Satellite-Derived Tropical Cyclone Intensities and Structure Change (TCS-08)

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LONG-TERM GOALS

Routinely map the life cycle of a tropical cyclone's (TC) intensity, inner-core structure and structure change with special attention to capabilities derived from satellite data, while incorporating the Tropical Cyclone Structure (TCS-08) field program data sets from August-September 2008.

OBJECTIVES

Develop accurate automated techniques to estimate TC intensity and intensity changes under all conditions (e.g., 24 hr/day, any global location, and strengths ranging from tropical depression to Category 5) and surface wind fields while incorporating TCS-08 data sets (Elsberry et. al, 2009).

APPROACH

The TCS-08 field program provided unique aircraft reconnaissance (recon) data that will be used to validate a suite of satellite-based TC intensity estimation methods. While Atlantic recon data has provided the only data to formulate these algorithms, western pacific (WPAC) data is sorely needed due to specific differences between TCs in both basins. Air Force WC-130J penetrations of the TC eye will be a key focus by incorporating dropsondes, Stepped Frequency Microwave Radiometer (SFMR) surface wind speeds, and flight level winds. The WC-130J derived minimum sea-level pressure (MSLP) and maximum sustained winds (Vmax) will form the basis for enhanced best-track values used to validate all satellite-derived intensity values.

Automated Dvorak Technique (ADT) intensities using IR data have been used operationally for multiple years, but suffer when a central dense overcast obscures vital storm structure (Hawkins and Velden, 2008). Microwave imagers, which can "see through" non-raining clouds, thus monitoring eyewall genesis, will be tested to see if they can add value to the ADT intensities until a clear eye permits the ADT to apply Dvorak "eye" rules. Our team will include the Cooperative Institute for Meteorological Satellite Studies (CIMSS, Chris Velden's group) who have created the original ADT

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14. ABSTRACT
Routinely map the life cycle of a tropical cyclone?s (TC) intensity, inner-core structure and structure change with special attention to capabilities derived from satellite data, while incorporating the Tropical Cyclone Structure (TCS-08) field program data sets from August-September 2008.

15. SUBJECT TERMS

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algorithms under NRL sponsorship and incorporated microwave eyewall structure information that has been advocated by NRL Monterey over the last decade via our TC web site: http://www.nrlmry.navy.mil/TC.html

WORK COMPLETED

1. Assisted the TCS-08 "best track" team in creating a high quality TC intensity and location data set for use in validating all satellite and model estimates,
2. Modified and tested the ADT microwave (ADT-MW) TC intensity technique with the incorporation of an automated microwave imagery center finding method; created ADT-MW results in near real-time; and validated ADT-MW beta results using TCS-08 derived best tracks.
3. Mapped dry air intrusions in several western pacific (WPAC) TCs during TCS-08, in particular those experiencing large shear,
4. Assisted in the creation of TC surface wind fields by providing enhanced satellite remote sensing surface wind speed data set for incorporation into H*Wind.

TECHNICAL RESULTS

Section 1: TCS-08 WC-130J Tropical Cyclone Intensity Validation Data Set

Atlantic basin recon penetrations represent the test/validation database for all satellite TC intensity methods. This situation has been the case since recon planes discontinued WPAC operations in 1987, except for a few eastern/central pacific cases. Unfortunately, the following fairly common WPAC TC characteristics are not found frequently in the Atlantic basin; a) monsoon gyres with huge wind fields from which multiple smaller TCs can form and then spin away, b) midget TCs with diameters of 100-150 km, c) tropical upper tropospheric trough (TUTT)-induced TCs, and d) supertyphoons, whose frequency of occurrence is typically much higher than in the Atlantic, with giant circulations and multiple concentric eyewall cycles. Also, the environmental pressure differs in the western pacific and the wind-pressure relationship can not readily be carried across all basins. Thus, the TCS-08 field program was viewed as an excellent means of collecting sorely needed calibration/validation (cal/val) in-situ intensity data sets by relying on WC-130J eye penetrations.

Unfortunately, nature did not cooperate and few storms were available during August as 2008 was an anomalous year with a distinct lack of westerly winds in the deep tropics. Typhoon Nuri was the lone TC of interest in August, with genesis occurring not far from Guam and then tracking at low latitudes towards the Philippines. Mechanical issues with the WC-130J limited Nuri cal/val flights as the storm reached typhoon status. The good news is that September conditions changed significantly and the WC-130J was able to repeatedly sample typhoons Sinlaku (11 fixes) and Jangmi (8 fixes), while the NRL P-3 also sampled Hagupit, with each storm well within the TCS-08 operations domain. Each flight pattern was designed to coincide with Advanced Microwave Sounding Unit (AMSU) overpasses by calculating upcoming AMSU passes and storm center coverage. Passes near nadir were highly prized, while edge of scan overpasses were downplayed since senor resolution degrades.

More than twenty WC-130J center fixes corresponded with AMSU overpasses (some fixes matched up with more than one AMSU) during TCS-08. WC-130J dropsonde-derived surface winds and pressures, SFMR ocean surface wind speeds and flight level winds (typically 10,000' for penetrations) were heavily used by a "best track" team independently assigned to determine TCS-08 storm intensity timelines. Thus, Nuri, Sinlaku, and Jangmi's best tracks were derived after the fact by a team of TC experts led by Professor Russ Elsberry at the Naval Postgraduate School, including members from the Navy, Air Force, academia, and the National Hurricane Center (I co-led the typhoon Nuri best track team due to my serving as mission scientist on all Nuri WC-130J flights).

Table 1 summarizes the results using 15 AMSU overpasses deemed good enough in terms of sensor swath position and coincident within +/- 3 hours of WC-130J derived center fixes. Blind Dvorak are values from an expert satellite analysis team who used manual Dvorak after the fact while not looking at any other data sets, "Oper Dvorak" is the consensus of Dvorak estimates from all western pacific operational agencies, "w/JMA Koba adj" incorporates the Japan Meteorological Agency's (JMA) wind pressure relationship, ADT are the ADR-IR values, and ADT w/MW are the ADT with microwave imager adjustments. Note the reduced absolute error (abs error) and root mean square error (RMSE) derived with the ADT w/MW versus the standard ADT method. In addition, the microwave adjusted ADT are better than the operational Dvorak, but not the "blind" Dvorak, illustrating how experts with 30+ years experience can outperform within this very limited sample. The sample size means these results are NOT statistically significant and further WPAC TC penetrations are sorely needed. The 2010 ITOP (Impact of Typhoons on the Pacific) field program will supplement the TCS-08 data set, especially since the oceanographic focus is on mature storms and not weak genesis systems.

Section 2: Utilize Microwave Imager Eyewall Details to Assist IR Intensities

A satellite-based automated technique has been created that taps a microwave imager's capability to "see through non-raining clouds" and map eyewall formation. A central dense overcast (CDO) blocks both human analysts and automated algorithms from seeing eyewall structure while this impediment does not exist for microwave imagers (Hawkins et. al, 2008). Thus, Dvorak methods have a known problem when dealing with CDO scene types, creating intensities that lag real values until the eye feature "pops out" and the Dvorak "eye scene" rules kick in. Thus, a fusion of the microwave signatures that monitor eyewall formation can potentially assist the ADT and bridge this difficult storm stage (typically 40-80 kts) and aid in producing more accurate satellite estimates.

This dilemma is illustrated in Figure 1 using Japanese MTSAT geostationary IR data and Advanced Microwave Scanning Radiometer (AMSR-E) on the NASA Aqua spacecraft to map typhoon Vamco's inner core. These August 18, 2009 images using the regular IR enhancement (left), Dvorak enhancement (middle), and the AMSR-E 89 GHz brightness temperatures (T_B) depict: a) CDO making the regular IR relatively useless, b) Dvorak IR hinting at a possible "warm spot" and eye development, but inconclusive especially for an automated routine to extract, and c) eyewall formation in progress in AMSR-E data with more details on the eastern quadrant rainband. A human analyst might be able to incorporate some of the microwave eyewall details in their intensity estimate by bumping up the manual Dvorak values, but an automated Dvorak IR-only method can not.

Our team has created an algorithm that extracts near-real-time eyewall structural features from microwave imagers. First, microwave imager data [Special Sensor Microwave/Imager (SSM/I), Special Sensor Microwave Imager Sounder (SSMIS), AMSR-E, TMI, and WindSat)] that adequately covers each TC is processed via a "center fixing" method (Wimmers and Velden, 2010). Figure 2 depicts how the technique starts with a first-guess location for the storm center and then uses a series of calculations: a) guided fine spiral, b) ring score, and c) combined score using thresholds to derive the eye center. Tests indicate the method works well for easy cases such as that shown here, as well as for more complex examples with incomplete eyewalls and asymmetrical eyewalls. In fact, the method has been tested on both IR and 37 GHz imagery and has done remarkably well (Wimmers and Velden, 2010).

The TC intensity technique uses T_B discriminators to analyze TC core structure and outputs "scores" related to TC intensity. The scheme estimates which microwave images have storm intensities > 65 kts and > 85 kts. Scores exceeding these thresholds in these intensity bins are passed to the ADT with current intensity (CI) values that override the ADT-IR based estimates.

Figure 3 highlights this classic issue using typhoon 11W Vamco by displaying coincident ADT intensity estimates using IR-only and IR with microwave augmentation. The initial intensification from 35-50 kts is captured by both methods and then bifurcates as the CDO precludes the IR-only method from viewing subsequent storm structural development and reaches a 55 kt plateau. Meanwhile, the microwave imager supplied index values enable the ADT-MW (microwave added to ADT) to intensify first to near 80 kts and then to 95 kts and eventually 125 kts. Note how the ADT-IR method quickly ramps up the intensity once a clear eye "pops out", but it never catches up to the ADT-MW and subsequently weakens more and thus lags for approximately two days. Additional 3-D eyewall details are available from the NRL P-3 Eldora radar and from the CloudSat cloud radar that infrequently samples TC inner core structure (Mitrescu et. al., 2008).

Section 3: Dry Air Intrusions

TC environments can include relatively dry air that can potentially inhibit a storm's convectively driven heat engine. Dry air can be created by 1) outflow from nearby TCs whose descending air warms and dries, 2) mid-latitude intrusions that dip down into the tropics due to a combination of synoptic and mesoscale conditions, and 3) occasional continental air from SW Asia under favorable atmospheric flow. Monitoring dry air can be accomplished on broad scales by using both microwave imagers and sounders to retrieve total precipitable water (TPW). There are enough microwave sensors to provide six hourly TPW updates to create a basin wide product (NRL) or use a temporal morphing technique to provide a seamless TPW animation (CIMSS).

Figure 4 illustrates one TPW example for typhoon 16W (TCS-037) as the storm moves northward towards Japan. TCS-037 encountered dry air and shear for several days as it moved into the mid-latitudes (as an early recurver) and dropsondes from the WC-130J, P-3 and the German Falcon aircraft all were able to verify the dry air, which likely helped inhibit further storm intensification.

Section 4: Surface Wind Fields

Creating reliable ocean surface wind fields for TCs is problematic, even in the Atlantic where there's an abundance of operational and research recon flights. TCS-08 WC-130J flights provided a rare case to apply dropsonde, SFMR and flight level winds to WPAC storm wind-field monitoring. This team effort was led by NPS with LCDR Patrick Havel using the study as his Master's thesis topic. One goal was to test the impact of the various aircraft and remote sensing data sets that were available in non-real-time.

Time compositing is needed for TC wind-field composition, thus a six (6) or more hour timeframe is used and all observations are adjusted for plotting in a storm-relative manner using the best-track storm data. The H*Wind routine developed by Mark Powell and his colleagues at NOAA's Hurricane Research Division was used since it has been extensively tested and used at HRD to support the National Hurricane Center's wind radii warnings (Powell et al, 2005). The method applies "weights" to each data "type" depending on their expected accuracy and then creates an automated wind field representative of a marine exposure at 10 meters. Data "weights" can be manually adjusted to test the impact of the various data inputs.

The H*Wind input data types include the QuikSCAT and ASCAT scatterometer wind vectors, WindSat wind vectors and the geostationary low-level cloud-tracked winds as noted above. In addition, NRL obtained a special set of microwave imager derived ocean-surface wind speeds from Remote Sensing Systems for inclusion into the H*Wind data set, as well as 3-km QuikSCAT scatterometer wind vectors from Dr. David Long (Brigham Young University). The wind speed algorithm used by RSS has been derived using more than 20 years of collocated in-situ data. To be included the microwave imager wind speeds, direction must be assigned by applying a consistent wind inflow angle based on the observations relative to the storm center. CIMSS also created additional rapid-scan geostationary winds for select timeframes when MTSAT-2R was instructed to operate in rapid-scan mode with sequential images ranging from 15 to as little as 4 minutes apart. The short time intervals permit enhanced wind vector retrieval when compared with standard 30 minute separation normally used (Berger and Velden, 2009).

Figure 5 highlights the sensitivity of H*Wind surface wind fields to satellite inputs as noted in Patrick Havel's recent MS thesis (Havel, 2009). Denial of any inner core winds (in this case QuikSCAT) radically modifies the output winds and significantly decreases the Vmax values as expected. Other methods exist to input a bogus storm vortex that assumes a TC wind field profile based on storm intensity and Rmax (radius of max winds), but that is not used in this specific case. Further research is ongoing to test the sensitivity of all available remotely sensed TCS-08 data sets.

IMPACT/APPLICATIONS

The TCS-08 field program has provided a valuable in-situ and remote sensing data set that will assist our satellite validation efforts on multiple fronts (TC intensity, surface wind fields, and storm shear). Our team has created an automated TC intensity algorithm capable of incorporating superior inner-core eyewall details, providing a means to mitigate inherent limitations in any IR-only based algorithm. In the process, the new microwave imager auto-centering module will speed a transition to operations. This has positive ramifications for global TC intensity monitoring efforts.

TRANSITIONS

We will transition the ADT-MW effort to a corresponding PMW-120 6.4 effort after finishing up the 6.2 testing in the next few months with potential operational transitions to NOAA's Satellite Analysis Branch and the Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, CA. ADT-MW values would then be available to the National Hurricane Center (Miami, FL) and the Joint

Typhoon Warning Center (Pearl Harbor, HI) as well as the global TC forecasting community in near-real-time.

Lessons learned from the TCS-08 field program will greatly aid any follow-on efforts such as those now planned for the ONR sponsored Impacts of Typhoons On the Pacific (ITOP) project slated for mid-August to mid-October, 2010.

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 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.

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Table 1: List of TCS-08 validated satellite intensity estimates using 15 AMSU overpasses compared to best track intensities incorporating WC-130J dropsondes, SFMR, and flight level winds with all other routine data sets showing the ADT-MW are superior to ADT values in this limited data set.

N=15	'Blind' Dvorak Consensus	Oper Dvorak Consensus	Oper Dvorak Consensus (w/JMA Koba adj)	ADT	ADT w/MW
Bias	5.0	4.1	3.6	0.0	-1.1
Abs Error	10.9	15.0	13.0	16.1	14.1
RMSE	14.0	18.0	15.2	19.4	17.6

Positive Bias indicates method estimates are too strong

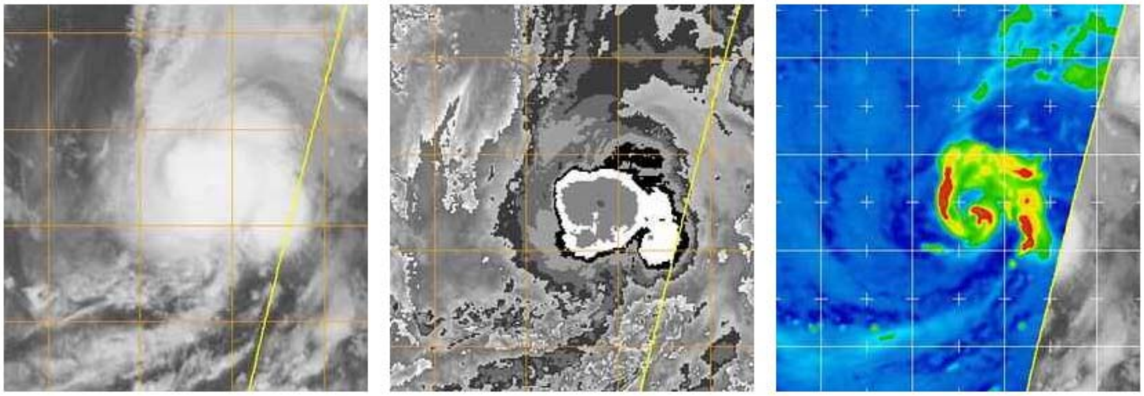

Figure 1: Intercomparison of satellite views of western pacific typhoon Vamco (11W) using geostationary IR (1537 Z: left frame – standard enhancement, middle frame – Dvorak enhancement) and microwave imager (right frame: AMSR-E 89 GHz at 1537Z) on August 18, 2009.

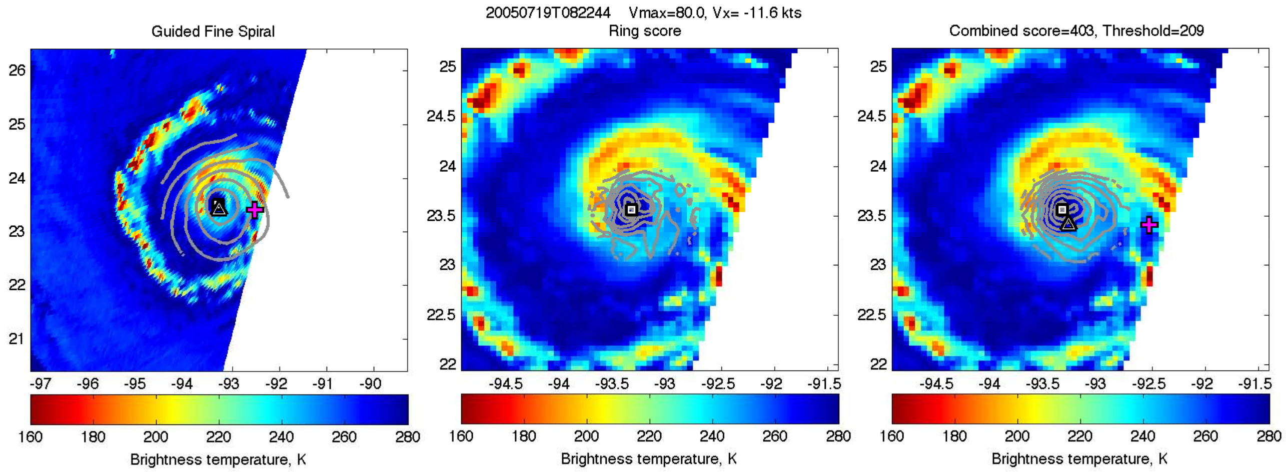

Figure 2: A microwave center finding algorithm working on 85 GHz T_B imagery illustrating the incorporation of a guided fine spiral, created of a ring score, and then the combination of both using a specific threshold. Cold T_B are represented by warm colors (red/yellows) while warm T_B are denoted by cool colors (blue). [Courtesy of Tony Wimmers, CIMSS].

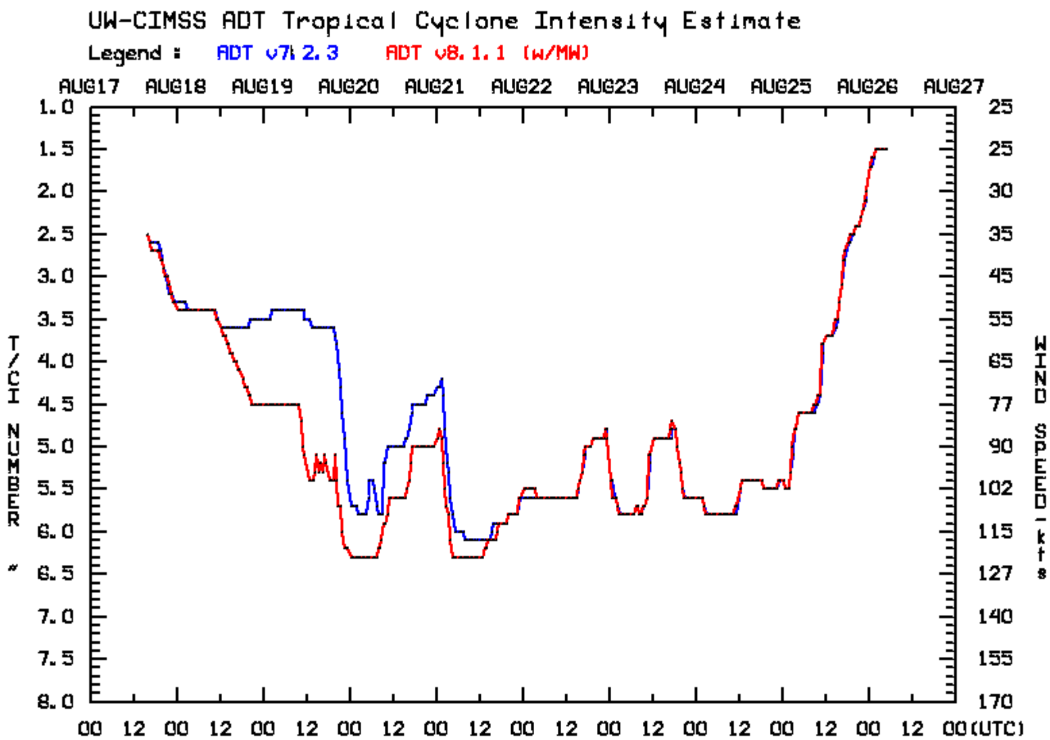

Figure 3: Time series of Automated Dvorak Technique (ADT) intensities for typhoon 11W in the western Pacific from May 27-31, 2008. Blue line: original ADT based on IR only, red: ADT with inclusion of microwave (old version), green: ADT with microwave (new version), [Courtesy CIMSS].

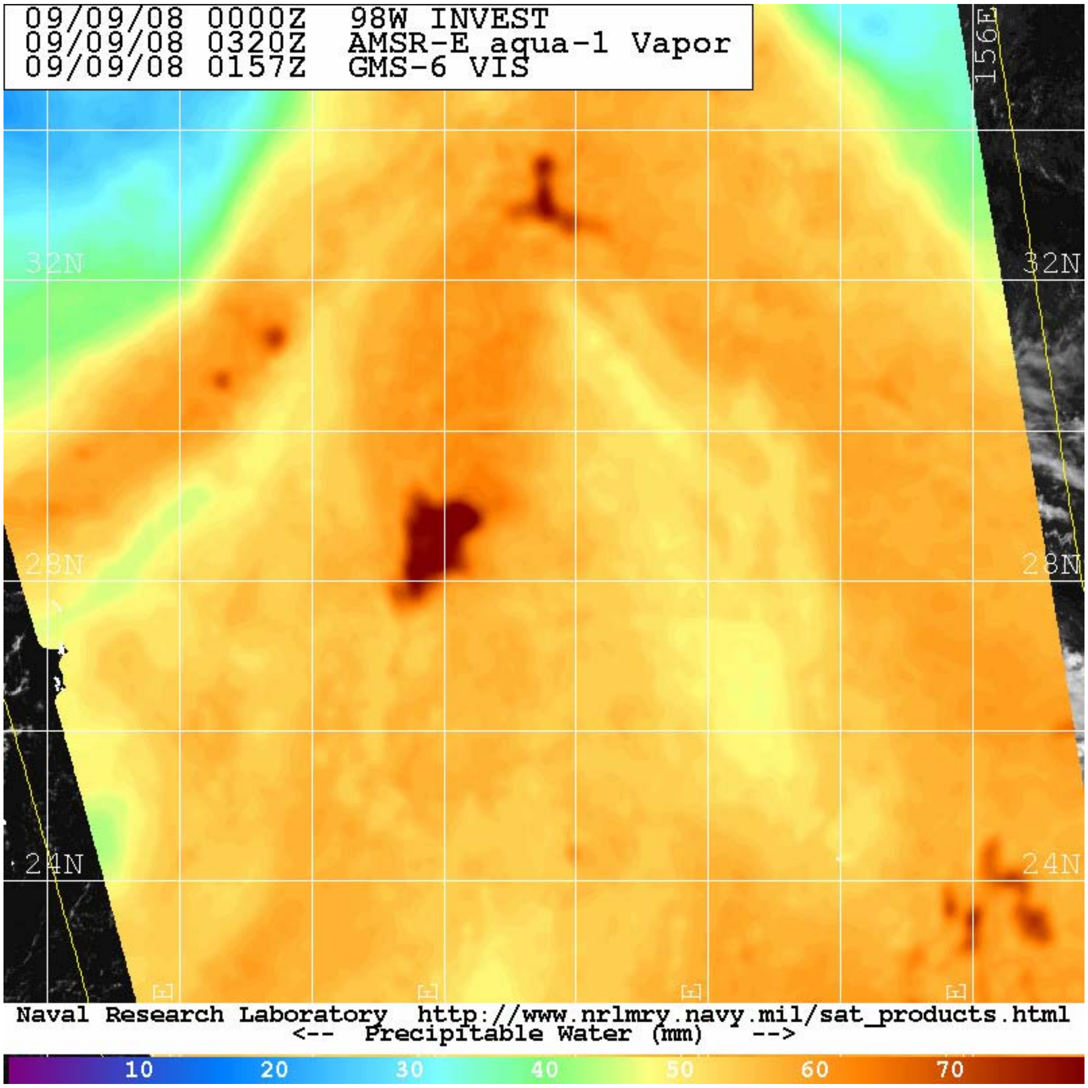

Figure 4: Total precipitable water (TPW) imager from DMSP SSMIS F-17 on Sept. 9, 2008 at 0320Z for typhoon 16W (TCS-08 storm 37W) depicting moist values (brown) associated with the typhoon, while very dry air (blues) exists just to the north and NW.

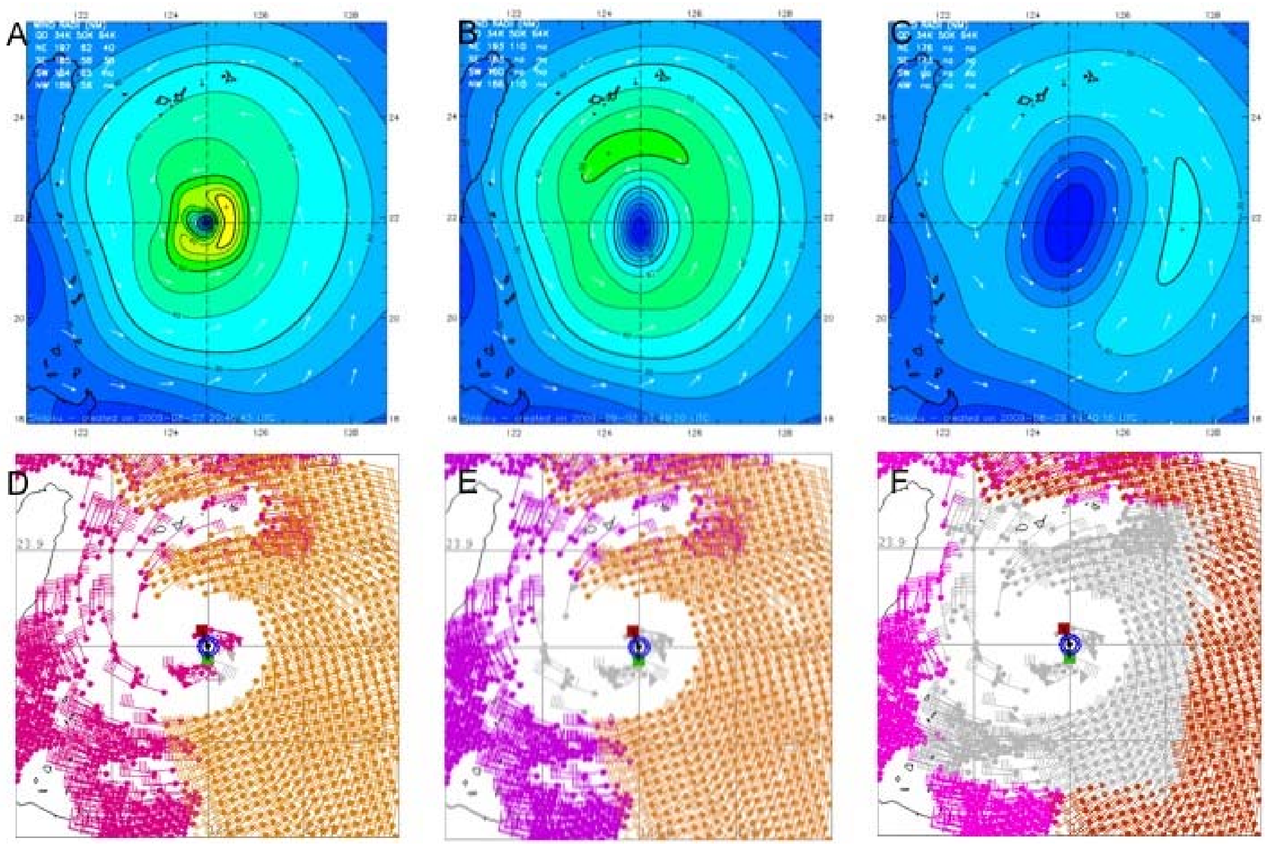

Figure 5: H*Wind ocean surface wind field analyses for typhoon Sinlaku on Sept. 11, 2008 (top panel) created by varying the input satellite surface wind data sets (left: all data, middle-screen inner core satellite, and right-screen 4 degree diameter satellite data centered on the storm. Note how analyzed surface winds dramatically weaken as any inner storm measurements are denied [Courtesy Patrick Havel, NPS Thesis].