6 B.1 TROPICAL CYCLONE MULTIPLE EYEWALL CONFIGURATIONS

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1. INTRODUCTION

Tropical cyclone (TC) inner core structure can vary significantly between storms and eyewall configurations within a single storm can evolve into multiple eyewall orientations (Hawkins, et al., 2004). Our ability to monitor eyewall structure has been routinely hindered by obscurations due to upper-level clouds created via vigorous convection. However, this impediment has been partially mitigated with the operational use of passive microwave satellite sensors that "see through" non-raining clouds and highlight heavy rain and frozen hydrometeors associated with rainbands spiraling in and creating the storm's eyewall. Passive microwave views clearly reveal TCs have multiple eyewalls more frequently than earlier observed with visible and infrared imagery from both geostationary and polar orbiter data.

Near real-time data from the following constellation of operational and research microwave sensors permit the monitoring of eyewall changes: the Special Sensor Microwave/Imager (SSM/I), Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), Advanced Microwave Scanning Radiometer (AMSR-E), Coriolis WindSat, Special Sensor Microwave Imager Sounder (SSMIS), the Advanced Microwave Sounding Unit (AMSU-B) and the Microwave Humidity Sounder (MHS). Each sensor has inherent advantages and disadvantages that hinge directly on the frequencies available, antenna size, altitude and orbital inclination.

Only by utilizing the entire constellation's capabilities (similar to the proposed Global Precipitation Mission (GPM) concept) is the temporal sampling sufficient to capture structural modifications outlined in this paper. All data used for this study were derived from the Naval Research Laboratory's tropical cyclone web page created and updated by the Marine Meteorology Division in Monterey, CA (NRL-MRY) (Hawkins et. al., 2001).

Any change in eyewall organization will be reflected in surface wind field modifications that must be accurately mapped and forecasted; otherwise destructive winds may catch unsuspecting areas off guard. Monitoring TC wind fields needed for warnings is difficult due to the lack of oceanic in-situ observations. However, the few island, buoy and ship reports are now augmented by two satellite scatterometers (QuikSCAT and ERS-2) and WindSat wind vector retrievals. These sensors have inherent problems producing viable vectors within the TC environment's extreme moisture and heavy rain, thus the data sets must be quality controlled. Low-level geostationary cloud-tracked winds can assist in mapping TC wind fields away from the inner core and passive microwave imager wind speeds (scalar only) are available away from rain and heavy moisture regions. In addition, aircraft stepped frequency microwave radiometer and dropsonde measurements near the surface round out the wind field data sets.

An earlier study by Hawkins, et. al., 2004 found that storms containing maximum sustained winds of 120 kts or higher frequently exhibited double eyewall structure. This paper highlights a continuation of that work by adding two years of global data and focusing on storm temporal evolution changes. Section 2 will cover the data sets incorporated, section 3 will outline eyewall detection, section 4 will summarize the frequency of multiple eyewalls and inter-basin variability, section 5 will highlight eyewall evolution within a single storm and section 6 will summarize the research findings.

2. DATA SETS AND PROCESSING

NRL-MRY ingests near real-time digital data from eleven microwave imagers/sounders via collaborative efforts with; 1) Fleet Numerical Meteorology and Oceanography Center (FNMOC), 2) Air Force Weather Agency (AFWA), 3) the National Aeronautics and Space Administration (NASA) and 4) National Oceanic and Atmospheric Administration (NOAA). Data from three operational SSM/Is sensors (F-13, F-14 and F-15), one SSMIS (F-16), the NASA TMI, three operational AMSU-Bs (N-15, N-16, N-17), the MHS (N-18), the NASA AMSR-E, and from the Navy's Coriolis WindSat sensor are gathered with 1-3 hour data delays from the time of satellite sensor acquisition. The brightness temperature (Tb) digital data are mapped to a storm-centered

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image with resolution commensurate to the satellite sensors and are online since 1997.

Also, SSM/I data was reprocessed using the method of Poe (1990) to create high-resolution (1-2km) products that can assist in inner-storm structural details. SSM/I data for most of the intense storms since 1997 have been processed to create a special data set known as TROPX. TROPX supplements the TC web page since some passes were unavailable due to real-time communication and/or processing issues.

3. CONCENTRIC EYEWALL DETECTION

Best track 1-minute maximum sustained wind (MSW) speeds were used from the National Hurricane Center (NHC, Miami) for the Atlantic and East Pacific and from the Joint Typhoon Warning Center (JTWC, Pearl Harbor) for the western Pacific (WPAC), Indian Ocean (IO) and southern hemisphere (SHEM). All storms with MSW greater than or equal to 110 kt (62 m/s) were then examined for double or concentric eyewalls during their lifespan.

85 GHz imagery from the SSM/I and 85 GHz and 37 GHz imagery from TMI were the main tools used to determine the existence of double eyewalls since they were added to the TC web page in 1997 and 1998 respectively. AMSU-B data was added in 2001, AMSR-E in 2003, WindSat in 2004 and most recently SSMIS in 2005 (Hawkins, et. al., 2006). The temporal sampling enhancements feasible with AMSR-E, WindSat and SSMIS data were able to capture several double eyewall scenarios not viewed with SSM/I, TMI and AMSU-B, thus it is possible some storms listed as not containing double eyewalls did indeed have these features.

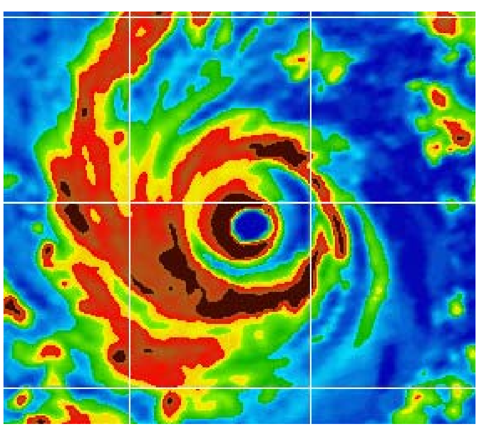

Figure 1: 85 GHz H-pol brightness temperature (Tb) image for typhoon Lupit in the western Pacific during 2003. Cold Tbs are red and they warm as the color changes to yellow, green and then finally blue. Grid lines are 2x2 degrees.

85, 89, and 91 GHz Tbs images were viewed first and then the polarization corrected temperature (PCT) and the NRL 85 GHz "color" products examined (Lee, et. al., 2002). The PCT data is especially helpful, since the use of the combined 85 GHz horizontal and vertical polarizations mitigates much of the ambiguity associated with cold background Tbs from ocean surfaces. Double eyewall criteria focused on qualitatively identifying "two distinct complete" brightness temperature rings encircling the storm center (relatively warm 85 GHz Tbs).

Figure 1 illustrates a prime example of double eyewalls using SSM/I data for typhoon Lupit. The easily identifiable concentric eyewalls are highlighted by very cold Tbs with Tb differences between the convective eyewalls and outside ranging from 50-80 deg K (color scale not shown). The very large Tb range enhances an analyst's ability to recognize partial or full eyewall encirclement.

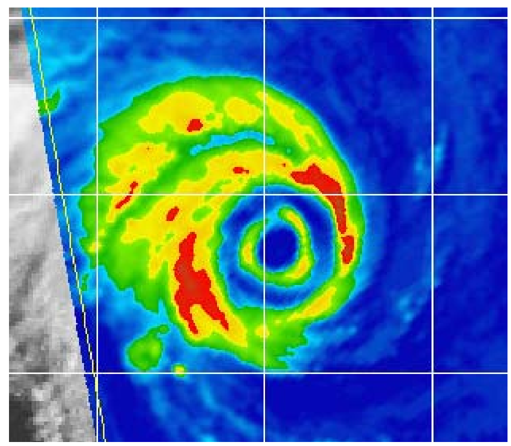

Figure 2: 85 GHz H-pol Tb image of tropical cyclone Frank in the southern Hemisphere during 2004. Colors and grids are the same as Fig. 1.

Figure 2 features tropical cyclone Frank with a weaker inner eyewall than typhoon Lupit (note lack of very cold "red" colors replaced by yellow-green values). In addition, the outer eyewall lacks the complete encirclement of very cold Tbs shown with Lupit and in general would be classified as a "weaker" system. Note that both Lupit and Frank have additional rainbands spiraling into the outer eyewall, while the inner eyewall is basically cutoff, especially in Fig 2. The sequence of events then leads to inner eyewall decay and collapse as the main outer eyewall decreases in diameter and constricts inward. This eyewall replacement cycle (ERC) can continue multiple times "if" environmental conditions are favorable for storm intensification.

Eyewalls are mostly circular in shape as observed in relatively coarse passive microwave resolutions (5-16 km at 85-91 GHz), but do on occasion take on distorted configurations, typically as shear is rapidly impacting storms. However, the advent of shear will typically cease the eyewall cycle, cause the collapse of the inner eyewall and the storm will revert back to one eyewall.

4. CONCENTRIC EYEWALL FREQUENCY

The earlier study by Hawkins et. al, 2004 found that the vast majority of tropical cyclones exhibiting double eyewalls had reached an intensity equal to or greater than 120 kts. On occasion some storms were able to maintain two eyewalls at lower MSW values, but typically while the storm was weakening (storm initially ramped up > 120 kts and then weakened and kept double eyewalls at values < 120 kts). The years 2004 and 2005 were then included in the database using best track MSW values (preliminary values for 2005 since the final versions have not been released by NHC and JTWC as of this writing).

The frequency chart in Figure 3 has thus been updated to include the two very active Atlantic basin years and reveal several important changes. 2005 included five Atlantic hurricanes meeting the 120 kt criteria and each one exhibited double eyewalls as viewed by passive microwave sensors. The concentric eyewalls were also captured by aircraft and land-based radar and were outlined by aircraft radial profiles of flight level tangential winds. The fact that all 5 storms had double eyewalls raised the frequency to 70% for the Atlantic basin, making it second only to the prolific western Pacific basin.

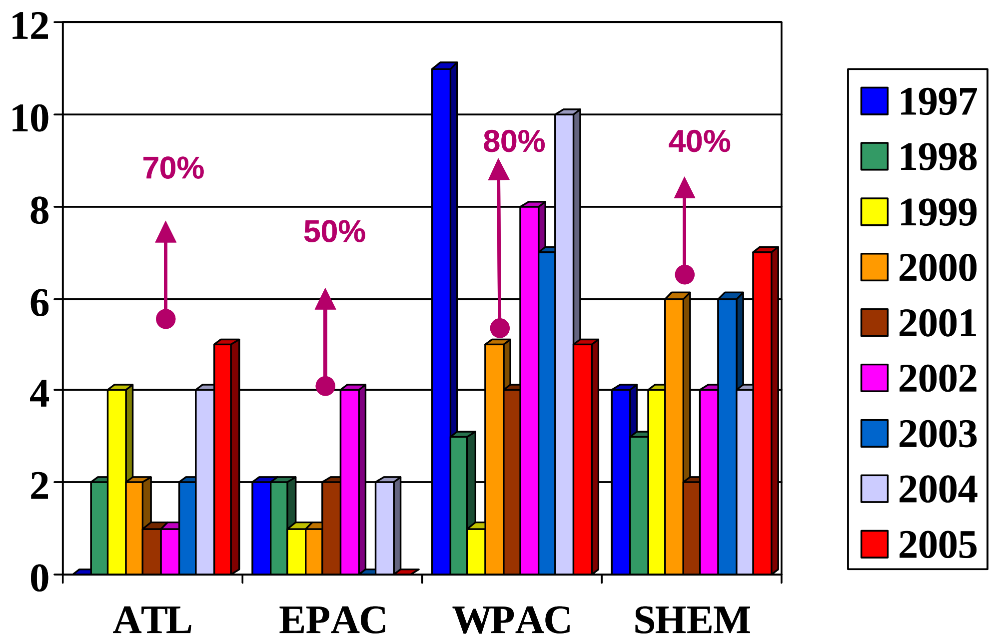

Figure 3: The number of TCs reaching best track (using NHC and JTWC resources) intensities of 120 kt and above during 1997-2005 for four ocean basins are plotted with each year highlighted by a different color per the right hand scale. The percent of the nine-year total found to exhibit concentric eyewalls using passive microwave data is displayed above each basin (Atlantic - 70%, Eastern Pacific – 50%, Western Pacific – 80%, and Southern Hemisphere – 40%).

As expected, the western Pacific experiences more intense storms, sometimes brewing up to 11 TCs per year with MSW reaching 120 kts. The WPAC also has more long-lived intense storms due to a combination of genesis regions far out to sea and more “room to grow” before encountering landfall or one or more unfavorable environmental conditions.

The Atlantic and EPAC average approximately two 120 kt or higher storms per year with the range from 0-5. Approximately 70% of the Atlantic and 50% of the EPAC intense storms reached concentric or double eyewall status. However, there is considerable variability in these percentages from year to year within each basin. For example, all five 2005 Atlantic basin systems obtaining 120 kts (Emily, Dennis, Katrina, Rita, and Wilma) exhibited double eyewalls during their lifetime as viewed by passive microwave imagery. Other years reveal much lower percentages, thus the overall value can be swayed toward one end or another with an active season using this relatively short timeframe. Therefore, these results should be tempered with the simple fact the database is limited to less than a decade.

Atlantic basin hurricanes typically have a limited lifespan while at 120 kts or higher unless early genesis Cape Verde type systems, but the 2005 tracks “favored” strong systems. Katrina tracked at modest speeds while making a big turn in the middle of the Gulf of Mexico, Rita managed to squeak through the Florida Straits (between Florida and Cuba) and begin its life on a stronger leg and then transited diagonally across the Gulf, and Wilma found a benign location in the Caribbean Sea to slowly move through while going through one and a half eyewall cycles. In each case there was a lack of upper-level troughs, cut-off lows, other shear mechanisms, and cold ocean eddies that could weaken the storms during the eyewall replacement cycle.

EPAC storms are frequently weak since many encounter landfall quickly (Mexico) or decay over cool waters into a low-cloud swirl. However, Cat 3, 4, and 5 EPAC storms do exist and they can form a “classic” double eyewall configuration. An EPAC Category 5 storm has even exhibited three (3) concentric eyewalls simultaneously (McNoldy, 2004).

The WPAC basin contains both the highest number of “intense” storms and the largest percentage attaining concentric eyewall status. Roughly 80% of the TCs over nine years had double eyes as viewed via passive microwave imagery. Note the number of “intense” storms can fluctuate greatly from year to year as evidenced by the eleven highlighted in Fig. 3 during the El Nino season in 1997. Most of these systems attained Cat 4 and 5 (Super Typhoon) status and existed for multiple days at a high MSW intensity.

The southern hemisphere (SHEM) averaged per 4 “intense” storms/year, but only ~ 40% attained double eyewalls. SHEM systems typically do not maintain 120 kts or higher for long as shear frequently cuts short the formation of concentric eyewalls. Thus, SHEM storms have strong rainbands beginning to wrap and create secondary eyewalls but are stopped in the process more often than in the WPAC.

4. MULTIPLE EYEWALL EVOLUTION - WILMA

Figure 4 below highlights a scenario encountered numerous times during eyewall replacement cycles using Hurricane Wilma as a case study. SSM/I 85 GHz H-pol Tb images covering a 512x512 km storm-centered domain are displayed using a false color table designed to “appear” like radar views. Data from SSM/I sensors on F-13, F-14 and F-15 are included and Tbs are color coded as in Figs. 1 and 2.

The time sequence starts on Oct 17^{th} at 1429 GMT and ends on Oct 24^{th} at 1419 GMT. During the one week, sixteen SSM/I views enable analysts to monitor the following storm structure

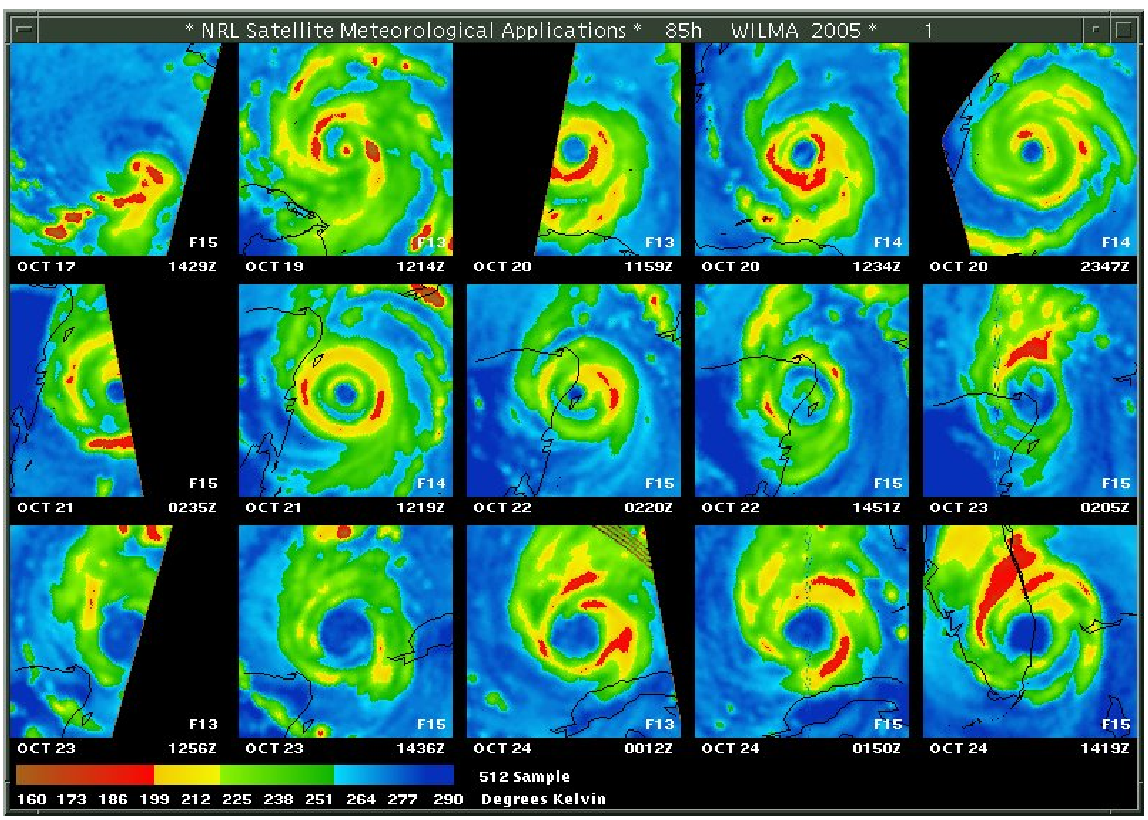

Figure 4: Time sequence of 85 GHz brightness temperatures (Tbs) using three SSM/I sensors to map rainband and eyewall evolution during Hurricane Wilma's lifespan. Color display same as Figures 1 and 2 and domain covers 512x512 km and is storm-centered.

evolution: the formation of a single eye by Oct 20 at 1159 GMT, completion of double eyewall by Oct 21 at 1219 GMT, and apparent decay of the inner eye while offshore Cancun on Oct 23rd. Thereafter, a large single eyewall is present as the storm heads toward the Florida peninsula. A closer view and other color tables indicate the storm maintained an inner eye slightly longer, but that does not impact the general story. Note also the warming of Tbs as the storm leaves Mexico in a weakened state after land interaction. Subsequent time over water leads to some reintensification and concomitant colder eyewall brightness temperatures.

The eyewall replacement cycle was thus interrupted by land interaction and the outer eyewall ceased shrinking and remained a constant diameter for an extended period. Cooling Tbs and added banding illustrate Wilma's positive atmospheric environment that permitted the storm to bring damaging winds over much of south Florida. This illustrates the simple fact that eyewall changes can have a dramatic impact on the areal coverage of MSW. When the outer eyewall becomes the primary eyewall and the maximum sustained winds shift from the inner to the outer eyewall, warnings must adapt to the new wind field configuration. This evolution can take place over 24 hours as noted in Figure 4 with Wilma.

4. SUMMARY AND FUTURE POTENTIAL

Double or concentric eyewalls exist in approximately eight tropical cyclones covering the Atlantic, Pacific and southern Indian Ocean basins each year. This number is far higher than previously thought since upper-level cloud obscuration often precludes visible and infrared imagery from capturing double eyewall structure. Thus the passive microwave data forming the basis for this study is "key" to monitoring eyewall replacement cycles and is sorely needed to enhance our knowledge inner storm configurations.

Eyewall replacement cycles have corresponding short-term storm intensity changes with MSW peaks occurring during the small single eyewall stages and "relative weakening" associated when a secondary eyewall forms. Real-time knowledge of eyewall replacement cycle status is crucial for accurate global intensity warnings. It is entirely possible that additional double eyewalls existed but were not sampled by the polar orbiters used for this database. Sun synchronous satellites with limited sensor swaths inherently suffer from temporal refresh issues. However, this has been partially mitigated by the TC observing constellation that NRL has effectively "cobbled" together via collaboration with FNMOC, AFWA, NOAA and NASA.

The constellation includes data from three SSMIs, TMI, AMSR-E, WindSat, SSMIS, and three AMSU-Bs and one MHS. The remote sensing satellite community is effectively in a "*golden age*" of passive microwave sensors and will not likely encounter this situation in the next 20 years due to multiple factors; 1) the combination of the two NOAA and DMSP satellite programs into one NPOESS 3-orbit configuration, 2) a decline in the number of research satellites with microwave imager channels as budgets decline, and 3) a trend to combine imager and sounder channels into one sensor.

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