Remotely Sensed Tropical Cyclone Structure/Intensity Changes

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LONG-TERM GOALS

Routinely map the life cycle of a tropical cyclone's (TC) three-dimensional (3-D) "environment" and inner-core structure in order to better understand a TC's intensity and varying surface wind field.

OBJECTIVES

Map TC inner-core structure changes and provide a consistent basis for understanding related storm intensity changes that have proven difficult to comprehend with the limited aircraft recon data sets. Develop accurate automated techniques to estimate TC intensity and intensity changes under all conditions (e.g., 24 hr/day, any global location, and tropical depression to Category 5) with special attention to surface wind fields.

APPROACH

Our ability to view a TC's inner structure is oftentimes obscured by upper-level clouds and thus negatively impacts real-time efforts to extract accurate intensity and surface wind field estimates sorely needed as input for warnings, ship and aircraft sorties, model bogus vortex inputs and emergency preparedness. This effort will incorporate passive microwave imager data from the current suite of operational and R&D sensors, including: three Special Sensor Microwave/Imagers (SSM/I) onboard the DMSP satellites (F-13, 14, 15), the NASA Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), the NASA Aqua Advanced Microwave Scanning Radiometer (AMSR-E), the Navy's Coriolis Windsat polarimetric radiometer, three Advanced Microwave Sounding Units (AMSU) on NOAA polar orbiters (N15/16/18), the Microwave Humidity Sounder (N-18), and the Special Sensor Microwave Imager Sounder (SSMIS, F-16 and F-17). We will acquire and process all sensors when overflying TCs globally to collect and study applications on TC monitoring.

The 85-91 GHz and 37 GHz passive microwave imager data will map TC structure, with particular focus on inner-core dynamics and eyewall cycle processes. Eyewall replacement cycles (ERC) have been a major earlier finding of this research, but "in-situ" measurements are lacking to outline when satellite "signatures" discern true surface wind field changes. Thus, microwave data will be studied with coincident Tropical Cyclone Structure (TCS-08) aircraft reconnaissance (recon) data (SFMR and surface dropsonde values) in the western pacific and the more plentiful Atlantic recon data sets to

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14. ABSTRACT
Routinely map the life cycle of a tropical cyclone?s (TC) three-dimensional (3-D) "environment" and inner-core structure in order to better understand a TC?s intensity and varying surface wind field.

15. SUBJECT TERMS

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provide the appropriate correlation between microwave features and surface wind field structure. Since microwave sensors can view eyewall genesis, but can this structural detail be used by the Dvorak IR techniques to mitigate inherent IR limitations and keep the ADT algorithm intensities from leveling off until an eye "pops-out" and then tries to rapidly increase values in an effort to catch up?

ONR/NSF sponsored the TCS-08 field program as part of the THORPEX Pacific Asian Regional Campaign (TPARC) with a goal of gathering critical observations from multiple platforms during August/September 2008 to answer fundamental questions on TC genesis, structure and structure change, satellite validation and extratropical transition. The Guam-based component included two WC-130J Air Force reserve weather squadron aircraft with flight level measurements, a Stepped Frequency Microwave Radiometer (SFMR) for surface wind speeds, airborne expendable bathythermographs (AXBT) to measure ocean thermal structure and nose-mounted C-band radar. In addition, the NRL P-3 aircraft collected not only flight level winds, but dropsondes, lidar winds and ELDORA Doppler measurements capable of extracting accurate 3-D wind fields out to 60-km. Driftsondes also dispensed miniature dropsondes as they drifted west from their Kauai launch point, the German Falcon jet based in Japan had dropsondes and lidar, while the Taiwan DOTSTAR had dropsondes for those systems near the island. All these platforms potentially provide observations that can assist the various satellite efforts noted here.

WORK COMPLETED

A unique global data set of passive microwave imagery overflights for all active TCs has been compiled and analyzed since 1997-2007 and is continuing into 2008 via the NRL TC web page product suite: http:www.nrlmry.navy.mil/TC.html. This decade long period encompasses the full suite of TCs from weak tropical depressions to Category 5 hurricanes and super typhoons. In addition, the database includes TCs ranging in size from midgets to monsoon depressions with radii of gale force winds exceeding 200-300 km.

An experimental method has been created to "add" eyewall information derived from microwave imagery to the automated Dvorak IR intensity algorithm. The enhanced structural details readily monitored via passive microwave can help the ADT module understand when eyewall formation is in progress and thus adjust the ADT values as appropriate. This modified ADT intensity can then be incorporated into the existing satellite consensus (SATCON) and create a superior single satellite TC estimate and is being validated with both Atlantic and now Pacific recon eyewall penetration datasets.

The TCS field project required contributions from many talented scientists, aircrew members and support staff in order to coordinate a successful two month mission deployed to Guam and Japan, encompassing five aircraft noted above while focused on flying in and through typhoons from genesis to Category 5 stages. As part of TCS-08, I carried out the following functions: a) served as C-130 mission scientist on ten (10) flights from Guam (65 flight hours) into systems ranging from pre-genesis to Category 1 typhoons, b) assisted Peter Black as Guam base operations manager for five weeks, helping carry out all functions from drafting flight tracks (locations for all dropsondes and AXBTs), go/no-go decisions, coordination amongst multiple planes and scientific disciplines, processing data sets and transmitting them to NPS, and c) worked as co-lead (with Russ Elsberry) in the NPS Monterey operations center while Pat Harr was on unexpected leave, helping coordinate all airborne assets into typhoon Sinlaku and Hagupit while planes were deployed to Kadena and Yokota, Japan.

TECHNICAL RESULTS

Eyewall replacement cycles:

A systematic review of passive microwave data from 1997-2007 (Fig. X) reveals that concentric eyewalls are highly correlated with storms reaching 120 kts or higher (Hawkins et al, 2006). 77% of Atlantic basin storms and more than three-quarters (81%) of western Pacific typhoons reaching best track intensities of 120 kts or more exhibited double eyewalls during their lifespan. Due to a lack of aircraft recon and surface observations, it is unknown whether all double eyewalls had double wind maximums manifested at the ocean surface. These statistics can vary dramatically during any given year and/or basin. Early years during this period were highly skewed towards the dominant western pacific basin, but more recent occurrences of Cat 5 TCs in the Atlantic basin (accompanied with double eyewalls) has now brought the Atlantic basin values more in line with the western pacific.

Eyewall replacement cycles (ERC) are associated with short term intensity changes that directly mirror the inner storm structure changes. Aircraft reconnaissance data is slowly gathering crucial double eyewall penetration data sets (flight level winds, Stepped Frequency Microwave Radiometer [SFMR] surface wind speeds and radar imagery) that will greatly aid in understanding the surface manifestation of passive microwave double eyewall signatures.

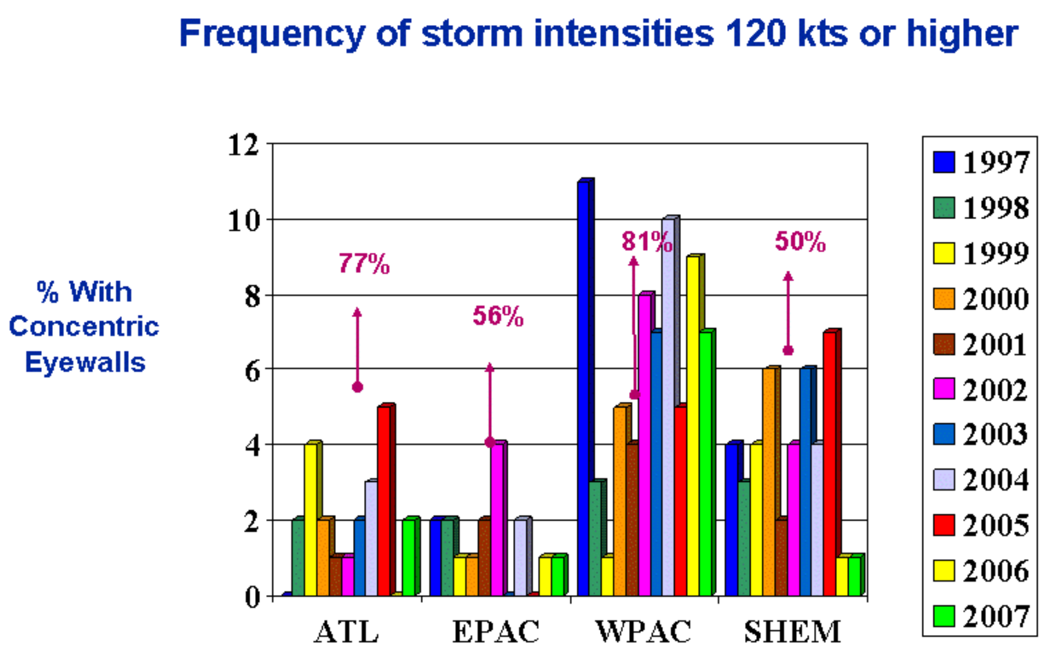

Figure 1: Number of tropical cyclones reaching a maximum sustained wind speed equal or greater to 120 kts for the Atlantic, Eastern Pacific, Western Pacific and southern hemisphere within 1997-2007. Over 77% of storms reaching 120 kts developed concentric eyewalls in the Atlantic, 56% in the eastern Pacific, while the western Pacific statistics reveal ~ 81% and SHEM 50%.

Satellite-Derived Tropical Cyclone Intensities:

Automated satellite-derived TC intensity algorithms now incorporate data from both geostationary IR (Automated Dvorak Technique, ADT) and microwave sounder methods using the Advanced Microwave Sounder Unit (AMSU, CIMSS/CIRA). The Dvorak method (whether manual or automated) frequently suffers when the eyewall is first forming since a clear eyewall view is not commonly seen due to clouds aloft and/or clouds within the eye itself. Thus, the team has created a beta algorithm that extracts near real-time eyewall structure features from microwave imagers and creates an "index" or score that increases as the rainband encirclement proceeds and as the eyewall brightness temperatures (Tb) get colder (more intense convection). The microwave eyewall index eventually reaches a threshold at which the ADT values are increased to compensate for the underlying eyewall development that the IR data simply can not view as seen in Figure 2.

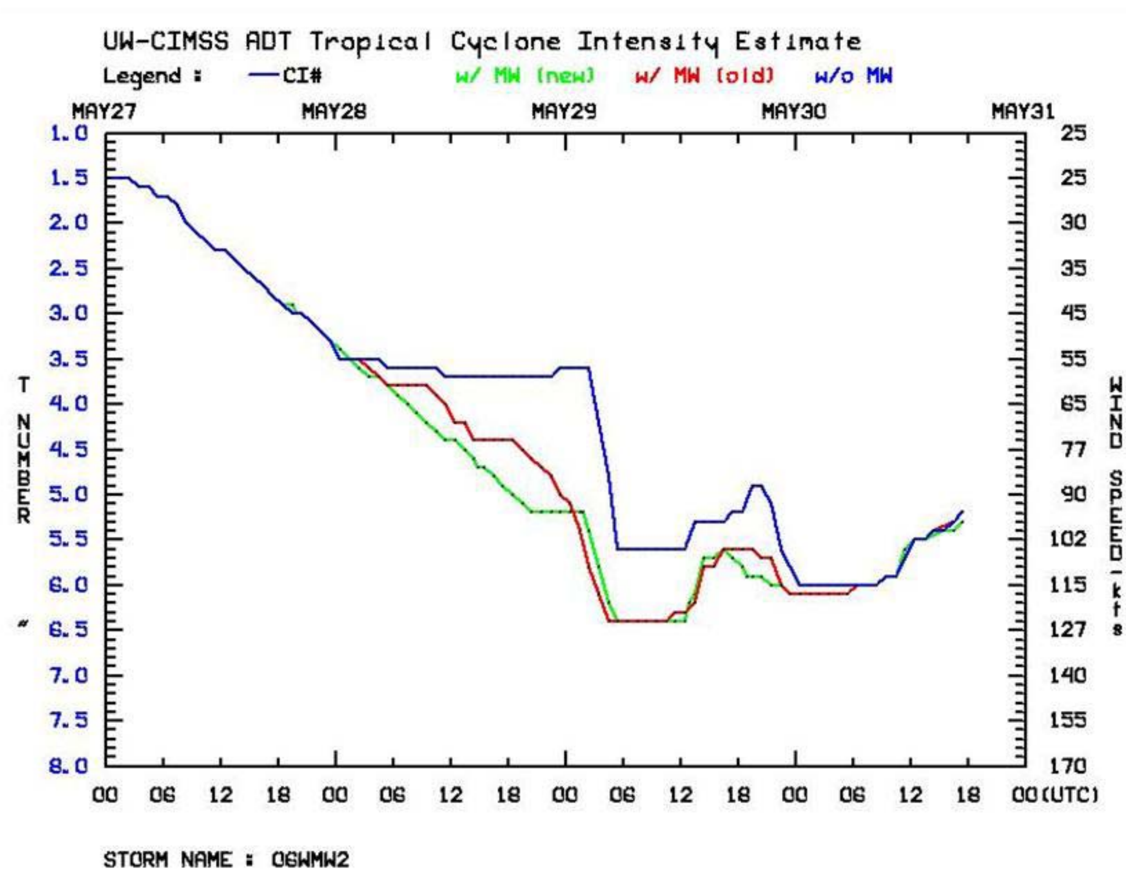

Figure 2: Time series of ADT TC intensities for typhoon 06W in the western Pacific from May 27-31, 2008. Blue line: original ADT based on IR only, red: ADT with inclusion of microwave (old version), green: ADT with microwave (new version), [Courtesy CIMSS].

Fig. 2 illustrates the "classic" Dvorak dilemma when the IR-based ADT does not see a "warm eye" and thus holds the intensity basically level until the eye appears and it rapidly compensates. However, TC formation is ongoing during the whole time as seen in both microwave versions as represented by steady intensity increases and underlying eyewall structure improvements. This common problem is treated in the satellite consensus (SATCON) by weighting ADT weakly in CDO scenes, but testing to date indicates the microwave addition will permit us to weigh ADT values higher over a broader range of TC lifespans. A microwave only version is in testing but does not currently compete with the ADT assisted with microwave technique.

Aircraft recon vortex messages from the Atlantic basin form the bulk of the test/validation database, with occasional sorties into the eastern and central pacific TCs. However, this year's TCS-08 project has accumulated more than twenty WC-130J center fixes corresponding with AMSU overpasses (some fixes matched up with more than one AMSU). WC-130J dropsonde-derived surface winds and pressures and SFMR surface winds will be used to assist in "best tracking" TCS-08 storms and help in describing some of the wind-pressure relationship differences existing between the Atlantic and Pacific basins. Preliminary matchups indicate SATCON did very well, thus illustrating the tuning to date and the value evident in a multiple algorithm combination.

TCS-08 Field Program

The field program effort consisted of three (3) phases: (1) near real-time satellite product support, (2) acting as mission scientist for WC-130J flights from Guam covering genesis to Cat 1 weather systems and (3) acting as co-lead for the Monterey operations center.

The TCS-07 summer dry run implemented the standard suite of NRL TC web page suite of satellite visible, IR, water vapor and most importantly microwave products for "experimental" TCS "invests" or areas of persistent convection that warranted further study as genesis candidates. For TCS-08, NRL added Google Earth (GE) capabilities in concert with NPS efforts to display multiple data sets [C-130 and P-3 real-time tracks, dropsonde information, driftsonde track and drop data, proposed aircraft flight tracks, ocean drifting buoys, land-based radar imagery and other in-situ observations]. GE enabled the Monterey operations center to visualize vis/IR and microwave imagery with real-time flight tracks overlain, greatly facilitating situational awareness with respect to specific TC structural features (rainbands and eyewall for ELDORA and eyewall and outer structure for the WC-130J). The satellite products were critical in coordinating crucial "real-time" aircraft track changes aimed at optimizing the limited flight times for both aircraft. Figure 3 captures an example of the NRL P-3 as it is able to "enter" the open northern eyewall of typhoon Jangmi on September 24, 2008. With no land radar for help, and visible imagery cloud covered in some key areas, microwave imagery was a key factor in safely vectoring the P-3 to the north in hopes of gathering ELDORA data within the storm's inner core. The P-3 went directly to the storm center and then backtracked out, while gathering superb 3-D wind field details that may possibly not been possible without multiple satellite microwave views.

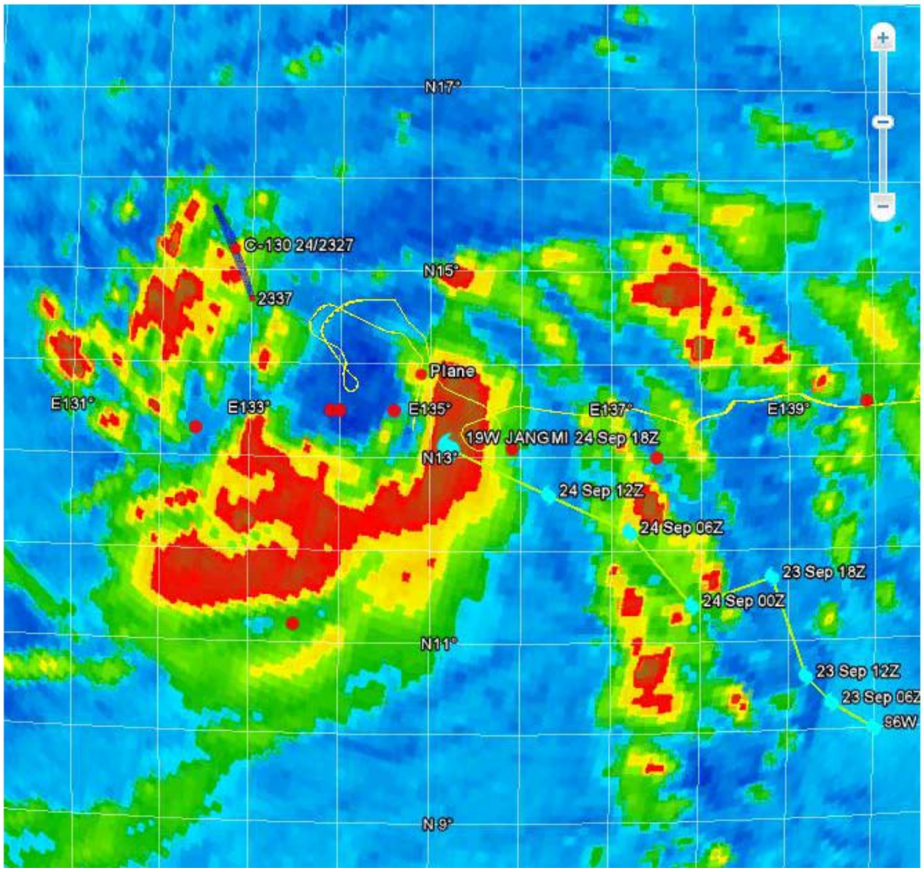

Figure 3: Passive microwave 91 GHz brightness temperature image from the SSMIS sensor on September 24, 2008 at 2305Z highlighting eyewall formation for tropical storm Jangmi. Overlain are the storm track and the P-3 track (thin yellow line). Note how the P-3 was able to use this product and its own radar to navigate in and out of the incipient eye on the weak north side. The P-3 is not to penetrate mature eyewalls for safety reasons.

As WC-130J mission scientist, led team effort to decide on track changes by analyzing dropsonde winds at multiple levels in real-time and coordinating track adjustments with Guam and NPS ops centers and plane navigator. In reality, most genesis cases required pattern shifts, sometimes up to two degrees, simply due to weak cloud organization not presenting a clear signal on surface circulation centers. This was typically accomplished after 3-5 dropsondes on the first leg indicating the circulation was offset from our anticipated location.

While co-lead at the NPS Monterey operations center, I helped Russ Elsberry in all facets of multi-day planning, decision making and coordination between the five aircraft and dozens of coworkers and aircrew deployed in Guam and Japan during the extratropical transition case for typhoon Sinlaku and the strong typhoon Hagupit that followed to the south. These tasks included carrying out the daily planning meeting via the Elluminate webcast each day, facilitating targeting discussions and the various WC-130J and P-3 go/no-go webcasts with critical decisions on flights and tracks to accomplish specific scientific objectives.

IMPACT/APPLICATIONS

Double eyewalls are now known to be "common" structural features for Cat 3 and above TCs globally, with the lions share occurring in the western pacific due to the combination of two factors: 1) 7-10 intense storms/season and 2) more than 75% exhibit double eyewalls. This information is now used by JTWC and other TC warning agencies when analyzing microwave imagery and is leading to enhanced theories on structure change mechanisms.

The manual Dvorak TC intensity method has been routinely used around the globe for 30+ years but suffers from inherent cloud cover issues that can be mitigated some by coincident microwave imagery. Our team has created an automated beta algorithm capable of telling ADT about eyewall development and thus increasing the intensity estimates, well before an eye is viewed in corresponding IR digital data. The addition of the microwave data can thus resolve one of the long standing Dvorak problems.

The successful TCS-08 field program will provide a wealth of digital data sets from multiple sensors that will help answer scientific TC questions by virtue of a) the unique western Pacific basin's TCs, b) the aircraft sensors utilized, c) the capture of TCs spanning from pre-genesis to Cat 5, and d) the combination of multiple aircraft and satellite sensors for both cross validation and composite views to address specific scientific thrusts.

TRANSITIONS

Double eyewall satellite signatures will likely transition to 6.4 as the recon validation data base encompasses a growing segment of these poorly understood structural phenomena.

The addition of the microwave imager to monitor eyewall structure and enhance the Dvorak IR intensity technique will be transitioned to 6.4 once the complete 2008 season results are compiled, using both Atlantic and TCS-08 aircraft recon center fix validation data sets.

Lessons learned from the TCS-08 field program will greatly aid any follow-on efforts such as those envisioned for the 2010 oceanographic component.

RELATED PROJECTS

This project is closely related to a 6.4 effort sponsored by the Space and Naval Warfare Systems Command (PEO C4I&Space/PMW-180) 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 and the National Hurricane Center and serves as the conduit to new products at FNMOC. Feedback from JTWC, NHC and the TC research community has been extremely positive as evidenced in recent technical conferences.

This project works closely with JTWC/NHC and FNMOC to understand the needs of the operational TC community via routine emails, phone calls and technical conferences (AMS, IHC, and TCC). 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.

SUMMARY

NRL has pioneered the user of microwave imager to extract accurate TC location and structure knowledge. Double or concentric eyewalls have become a common topic of discussion, not only in the satellite community, but amongst the modeling and dynamically researchers trying to figure out the various mechanisms that can account for these fast changing features that have a direct impact on surface wind fields, sometimes during landfall (Jangmi, Katrina, and Rita). The inclusion of a microwave component to the ADT algorithm has shown great promise and will be transitioned to 6.4. TCS-08 was a huge field program success due to its ability to gather a suite of unique measurements for the first time in fifteen years in the western Pacific with the potential to directly aid JTWC forecasting.

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