P3.20 NRL TROPICAL CYCLONE R&D WEB RESOURCE AUGMENTATIONS

Jeffrey D. Hawkins[1], Tom F. Lee[1], F. J. Turk[1], Kim L. Richardson[1], Steven M. Miller[1], Charles R. Sampson[1], John E. Kent[2], and Rob Wade[2]

[1]Naval Research Laboratory, Marine Meteorology Division, Monterey, CA
[2]Science Applications International Corp., Monterey, CA

1. INTRODUCTION

The Naval Research Laboratory's Marine Meteorology Division in Monterey, CA (NRL-MRY) has successfully added two new satellite platforms to the NRL tropical cyclone web page (www.nrlmry.navy.mil/tc_pages/tc_home.html). The two new passive microwave sensors augment the previous total of eight (8) and assist in mitigating temporal coverage issues inherent in polar orbiter data sets. The Coriolis WindSat polarimetric radiometer contains unique measurement characteristics and the Special Sensor Microwave Imager Sounder (SSMIS) carries on the legacy of the Special Sensor Microwave/Imager (SSM/I) with several modifications.

The NRL tropical cyclone web page was the first effort to distribute near real-time passive microwave imagery worldwide, enabling users to view storm structure within active TCs globally (Hawkins et. al., 2001). Although originally intended to directly support the Joint Typhoon Warning Center (JTWC) and the National Hurricane Center (NHC), the Internet web page methodology swiftly provided all Internet users with new TC monitoring tools. NRL exploited the 37 and 85 GHz channels on the Special Sensor Microwave/Imager (SSM/I) flown aboard the Defense Meteorological Satellite Program (DMSP) beginning in 1997. The 1400-km swath and three (3) operational sensors typically observed each TC via 2-4 views per day, increasing as storms moved poleward.

The Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) was added in 1998 and enabled higher spatial resolution views (5-km versus 12–km at 89 GHz) by virtue of its low 350-400 km orbit (Lee et al., 1999). Thus, small-scale features such as inner storm structure (eyewall formation and concentric eyewalls) could be mapped with enhanced accuracy and fidelity. TRMM's 35 degree non sun synchronous tropical inclination also boosted the TC viewing frequency, especially for storms in the 28-37 degree latitude belt.

Corresponding author address: Jeffrey D. Hawkins, Naval Research Laboratory, 7 Grace Hopper Ave, Monterey, CA, 93943; e-mail: hawkins@nrlmry.navy.mil

The Advanced Microwave Sounding Unit (AMSU-B) moisture sounder was added in 2001 via 89 GHz channel products. Although a sounder with relatively coarse spatial resolution (16-km at nadir), the 89 GHz channel imagery products permitted users frequent TC views by virtue of the 2343-km swath and three (3) operational sensors. Thus, general TC information on structure patterns was available at times different from those of SSM/I and TMI, improving the temporal continuity.

The Advanced Microwave Scanning Radiometer (AMSR-E) onboard NASA's Earth Observation System (EOS) Aqua spacecraft was later added to take advantage of the 1600-km swath and superb TMI-like horizontal spatial resolution. AMSR-E serves TC mapping well with ~5-km footprint at 89 GHz due to the two-meter antenna. This functionality is sorely needed to identify many finer scale features, including certain double eyewall configurations.

The NRL TC web page's success in providing the global TC community (operations and research) with novel microwave products led directly to its transition to 24/7 operations at the Fleet Numerical Meteorology and Oceanography Center (FNMOC). In 2001, the FNMOC supported TC web page then provided a stable platform and the reliability required by many warning centers in addition to JTWC and NHC. Day to day management of the active tropical disturbances depicted on the web page is performed by forecasters at the JTWC in Pearl Harbor, the NHC in Miami, and the Central Pacific Hurricane Center (CPHC) in Hawaii. Graphical representations of their forecasts are included on the web page when available via the Automated Tropical Cyclone Forecasting (ATCF) system (Sampson and Schraeder, 2000).

2. UNIQUE NEW DATA SETS - WindSat

The WindSat polarimetric radiometer represents a novel application of fully polarimetric channels at 10.7, 18.7 and 37.0 GHz and dual polarization at 6.8 and 23.8 GHz, designed to demonstrate ocean surface wind retrievals via a passive sensor (Gaiser, et al., 2004). WindSat was launched aboard the CORIOLIS spacecraft in January 2003. Although it does not contain an 85/89 GHz channel, the huge two-meter diameter dish (similar to AMSR-E in size) permits excellent 37 GHz spatial resolution (8x13km), across its 1025-km swath. The 37 GHz brightness temperatures (Tbs) map the TC structure by highlighting variations in the moisture fields (cloud liquid water and total precipitable water) within and around the TC.

Tropical cyclone structure includes features across the entire mesoscale range. For example, TC eyewalls may vary in diameter from miniscule pinhole eyes (6-12 km) such as found in Hurricane Charley (Lee, et. al., 2005) to behemoths in excess of 150-km. Also, the ability to monitor concentric eyewalls requires adequate resolution to discern these oftentimes small scale inner eye features (5-20 km). WindSat's 37 GHz channels are able to detail most eyewall structures as illustrated in Figures 1 and 2.

The 37 GHz H polarization brightness temperature (Tb) false colored image in Fig. 1 depicts an F-15 SSMI product for Typhoon Songda on September 5, 2004 at 0049 GMT. The storm is outlined by a large mass of moisture and rainbands spiraling in from the southeast and wrapping completely around the system. In addition, there are some "relatively" low moisture values (warm Tbs) near the center region, which might correspond with a warmer-dryer eye.

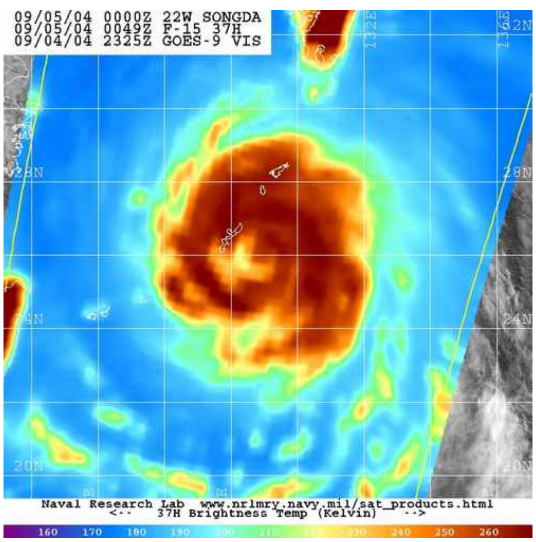

Figure 1: F-13 SSMI 37 GHz H polarization brightness temperature image (Tb) for Typhoon Songda on September 5, 2004 at 0049 GMT. The false color scale ranges from cold values in blue (~170-190K) to warm values in orange and brown (~240-260). Note the inability to view a "clear" eyelike feature. Two degree latitude and longitude lines are noted in white.

This "blurry" SSMI view of Songda's inner structure becomes focused via use of WindSat's larger antenna as shown in Figure 2. Concentric eyewalls are now obvious, with the inner eyewall set slightly to the right side of the larger outer eyewall's center. A clear (cold Tb) separation exists between the two eyewalls indicating a lack of convective elements in this potential moat region. Eyewall replacement cycles (ERC) are important short-term (12-18) to medium term (1-2 day) structural evolutions closely tied to TC intensity and occur more frequently than previously thought thanks to passive microwave viewing (Hawkins and Helveston, 2004). Small eyewalls typically represent a relative maximum in storm intensity, while the existence of double eyewalls usually marks a relative minimum in storm strength.

Monitoring storm ERCs is thus critical to understanding short-term intensity trends and can only be accomplished with sufficient temporal sampling by adequate resolution passive microwave sensors such as TMI, AMSR-E and WindSat at 37 GHz.

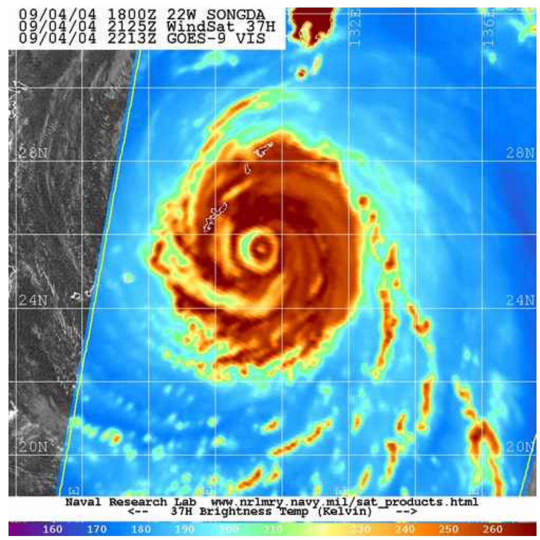

Figure 2: Coriolis WindSat 37 GHz H polarization Tb product shown for Typhoon Songda on September 4, 2004 at 2125 GMT. Note the double eyewall now visible and the much sharper rainband structural details. Two degree latitude and longitude lines are noted in white.

WindSat ocean surface wind vectors can assist the TC community in mapping the radial extent of gale force winds and storm wind field asymmetries. WindSat's unique cross polarizations measure the 3rd and 4th Stokes parameters, providing sensitivity to wind directions. Although the signal of wind direction is two orders of magnitude smaller than wind speed (Gaiser, et al., 2004) WindSat calibration and validation has shown skill when mapping gale force winds (15-20 ms^{-1}) in non-raining conditions (Bettenhausen, et al., 2005).

Figure 3 focuses attention on the highly asymmetric wind fields TC's can exhibit when experiencing strong shear. Westerly shear has removed all convection in the western semicircle and exposed the small low-level circulation as Irene weakened to a tropical depression. Winds < 10 kts occupy the southwest quadrant, 10-20 kts the northwest quadrant and much higher wind speeds in the eastern sector are accompanied by rain and likely gusty conditions. Although WindSat was not designed to retrieve winds in rain, Fig. 3 depicts how the sensor can provide significant wind field information under a variety of cloud conditions. The lack of gale force winds in the western semicircle is important information for real-time advisories for both ships and numerical weather forecasting (NWP) model initialization. Ship routing decisions key on past, present and future wind distributions to safely direct ship traffic via the most efficient path. In view of the fact that QuikSCAT is the only other satellite sensor capable of retrieving surface wind vectors (note SSM/I, AMSR-E, TMI and SSMIS measure scalar wind speeds only), WindSat can provide highly beneficial vector data in the data void tropical oceanic basins.

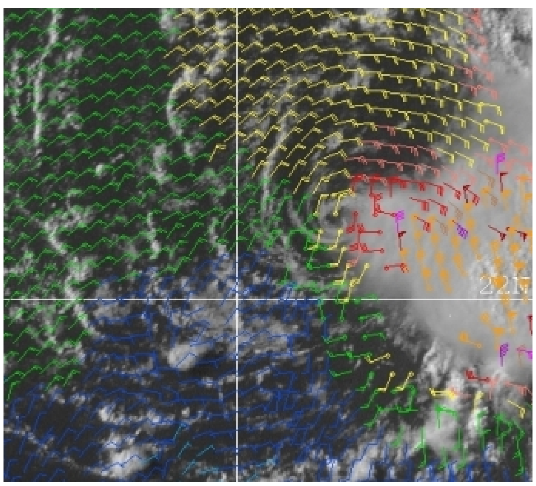

Figure 3. WindSat ocean surface wind vectors are mapped on top of coincident geostationary visible imagery for tropical depression Irene on August 8, 2005 at 2113 GMT. The wind vectors are color coded by wind speed (blue < 10 kts, green 1-15 kts, yellow 15-20 kts, peach 20-25 kts, red 30-35 kts, brown 30-35 kts, purple 40-50 kts, dark red 50-60 kts and orange > 60 kts). Latitude and longitude lines are every two-degrees highlighting the extremely small scale of this tropical cyclone.

Figure 4 represents the other extreme with a WindSat swath perfectly enveloping Category 5 Hurricane Rita on September 21, 2005 at 2339 GMT. As expected, no vectors are available within the intense inner core region dominated by heavy rain, but many wind vectors are observed that can assist in understanding the storm's wind structure. Several important features are: 1) a zone of light 15 kt winds between rainbands in the southwest quadrant, 2) a region of 30-60 kts winds between rainbands in the southeast quadrant (although directions are incorrect), and 3) the ability to map the radius of gale force winds in each quadrant, though difficult with the Cuban land mass in the southeastern sector.

WindSat TC wind vectors are being studied via several comparison methods: a) QuikSCAT surface wind vectors, b) hurricane aircraft measured passive microwave wind speeds and c) H*wind produced wind field maps that assimilate all available data sets.

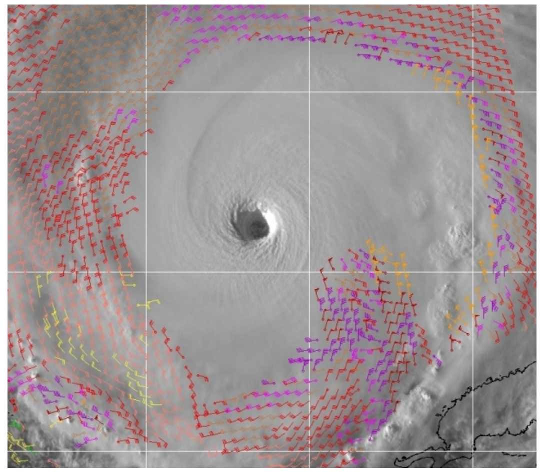

Figure 4: WindSat ocean surface wind vectors within Category 5 Hurricane Rita in the Gulf of Mexico on September 21 at 2339 GMT. Wind vector color scale the same as Fig. 3. Latitude and longitude lines are labeled every two degrees in white.

3. UNIQUE NEW DATA SETS - SSMIS

The Special Sensor Microwave Imager Sounder (SSMIS) was launched in October 2003 to upgrade the heritage SSM/I and the SSM/T1 and T2 sounders (Wessel, et al., 2004). The SSMIS on the F-16 DMSP spacecraft represents the first of five (5) to continue the SSM/I data record begun in 1987. With launches slated for F-17, 18, 19 and 20, SSMIS data is likely to be operational into the 2015 timeframe. The SSMIS essentially contains the same channel suite and spatial resolution as the SSM/I and thus enables users to quickly fold the data set into a wealth of mature applications.

The 12-km 91 GHz SSMIS footprint matches the similar fidelity for SSM/I's 85 GHz channels that have proven adept in mapping TC structural changes. Figure 5 highlights how SSMIS near real-time products assisted in understanding the temporal fluctuations in Hurricane Rita's eyewall replacement cycle. In the crucial time leading up to landfall, SSMIS data proved timely by upgrading our knowledge of the eyewall cycle phase.

Hurricane Rita rapidly intensified while transitioning south and southwest of Key West over the warm Loop Current waters. Rita reached Category 5 intensity and began an eyewall replacement cycle with associated weakening. TMI data on Sept. 22 at 1422Z revealed a double eyewall configuration in process and raised a central question on how the timing of the ERC would coincide with landfall in Texas and/or Louisiana. Would Rita's eyewall configuration be a single small eyewall and thus at a relative maximum intensity or would two eyewalls be in place and contribute to reduced strength during landfall?

SSMIS data in Figure 5 clearly depicts a double eyewall pattern on Sept. 23 at 0156Z. More importantly, the time evolution from previous passive microwave images suggested the consolidation from two eyewalls to one was being prolonged and would not likely transition from two to one prior to landfall. This represented good news from the perspective of landfall intensity, but also poor news since the radius of maximum winds would likely be large, even if the outer eyewall diameter contracted some from its widest configuration.

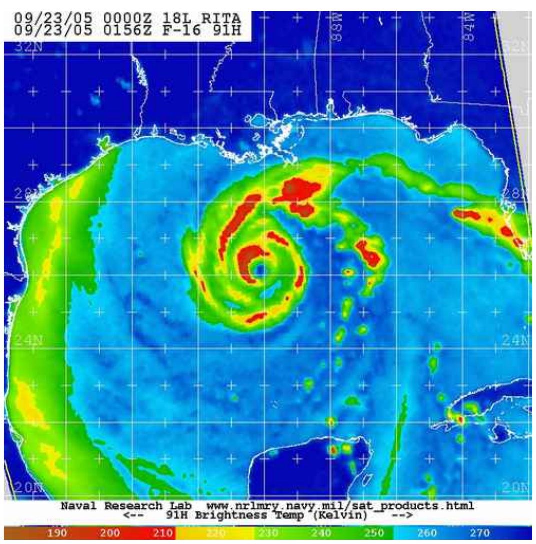

Figure 5. SSMIS 91 GHz horizontal polarization image on September 23, 2005 at 0156 GMT false colored according to the bottom color scale. Heavy rain and convection are represented by red and yellow (low Tbs) while ambient conditions are evident in warmer Tbs shown in blue. Latitude and longitude lines are noted in two-degree increments with hash marks at one degree.

Subsequent views 6 hours later by AMSR-E on Sept 23 at 0808Z (not shown here) reinforced the likelihood Rita would not complete an ERC prior to landfall. An F-13 SSMI overpass also confirmed two eyewalls on Sept 24 at 0036Z as the storm was just offshore and was confirmed by landfall radar. Thus the SSMIS assisted by filling in a temporal gap within the passive microwave imagery constellation now used operationally by the National Hurricane Center and numerous other TC operational and research members.

4. SUMMARY AND FUTURE POTENTIAL

The NRL-MRY tropical cyclone web page has added two new passive microwave imagers (WindSat and SSMIS) for use by the tropical cyclone community. The WindSat polarimetric radiometer provides superb 37 GHz products with resolutions capable of mapping TC structure in addition to the ocean surface wind vectors in non-raining regions. WindSat wind vectors can assist in determining storm wind fields in concert with QuikSCAT scatterometer vectors and surface wind speeds from SSM/I, TMI, AMSR-E and SSMIS. The wind vectors are currently undergoing verification in hurricane conditions to determine their full capabilities and limitations.

The SSMIS continues the SSM/I legacy and ensures the operational presence of passive microwave imagers into the 2015 timeframe. The ability to count on SSMIS comes during a critical period when the next generation system [National Polar-orbiting Operational Environmental Satellite System (NPOESS)] launch dates are likely to be delayed from the planned 2010 goal. When available, the Conical Microwave Imager Sounder (CMIS) will continue the WindSat proof of concept by retrieving surface winds via polarimetric radiometry. The timing of the Global Precipitation Mission (GPM) will be closely watched since meshing GPM, CMIS and SSMIS sensor data availability will directly impact tropical cyclone structure monitoring globally.

Acknowledgments. Special thanks are given to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for access to WindSat and SSMIS data sets. We gratefully acknowledge the support of our research sponsors, the Office of Naval Research, Program Element (PE-0602435N) and the Oceanographer of the Navy through the program office at the Space and Naval Warfare Systems Command, SPAWAR PEO C4I&Space/PMW-180 (PE-0603207N). The U.S. operational tropical cyclone forecast centers (JTWC, NHC and CPHC) are also acknowledged for their contributions.

4. REFERENCES

Bettenhausen, M. H., C. K. Smith, R .M. Bevilacqua, N. Wang, P. W. Gaiser, and S. Cox, 2006: A nonlinear optimization algorithm for WindSat wind vector retrievals, Submitted to

IEEE Transactions on Geoscience and Remote Sensing.

Gaiser, P. G., K. M. St. Germain, E. M. Twarog, G. A. Poe, W. Purdy, D. Richardson, W. Grossman, W. L. Jones, D. Spencer, G. Golba, J. Cleveland, L. Choy, R. M. Bevilacqua, and P. S. Chang, 2004: The WindSat spaceborne polarimetric radiometer: Sensor description and early orbit performance, IEEE *Trans. Geosci. Remote Sensing*, 42, 11, 2347-2361.

Hawkins, J. D., and M. Helveston, 2004, Tropical cyclone multi-eyewall characteristics, AMS 26th Hurricane and Tropical Meteorology Conference, 276-277.

Hawkins, J. D., T. F. Lee, K. Richardson, C. R. Sampson, F. J. Turk, and J. E. Kent, 2001: Satellite multi-sensor tropical cyclone structure monitoring, *Bull. Amer. Meteor. Soc*., **82**, 4, 567-578.

Lee, T. F., J. D. Hawkins, F. J. Turk, K. Richardson, C. Sampson, and J. Kent, 1999: Tropical cyclone images now can be viewed “Live” on the web, EOS*, Trans. Amer. Geophys. Union*, **80**, 50, 612-614.

Lee, T. F., J. D. Hawkins, J. Turk, K. Richardson, C. Sampson, 2005, Probing the eye of the storm: Hurricane hunting satellites, Earth Observation Magazine, Online.

Sampson, R. C., and A. J. Schraeder, 2000: The Automated Tropical Cyclone Forecasting System, version 3.2, *Bull. Amer. Meteor. Soc.,* 81, 1231-1240.

Wessel, J., J. Cornelius, R. W. Farley, A. Fote, J. Haferman, B. Gardiner, Y. Hong, D. B. Kunkee, G. Poe, S .D. Swadley, D. J. Tesmer, B. H. Thomas, E. Uliana, and D. Boucher, 2004: First observations from the DMSP SSMIS, 13th AMS Conference on Satellite Meteorology and Oceanography.