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Tropical Cyclone Structure and Intensity

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LONG-TERM GOALS

Sub-tropical (ST) cyclones are often ambiguous in their identity, and a universal method to classify them has remained elusive. Yet, they can often bring considerable oceanic hazards to the fleet, and occasionally transform into more vigorous tropical cyclones. The JTWC presents the need for classification and intensity estimation of ST cyclones as high on their priority list for the research community. Our study aims to develop a method to estimate ST intensity objectively using satellite-derived observations.

Through the analysis of robust microwave imager data set, the goal is to better constrain tropical cyclone (TC) structure (using satellite-derived center location, inner core organization, size, and intensity) and their time evolution from pre-genesis to a mature storm and to better understand and forecast intensity changes and better understand structural regimes (e.g., inner core changes, rainband organization, etc.) in the TC lifecycle. This unique satellite-derived digital data set of TC structural evolution from birth, to maximum intensity, and through decay will permit discoveries not earlier possible on the potential multiple "pathways" TCs possess: a) eyewall formation, b) secondary eyewall formation, cycles, and inner eyewall decay, c) new insight into rainband and inner core impacts due to shear, cool sea surface temperatures and dry air intrusions (such as Saharan Air Layer or mid-latitude sources).

OBJECTIVES

Develop a robust, objective and fully-automated method to estimate ST cyclone intensity, based on observable criteria from satellite-based remote sensing.

Develop accurate, automated, and objective satellite remote sensing techniques to derive TC location, inner core characteristics, size, intensity, and changes in intensity and structure under all conditions (e.g., 24 hr/day, any global location, and strengths ranging from tropical disturbance through Category 5).

Create, demonstrate, and test product algorithms that will enable the TC community to more accurately assess the current and changing state of the TC via the exploitation of multiple satellites via sensor data fusion.

TC storm structural life cycles will assist the TC community, observational, theoretical, and modeling due to a more complete understanding of fundamental storm variations. This will be particularly true for most of the global TCs since only the Atlantic has aircraft recon that can attempt to provide in-situ flight level and radar data to monitor vital storm characteristics. Research results will assist the global TC community in more accurately specifying the true TC structural landscape that encompasses nature's diversity.

APPROACH

To estimate ST cyclone intensities, we must first understand the structures and processes that lead to these cyclone phases. We will first familiarize with the available literature on ST cyclones, and interact with tropical forecasters at JTWC to determine their working definitions of these events. Next we will examine the current subjective methods used to classify ST systems to provide the foundation for the development of an objective and fully-automated technique. We will then explore the adaptation of an operationally available remote sensing tool, the Advanced Dvorak Technique (ADT) to automate the ST cyclone intensity estimates. The available ST cyclone identification information will be input into a version of the ADT, to be tested and evaluated on independent cases for robustness.

Satellite sensors represent the only viable observing platform that can provide the geographic coverage, and spatial, spectral, and temporal sampling required to monitor TC parameters in a near real-time mode globally. This project will focus on developing new satellite-based tools that assist the TC community in mapping storm structure (location, inner core characteristics, size, and intensity). Previous long term efforts have focused on visible/infrared (vis/IR) imagery that provide 30-minute refresh within the tropical oceanic basins. This effort will exploit the data fusion possible by combining microwave imagers and sounders (that better visualize internal storm structure through hydrometeor representation) with the more traditional vis/IR sensors and take advantage of the inherent capabilities to view storm characteristics in all-weather conditions.

Combining digital data from a suite of geostationary (GEO) and low earth orbiting (LEO) satellites for near real-time applications on 5-8 ongoing storms (typical for the Joint Typhoon Warning Center (JTWC, Pearl Harbor, HI) can create chaos in an operational setting when multiple products need to be queried from different computer systems and visualization platforms. Thus, one goal is to simplify the GEO-LEO data fusion, while extracting the best traits from each digital data set and thus enhance Navy/DOD ability to accurately monitor global TCs.

Previous efforts utilizing microwave imager data have outlined the ability to view storm structure generically, but have only recently delved into the more difficult quantitative analyses. Our project will enable the next step by recalibrating multiple sensors to a "standard" frequency that will permit advances in storm signals not feasible earlier. In addition, we plan to significantly add to the temporal sampling of TC intensity by incorporating new microwave sounders that will be in the operational constellations for years to come.

The fact we have a consistent channel (89 GHz), remapping applied to all sensors, and centered images is crucial to the overall goal of creating a technique that can exploit the spectral advantages within microwave imagers. The data set has recalibrated 89 GHz images that are remapped, creating higher resolution imagery products, and a re-centering routine (ARCHER) that accurately centers the microwave images around the storm center. These three processing stages provide a unique data set that is well suited to identify and extract key storm features that are associated with TC intensity.

Earlier efforts in using microwave imager data to estimate TC intensity met with some success, but were severely limited by the very small data set (~300) which did not contain the full range of "feature space" that exists within "nature". This drawback is no longer prevalent and the 100,000+ data set and coincident recon provide a robust opportunity to succeed in exploiting microwave imager data to produce an accurate independent TC intensity algorithm.

WORK COMPLETED

1. Identified the observable criteria of ST cyclones via literature review and forecaster interaction, and have examined the current approach (subjective) utilized by JTWC to extract baseline information, to be utilized as input to the objective algorithm to estimate ST cyclone intensities.
2. Gathered available operational metrics for intensity and eye/eyewall size and structure (i.e., the global best track information from NHC/CPHC/JTWC and aircraft reconnaissance vortex messages. Performed analysis of TC structure/intensity combinations and trends to create baseline of performance and validation dataset for objective microwave

   structure analysis.
3. Performed tests on available interpolation schemes to preserve physicality and microwave data fidelity for data transformation from conically scanned microwave grid to storm centered polar coordinates. Bi-cubic spline is found to be superior for preserving brightness temperature gradients and maintaining proper shape of convective structure over new analysis grids.
4. Completed a version 2 revision of the microwave structure dataset that adds additional best track and ARCHER metadata, linear and cubic spline interpolation estimates of the TC position and speed/direction at the overpass time, and a consistent cubic spline interpolation scheme.
5. Performed initial research on TC-microwave structure metrics derived from an axisymmetric polar coordinate reference frame as well as from the ARCHER analysis. Preliminary results show that simple microwave-based structure indices replicate best track/aircraft eye/eyewall observations quite well.
6. Preliminary analysis on TC structural features towards improving intensity estimates indicates a robust ability sample relevant features from previous analyses as well as the potential to expand those metrics in the polar coordinate reference.

RESULTS

Topic 1: Objective Classification of Sub-Tropical Cyclones (CIMSS Collaboration)

The JTWC has designed a prototype subjective method to classify cyclonic systems. It is a repeatable, guided process to classify cyclone phase, aided by an on-line Classification Worksheet. From Kucas et al. (2014) and personal communication, a list of 13 observable criteria related to cyclone phase for which associated, near real-time data are routinely available have been identified and are included in an initial version of the cyclone phase classification worksheet:

• Moisture signature (total precipitable water)
• Symmetry of the low level circulation center (LLCC)
• Radius of maximum winds

• Symmetry of the 850 mb vorticity signature
• 850 mb maximum vorticity
• Deep convection structure
• Size of convective envelope
• Vertical wind shear
• Sea surface temperature
• Baroclinicity
• Core temperature anomaly
• LLCC position relative to the 500 mb subtropical ridge axis
• LLCC position relative to upper low

The phase classification worksheet includes multiple "value bins" corresponding to typical data ranges for each of the observable criteria. Numerical values are assigned to each value bin – near-null values to typical characteristics of subtropical cyclones. Total score ranges were then developed to provide a "best fit" to subjective assessments of ST phases. This methodology will provide the basis for the development of a scheme to inform the ADT of STC phase events, and furthermore to objectively estimate intensities.

Topic 2: Tropical Cyclone Structural Evolution

There is a wide body of research that indicates which TC structures may be important indicators of intensity and/or stages in cyclone development. To better orient this research with respect to past work on TC structure, the climatology of all available operational structural metrics (composed of the best track record and real-time aircraft reconnaissance data) is gathered and analyzed first. This dataset provides the baseline truth that can be used to compare against satellite-derived structural metrics, as well as the foundation from which new objective structural metrics may be derived.

The spatial distribution of this operationally derived data is found in Figure 1. While the best track information (Fig. 1a) shows a representative sample of global TC activity (with respect to location, intensity, RMW, etc.), the operational aircraft information is largely limited to the western Atlantic (Fig. 2a). Although aircraft reconnaissance provides much more information than is demonstrated here, these spatial plots serve to emphasize the limitations of sampling only a small fraction of all TCs that occur globally. While such in situ information provides invaluable data on the state and tendency of TC development within NHC/CPHC regions of responsibility, such efforts are costly, use subjective estimates by the flight crew, and are not available for all TCs of interest. As will be shown below, this study will create objective satellite-based metrics to replicate the gross intensity and structural information provided by aircraft.

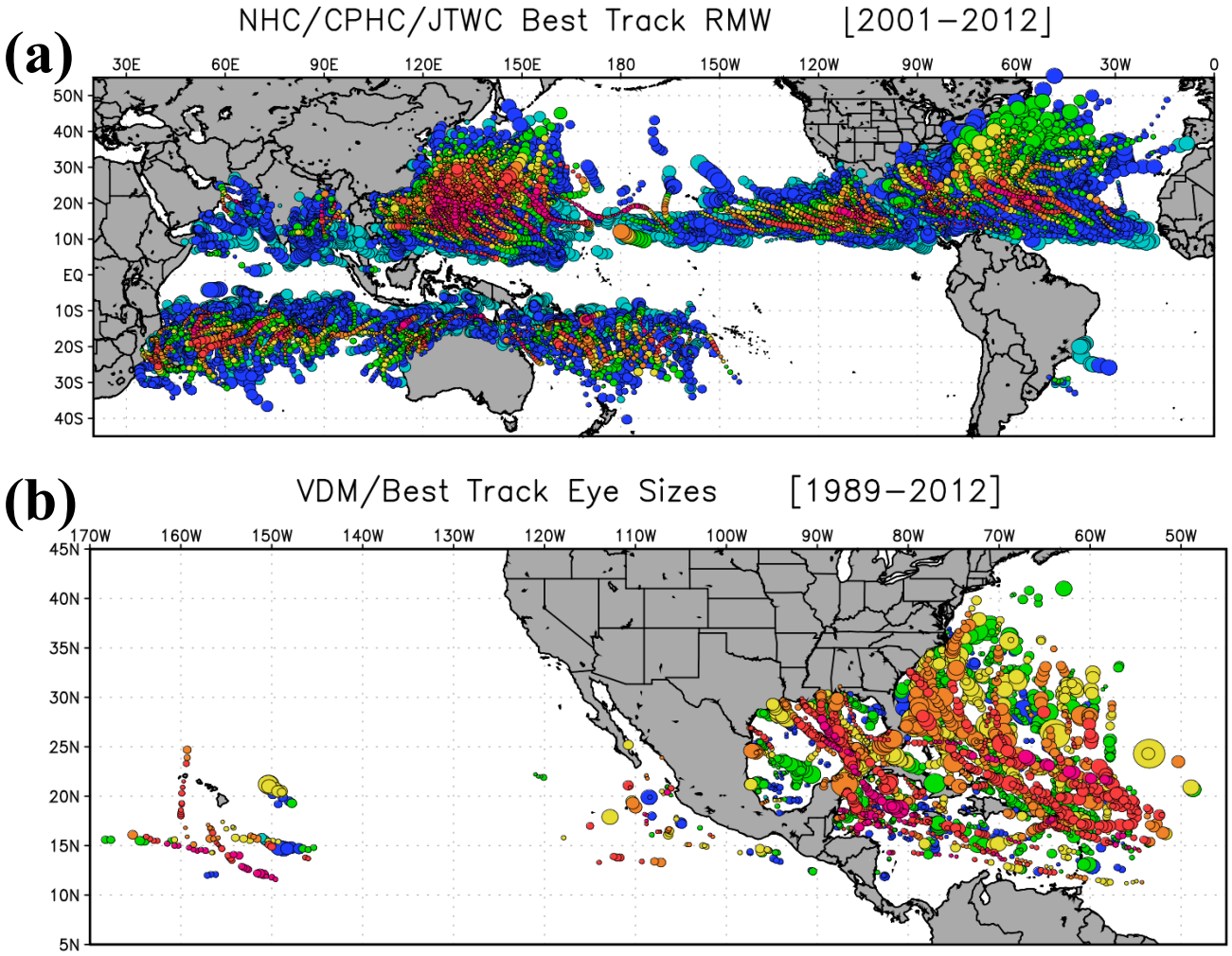

Figure 1: Locations of the operational/verification data used in this study, where the shaded colors indicate intensity (warmer colors are stronger storms) and the size of the dot represents the size of the RMW (a) or eye size (b). Figure (a) shows the global locations of all TCs from 2001-2012. Figure (b) shows aircraft reconnaissance vortex data message (VDM) fixes with a measured eye size and best track intensity from 1989-2012.

However, before performing a structure analysis on the microwave dataset presented in previous reports and publications (e.g. Cossuth 2014, Yang et al. 2014, Cossuth et al. 2015), there are several updates to improve standardization and analysis. To improve the precision and ease of spatial, temporal, and intensity analyses, more precise cubic interpolation was performed on the best track data to provide a higher order precision to the TC vital information. Furthermore, additional metadata from the ARCHER centering analyses (e.g. Wimmers and Velden 2014) are preserved and added to the digital microwave dataset.

Beyond metadata enhancements, an in depth study was performed to determine the robustness of interpolation methods on this dataset. Because of the non-regular grid of observations provided by conically-scanning microwave radiometers, microphysical features may appear slightly distorted (e.g., jagged edges and unrepresentative gradients). In addition, many objective structural analyses for this study will be performed in a storm-relative polar coordinate framework (i.e., centered on the storm and

transformed into radius and angle coordinates). Figure 2 provides a small example of how the original resolution and scan configuration (a) is smoothed and regularly spaced using two different interpolation methods (c) and (d). Although these interpolated fields look qualitatively similar, the difference field in (b) indicates up to ~15 K differences in brightness temperature based on how the interpolation schemes interpret the gradient locations. Overall, a bi-cubic spline interpolation scheme showed improved fidelity of brightness temperature magnitudes, more reasonable representation of gradient and gradient magnitudes, and qualitatively better physical representation of convective phenomena. A publication that examines the numerical and physical considerations of interpolating conically scanned data in storm-centric polar coordinates is in preparation.

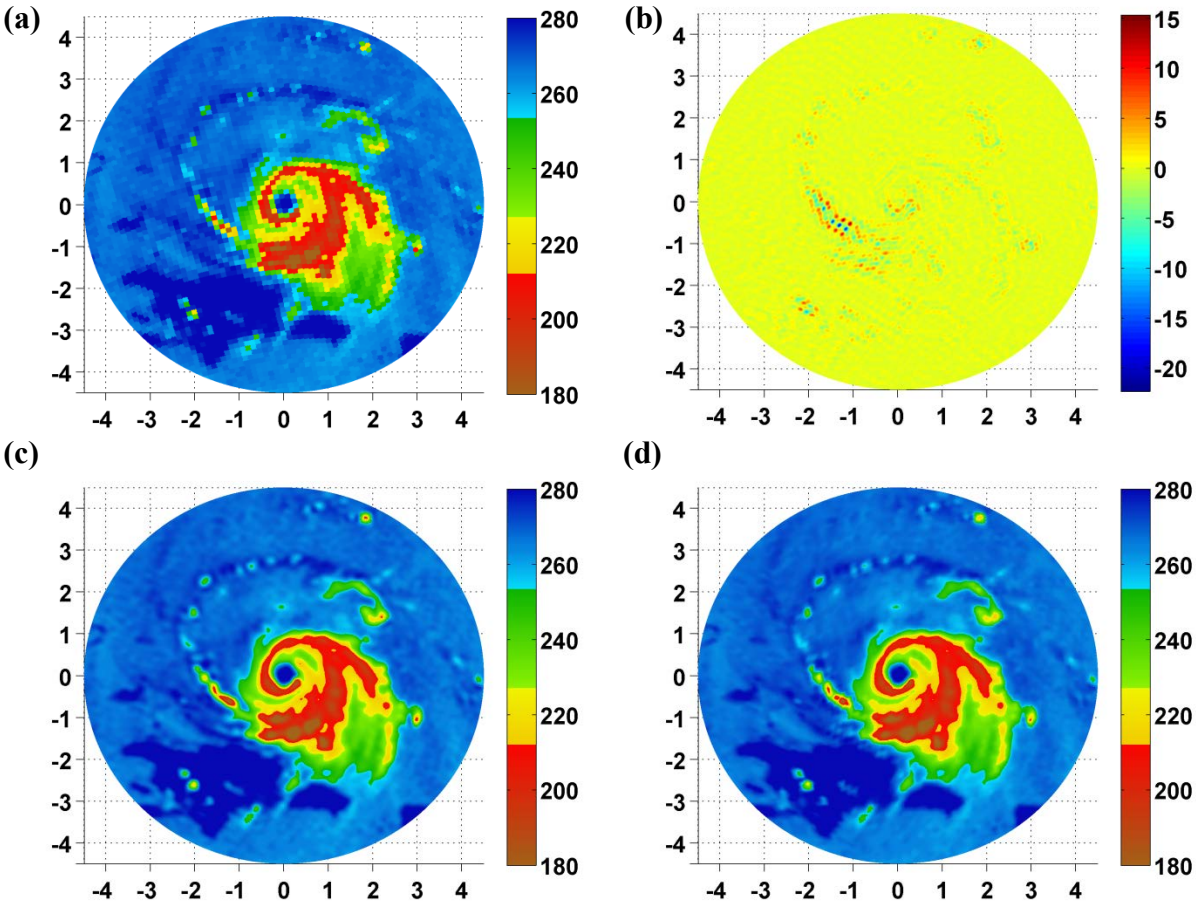

Figure 2: F17 SSMIS overpass of Hurricane Ike at 2158Z September 06, 2008. Test plots of interpolation methods showing (a) the original data resolution, (c) the Backus-Gilbert optimal interpolation, (d) bi-cubic spline interpolation, and (b) the difference fields between (c) and (d).

After reprocessing the ~100,000 global TC-microwave case dataset with the additional metadata and improved interpolation methodology, initial research was performed toward objective structural analysis. The first steps involved determining methods to analyze the TC eye and eyewall to provide a comparison with the operational (i.e., best track and aircraft reconnaissance) metrics. Axisymmetric analyses of the brightness temperature fields were chosen as a starting point of determining structural regimes, where the "eyewall" is defined as the minimum azimuthally averaged value and the "eye size" is defined by minimum inflection point in brightness temperature (i.e. where the gradient between the eye center and eyewall is largest).

A comparison of the objectively defined axisymmetric eye size in microwave imagery and the eye size found subjectively by operational aircraft reconnaissance is shown in Figure 3. The overall shapes of the profiles are similar – the combination of eye sizes and intensities occur in a roughly triangular continuum, with the strongest storms displaying the smallest eyes and weaker storms occurring in greater frequency with a positive skew towards larger eyes. However, note that in the microwave imagery both the number of cases and the extent of the possible range of cases are much broader.

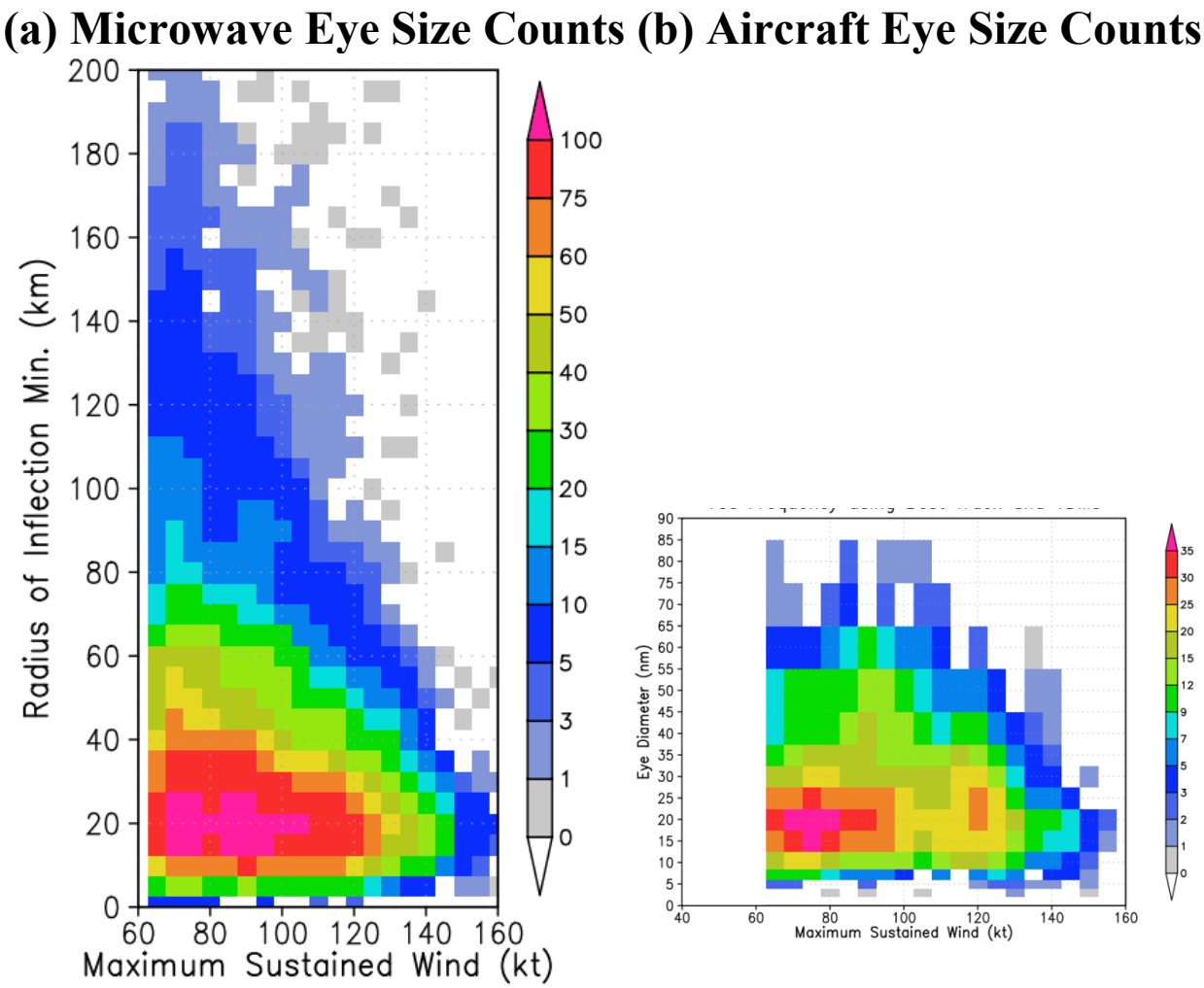

Figure 3: Two dimensional histogram showing the frequency distribution of hurricane strength TCs based on eye size and best track intensity. (a) Shows axisymmetric eye sizes objectively derived from the digital microwave database. (b) Shows eye sizes estimated by operational aircraft reconnaissance, except the axes scaled to approximately match the ordinate axis of (a).

Although the figures above show a brief and preliminary look at the conclusions of this tropical cyclone analysis, the results are encouraging. It appears that objective satellite microwave-derived estimates of inner-core size and intensity comparisons align well with – and expand upon –operational metrics currently available with aircraft reconnaissance. Work continues on defining eyewall replacement cycles and band formation/decay using a similar axisymmetric methodology. Beyond that, a broader range of feature-based analysis is being performed to gain additional dimensionality in assessing the range of structural states for quantifying TC evolution and estimating TC intensity.

Topic 3: Tropical Cyclone Intensity Estimates

As a database of microwave-based structural features is developed for Topic 2, the statistical relationship and significance of those features as it relates to current intensity estimation will be examined. While the analysis methodology will be similar to Bankert and Hawkins (2012), updates in the dataset, software, and analysis techniques suggest an improved analysis path. Steps undertaken include a literature review of possible predictors, testing of statistical analysis software packages, and the exploration of new structural features beyond Topic 2.

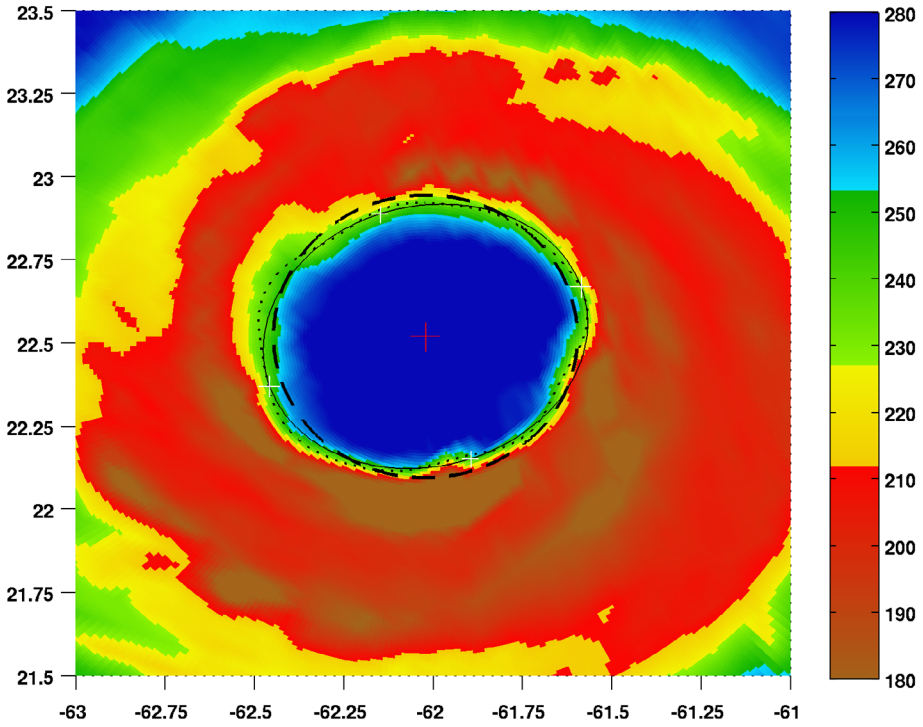

Figure 4: AMSR-E overpass of Hurricane Isabel at 1709Z September 13, 2003. Objective polar coordinate analysis of 235 K eyewall at wavenumber 0 (circle; dashed line), wavenumber 2 (ellipse; thin solid line), and wavenumber 4 (dotted line).

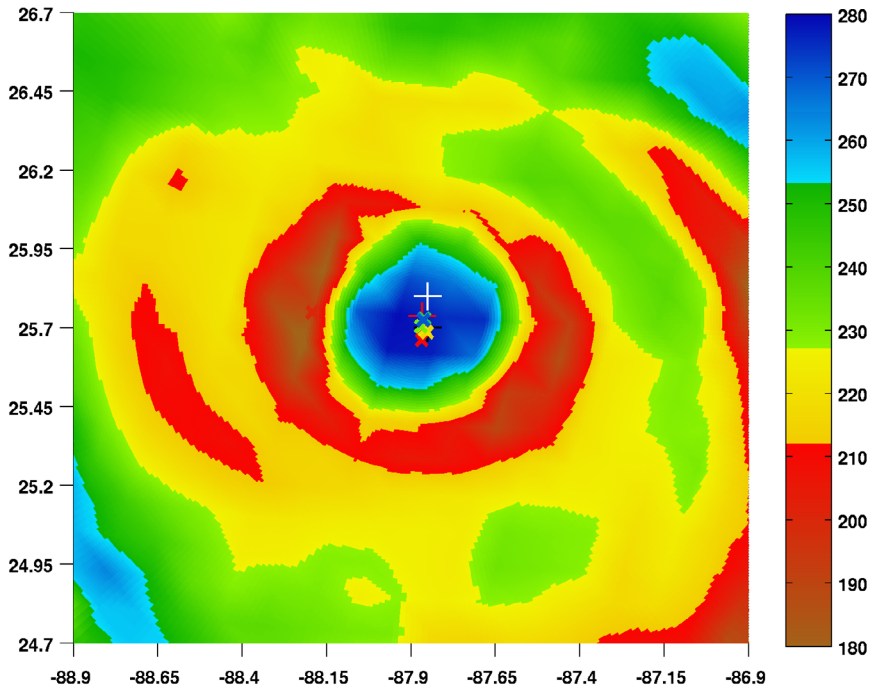

Figure 5: F13 SSM/I overpass of Hurricane Katrina at 1244Z August 28, 2005. Objective polar coordinate analysis of TC centers. First guess information shown by large plus signs. Geometric eyewall centers at different brightness temperatures plotted in small X's.

Background research into statistical methods and previous metrics related to intensity estimation via satellite images was performed through a literature review. An assortment of methodologies from different fields including statistics, image processing, and morphometrics are gathered for their potential in characterizing microwave imagery for TC intensity. Furthermore, preliminary work began on testing various statistical processing packages (including Cubist, R, and Matlab) for their ability to create and diagnose regressions and neural networks.

Finally, exploratory work has begun on characterizing TC structural asymmetries that previous work has shown may relate to intensity. This includes the wavenumber structure of the eye (Figure 4) and convective location relative to shear, as well as storm tilt (inferred by the spread and direction of geometric centroids in Figure 5). This work is ongoing in continues to show promise for use as a transitioned tool for enhanced TC analysis.

IMPACT/APPLICATIONS

- Automation of currently used subjective analysis of microwave imagery.
- Additional improved intensity analysis and forecast guidance that does not use current techniques (adds variance to current methods).
- Provides the first guidance for structure and structure change analysis.
- Provides insight into constraining TC lifecycle, suggesting future theoretical and empirical work.

While microwave imager data has proven useful for near real-time warning applications, the full potential of gleaning storm evolution has not been realized due in part to the lack of a consistent high resolution data set covering multiple decades and oceanic basins.

TRANSITIONS

The microwave-derived TC intensity estimate algorithm will be transitioned to a corresponding 6.4 work unit funded by PEO C4I PMW-120, where an ongoing near real-time demo of TC products is underway with validation in concert with JTWC. Additional coordination of intensity estimate algorithm with CIMSS SATCON and introduction of analysis to ATCF will also be initiated.

RELATED PROJECTS

This project is closely related to a 6.4 effort sponsored by the Program Executive Office for C4I&Space/PMW-120 entitled "Tropical cyclone intensity and structure via multi-sensor combinations", funded under PE 0603207N. The 6.4 project serves as the transition vehicle, works closely with JTWC, the National Hurricane Center and the Central Pacific Hurricane Center and serves as the conduit to new products at FNMOC. Feedback from JTWC, NHC, CPHC and the TC research community has been extremely positive at multiple technical conferences and via email sent directly to NRL-MRY.

NOAA JHT projects that started in September, 2015 provide another research avenue to get operational feedback to improve the realtime application of these products.

This project works closely with JTWC, NHC, CPHC and FNMOC to understand the needs of the operational TC community via routine emails, phone calls and technical conferences (AMS, IHC, TCC, and IWTC). Feedback is routinely solicited from all operational partners in order to understand how the 6.2 efforts outlined here can best be aligned to answer real world requirements and needs.

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HONORS/AWARDS/PRIZES

2014 Alan Berman Award (Previous ONR-sponsored project for this work - awarded in 2015): Yang, S., J. Hawkins, and K. Richardson, 2014: The improved NRL tropical cyclone monitoring system with a unified microwave brightness temperature calibration scheme. Remote Sens. 6, 4563-4581; doi:10.3390/rs6054563.