4D.1 SATELLITE-BASED INTENSITY ESTIMATES OF TROPICAL CYCLONES: WHERE DO WE GO IN THE FUTURE?

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1. INTRODUCTION

The first meteorological satellite (TIROS I) was launched on 1 April 1960. Since that time, meteorological satellite data have become an indispensable part of tropical cyclone (TC) forecasting operations (Sheets 1990). Meteorological satellites can detect TCs and disturbances that could become TCs in areas where no other data are available. This has provided invaluable early warning to forecasters, emergency managers, and the public, as well as had a lasting impact on TC climatology.

A key part of monitoring TCs with satellites is the ability to determine the TC intensity. Meteorological satellites have been for the most part incapable of directly measuring the maximum winds or central pressures of a TC. Thus, the intensity must be inferred, usually from an examination of the TC convective cloud pattern or from some other quantity a satellite can measure. Development of techniques to make TC intensity estimates (TCIE) started shortly after the first satellite launch and continues to the present. Additional technique development should occur due to new data types that are (or will be) delivered by current and next generation satellites.

This paper reviews the history of satellite-based TCIE. It then covers the current state-of–the-art of the techniques, along with some possibilities for improvements based on currently available data. After that, it looks at the possible future of TC forecasting, the need and expectation of increased satellite data for that forecasting, and how TCIE might evolve as a result.

2. THE FIRST TECHNIQUE

Satellite imagery was first used in TC forecasting at the National Hurricane Center (NHC) soon after TIROS I was launched, with NHC archives showing qualitative interpretations of TC locations and cloud patterns as early as the 1961 hurricane season. The first attempt to relate the observed cloud patterns to TC intensity was started in 1964 by Timchalk et al (1965), with subsequent additional work resulting in the Hubert-Timchalk Technique (1969). This technique examined the size and shape of the TC cloud pattern, including the presence or lack of an eye, and put the patterns into various stages and categories.

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This early technique was generally unsuccessful in operations (Velden et al. 2006). However, the premise of a relationship between TC cloud patterns and intensities was sound. Increasingly frequent imagery from new geostationary (GOES) satellites would allow for the relationship to be developed more rigorously.

3. THE DVORAK TECHNIQUE

This development took the form of one of the most remarkable methods of satellite imagery interpretation - the technique developed by Vernon Dvorak (1975) that today bears his name. His statistical pattern-matching methods to estimate TC intensity from visible (VIS) and infrared (IR) satellite imagery are still used operationally world-wide after more than 30 years, and they serve as the basis for current and future automated techniques.

The development of the Dvorak Technique (DT) spanned more than 20 years and is summarized by Velden et al. (2006). The key features included: 1, an enhanced recognition and description of the TC cloud patterns (Fig. 1); 2, improved methods for quantifying the cloud patterns and the associated intensities; 3, a set of rules regarding intensification/weakening rates and exceptions to the cloud pattern-intensity relationships; and 4, rules for short-term forecasting. The current DT uses a 10-step process of locating the TC center, estimating the intensity from the observed cloud pattern, and then applying rules to derive the final intensity estimate (Dvorak 1984).

The DT is human interpretation of satellite imagery, and the associated cloud pattern measurements and rules are somewhat subjective in nature. Despite this, the DT has a good operational record for accuracy. Brown and Franklin (2004) compared DT intensity estimates to aircraft-based best track intensities in the Atlantic and found that 50% of the DT estimates had errors of 2.6 ms^{-1} or less. Seventy-five percent of the DT estimates had errors <6.2 ms^{-1}, although there were

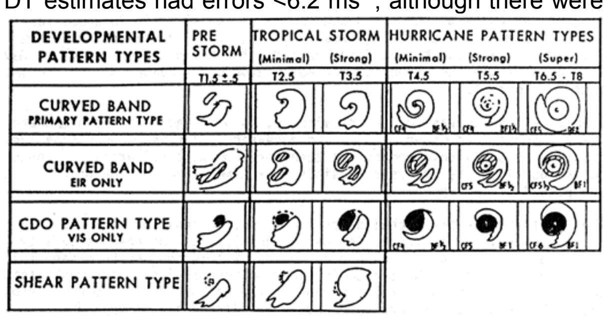

Figure 1. Dvorak technique cloud patterns and related intensities. From Dvorak (1984).

outliers with errors of >15 ms^{-1}. This level of accuracy has given the DT its longevity, as other TC intensity estimation techniques have yet to significantly exceed its standards.

The subjective nature of the DT has spawned efforts to make it more objective or automated. The first (Dvorak 1984) focused on automating the DT estimates for TC with eyes in IR imagery. Subsequent work has produced improved automated recognition of all the DT cloud patterns. The latest version is the Advanced Dvorak Technique (ADT, Olander and Velden 2007), which incorporates all of the DT cloud patterns as well as many of the rules.

The DT relies on standard VIS and IR imagery originally developed in the 1960s and 1970s. A possible area of improvement to be covered in the next section is the potential use of more advanced types of data.

The success of the DT has led to spin-off techniques for estimating the intensity of other types of atmospheric cyclones. The most successful of these is the Hebert-Poteat (1975) Technique for evaluating subtropical cyclones, which share characteristics of both tropical and extratropical cyclones. This technique was designed to serve as a complement to the DT and is in use at TC warning centers today.

4. OTHER APPROACHES AND DATA TYPES

Satellite-based microwave imagery has become a staple of TC operations during the past 15 years (Hawkins et al. 2001). However, a technique for DT-like TCIE from this imagery has been elusive. Since microwave imagery shows TC convective structure more efficiently than visible or IR, a DT-like approach could deliver useful intensity information if the proper pattern-intensity relationships can be determined.

In an approach independent of the DT, a microwave sounder like the Advanced Microwave Sounding Unit (AMSU) can produce a TCIE by measuring the warm temperature core in the upper levels of a TC (Fig. 2). This measurement is related to the intensity through statistical or physical relationships. The NHC uses AMSU algorithms developed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS, Herndon and Velden 2004) and the Cooperative Institute for Research in the Atmosphere (CIRA, Demuth et al. 2004) in its operations.

The DT and the AMSU-based TCIE have strengths and weaknesses involving temporal sampling, instrument viewing angles, and instrument footprint size. Thus, there are circumstances where one or more of the approaches produce bad intensity estimates. However,

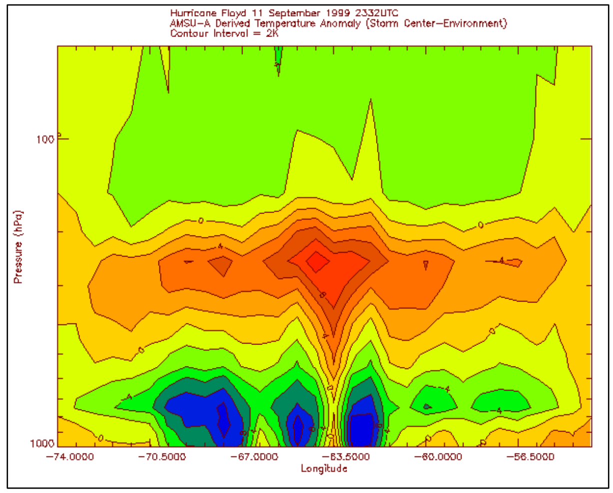

Figure 2. East-west cross section of temperature anomalies measured by the AMSU instrument in Hurricane Floyd at 2332 UTC 11 September 1999. Pressure is in mb and the contour interval is 2K. Image courtesy of the Cooperative Institute for Meteorological Satellite Studies.

it is possible to combine the approaches in a way that maximizes the impact of the best estimate and minimizes that of the worst. This is the premise of the CIMSS Satellite Consensus (SATCON) technique (Velden et al. 2006). This technique is a weighted average of the DT and two AMSU estimates, with the weights based on knowledge of which components might be problematic. Future TCIE techniques will likely be incorporated into this methodology.

A new approach to quantifying TC cloud patterns is based on the Deviation-Angle Variance Technique (Piñeros et al, 2008). This examines TC cloud patterns in a fashion totally different than that of the DT. While this system is not yet ready for operations, it offers the opportunity for a fresh objective look at TCIE and on the cloud pattern-intensity relationships. It also has the potential to be used with a variety of image types.

The DT and its automated descendant do not take full advantage of recent advances in satellite imagery. For example, the ADT does not currently use higher-resolution visible imagery, while the DT is limited to the standard visible and IR imagery. Additional satellite data is available at other wavelengths (e. g. 6.7 μm water vapor (WV) imagery), and it is now routine practice to create multispectral imagery by combining image data to highlight important features (Fig. 3). A drawback of IR imagery is that it can be difficult to differentiate between cirrus and convective clouds when making a DT intensity estimate. A multispectral combination that highlights that difference could (in theory) improve TCIE. Finding the right combination of frequencies and the best cloud patterns will require significant developmental work.

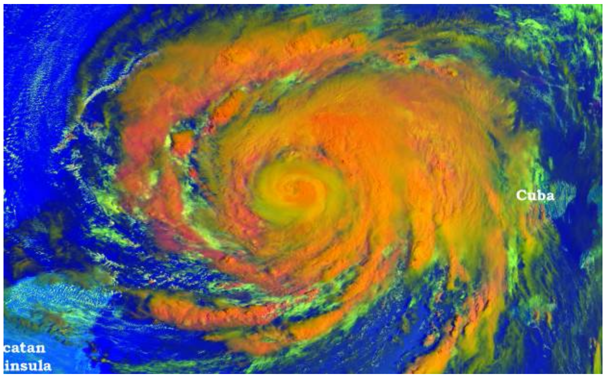

Figure 3. METOP-A multispectral image of Hurricane Ike at 1525 UTC 9 September 2009. Image courtesy of EUMETSAT.

5. THE FORESEEABLE FUTURE

Major advances in both satellite data and numerical weather prediction (NWP) models are expected during the next 5-10 years. These advances are likely to have a positive impact on TC forecasting capabilities, and to some extent they are linked together. These advances may change the methods of satellite-based TCIE, and perhaps even its role.

The U. S. next-generation geostationary satellite series (GOES-R) is scheduled to become operational in 2017. These satellites are designed to carry the Advanced Baseline Imager (ABI, Schmit et al. 2005). This imager has 16 channels compared to the current 5, and the spatial resolution for all channels is planned to be a factor of 2 finer than those of the current GOES series (Table 1). In addition, images of TCs should be available every 5-15 min instead of the current 15-30 min. These changes will increase the amount of data received from each satellite in the series by 1-2 orders of magnitude over that of the current GOES satellites.

The National Oceanic and Atmospheric Administration's Hurricane Forecast Improvement Project (HFIP) is a 10-yr effort to improve all aspects of TC forecasting, with the primary emphasis on intensity (Rappaport et al. 2009). HFIP covers all aspects of the problem, including atmospheric and oceanic observations, NWP models and their associated dynamics and physics, and data assimilation issues. The fruits of its research should be available around the time that the GOES-R satellites become operational.

HFIP is investigating the horizontal and vertical resolution necessary to skillfully forecast TC intensity. The current consensus is that it will require horizontal resolutions of ~1 km and many (100?) levels in the vertical. A natural question is how will the TC vortex be initialized in the model at those scales? This will require large amounts of data, much of which will come from aircraft. However, aircraft are not likely to sample all parts of all TCs all of the time. The aircraft gap will need to be filled by satellite-based platforms both spatially and temporally, which brings up the question of "How?"

The GOES-R satellites should deliver much of the needed data in terms of the horizontal and temporal resolution. However, the ABI will still not be able to directly measure TC winds and pressure, or effectively see through the TC cirrus canopy. An advanced scatterometer or properly designed microwave radiometer could in theory directly 'measure' TC surface winds, although it is unclear when such instruments will be available. Advanced IR sounding instruments such as AIRS and IASI may aide in the analysis of the TC upper levels (Ackerman 2009). However, it will likely require microwave instruments to fully probe a cyclone in three dimensions. The most probable answer to "How?" is to combine the various types of satellite data in an advanced data assimilation system that extracts the maximum value from each type of instrument.

What would be the role of the satellite-based TCIE in this future? In the short-term, it is like to retain its importance to the forecasters, as it provides information not yet assimilated in NWP. In the longer term, it is possible that new data sources and techniques could change the role of the TCIE. One possibility is that the TCIE could be incorporated into a three-dimensional TC analysis system. This hypothetical system might resemble an expanded version of the H*WIND system (Powell et al. 1998) or CIRA's multiplatform analysis system (Knaff and Demaria 2006). In theory, such a system could provide a 3-D first guess field for use in data assimilation for NWP, or it could directly provide an initial state for NWP similar to that of the vortex 'bogusing' systems used today (Bender et al. 2007).

ABI Band	Wavelength range (μm)	Central wavelength (μm)	Pixel size (km)	Potential Uses
1	0.45-0.49	0.47	1	VIS aerosol
2	0.59-0.69	0.64	0.5	VIS
3	0.846-0.885	0.865	1	VIS aerosol
4	1.371-1.386	1.378	2	VIS cirrus
5	1.58-1.64	1.61	1	VIS multi-use
6	2.225-2.275	2.25	2	VIS multi-use
7	3.80-4.00	3.90	2	Shortwave IR
8	5.77-6.6	6.19	2	Upper-level WV
9	6.75-7.15	6.95	2	Mid-level WV
10	7.24-7.44	7.34	2	Low-level WV
11	8.3-8.7	8.5	2	Cloud phase, dust, SO2
12	9.42-9.8	9.61	2	Ozone, turbulence
13	10.1-10.6	10.35	2	Surface, clouds
14	10.8-11.6	11.2	2	IR window
15	11.8-12.8	12.3	2	Volcanic ash
16	13.0-13.3	13.3	2	Air temperature

Table 1. Planned specifications of the GOES-R ABI (Schmit et al. 2005).

6. SUMMARY

The science of estimating the intensity of a TC has changed significantly over the past 50 years, going from subjective interpretation of irregular imagery through the more rigorous, but still subjective, Dvorak Technique, to the automated methods currently under development. More changes are likely as new data sources become available, and it is possible that in the future the form, methods, and role of the satellite-based TCIE could become significantly different from what it is currently.

During the satellite era, the amount and types of satellite data has developed faster than the ability to utilize it for TCIE. There is a large amount of untapped potential even in today's data. If current plans come to fruition, the amount of untapped potential will increase further. It should be noted that this paper is somewhat GOES-centric, as geostationary satellites are the TC forecasters most reliable and timely data source. However, the planned improvements in the GOES-R series are just a part of the bigger picture of steadily increasing data available to the forecasters and to NWP.

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