall. Also, measurements of minimum MSLP within the storm environment can be used and converted to wind speed using either the standard pressure/wind speed relationship presented in Section 3.4.2.5 or with newer/experimental methods such as discussed in Section 3.3.2.5. Whichever method is used to convert the MSLP to wind speed should be consistent with the methodology used in the derivation of the HIE wind speed estimate values.

If direct in situ aircraft measurements of the TC intensity are not available, official “Best Track” estimates of intensity can be used as a proxy for the in situ data. The official Best Track is derived for every storm identified by the TCFC responsible for the basin in question. The Best Track values are derived using all available methods of measuring and/or estimating TC intensity, including in situ aircraft measurements (when available), satellite-based estimation algorithms (including the ADT and SDT), surface reports from fixed land and ocean-based observing stations, ship reports, and scatterometer measurements. When aircraft measurements are not available, the Best Track data quality is obviously degraded and will tend to more conservative estimates, but the information can still be used as a method of validation, especially in ocean basins outside of the Northeastern Atlantic Ocean where aircraft reconnaissance does not exist.

During the pre-launch phase of the GOES-R program, the validation activities are aimed at characterizing the precision and accuracy of the HIE algorithm to make sure it meets the AWG specifications for algorithm quality. Also, comparisons between the offline and framework versions of the algorithm will be conducted to characterize any differences between the versions based upon the implementation environments. These data sets have been described in Section 4.1.

Post-launch verification will be conducted in much the same fashion as the pre-launch verification. Characterizations of the algorithm precision and accuracy will be derived preferably using in-situ measurements of TC intensity from aircraft reconnaissance, but TCFC Best Track estimates can be used in regions where no in situ data is available.

Validation methodologies and tools developed and tested during the pre-launch phase will be automated and applied as necessary. More specific details on the HIE product validation activities can be found in the Product Validation document for the HIE algorithm.

6 ASSUMPTIONS AND LIMITATIONS

The following sections describe the current limitations of the ADT code, and assumptions when utilizing the code operationally.

6.1 Performance

When the ADT is utilized in the GOES-R operational environment, the following will be assumed when the algorithm is executed and its performance is analyzed.

1. The ADT will be executed in a completely automated fashion without any user interaction. Official TCFC forecasts are updated every 6 hours, immediately available upon official public release, and are properly formatted. This information will provide initial guess positions for the ADT auto-positioning logic.
2. Satellite imagery is available minimally every 30 minutes. Utilization of imagery at a lower temporal resolution will negatively impact the performance of the ADT, especially the time-averaging routine and time-dependent intensity change rules. Use of higher temporal resolution data has not yet been specifically quantified but has been shown in Section 4.2 to marginally improve the accuracy of the algorithm. This experiment was limited to a small sample of data, so any information gleaned from this study should be investigated further with a larger sample.
3. The ADT is executed only over ocean surfaces. The ADT should not (and will not in the default execution) be operated over land surfaces.

6.2 Assumed Sensor Performance

The following satellite sensor characteristics will be assumed when utilizing the ADT.

1. All satellite channel calibration will be correct and uniform from image to image. Correct intensity estimations are reliant upon satellite cloud top temperature information.
2. Satellite navigation errors are within specifications as defined in the Performance and Operational Requirements Document PORD. Correct satellite navigation is imperative for automated storm center determination and TC center position placement following the forecast interpolation process.
3. The ABI instrument will perform within the noise specifications defined in the PORD. The ADT can detect certain discrepancies in satellite data accuracy/availability, however large regions of invalid data will cause failure of the algorithm.

6.3 Pre-Planned Product Improvements

The ADT is constantly undergoing modifications to improve the accuracy of the intensity estimates determined by the algorithm. Issues or biases are often discovered during the utilization of the ADT algorithm during a specific TC season. Many of these are minor improvements; however some are more drastic, requiring a more in-depth research and development process. Below are issues that are currently being investigated to improve aspects of the ADT operation and performance as noted by CIMSS scientists and/or operational TCFC forecasters who utilize the ADT.

6.3.1 Improvement 1

Intensity estimates during TC land interaction (leading up to landfall and after re-emergence). Further research to optimize the ADT performance in these situations should be conducted

6.3.2 Improvement 2

Improvement of the intensity estimates produced during weak TC situations prior to formation of an eye. This situation is commonly referred to as the “central dense overcast” (CDO) case when a uniform (temperature) cloud shield masks a possibly forming eye underneath. Additional ancillary information can further improve the ADT accuracy. These include:

- a. Utilization of an externally-derived “eye score” parameter obtained from coincident passive microwave imagery from polar orbiting satellites. This technique is currently being investigated at CIMSS in an experimental mode. Further modifications and complete evaluation of the technique will be performed before incorporation into the GOES-R HIE. (Update: This has been incorporated into the HIE algorithm and presented in Sections 3.4.2.12 and 4.4)
- b. Utilization of an infrared and water vapor channel differencing scheme to detect and measure intense convection near the storm center. This method can be used to aid in the storm center determination process during the CDO cases when the IR image proves to be inadequate for identifying a storm center. Initial research studies are encouraging, with more investigation needed before integration into the GOES-R HIE.

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Appendix 1: Common Ancillary Data Sets

1. *SFC_ELEV_GLOBE_1KM*

a. *Data description*

Description: Digital surface elevation at 1km resolution.

Filename: GLOBE_1km_digelev.nc

Origin: NGDC

Size: 1843.2 MB

Static/Dynamic: Static

b. *Interpolation description*

The closest point is used for each satellite pixel:

- 1) Given ancillary grid of large size than satellite grid
- 2) In Latitude / Longitude space, use the ancillary data closest to the satellite pixel.