SEVENTH INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES

1.4 Observation Capabilities and Opportunities

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*RMSC: WMO Regional Specialized Meteorological Center

#TCWC: WMO Tropical Cyclone Warning Centre
1.4.1 Introduction

This chapter describes the key accomplishments and developments that have occurred since the IWTC VI meeting with regard to observational capability of measuring tropical cyclone structure and intensity. The closest topic in IWTC VI was written by Mark Lander and was titled “Operational Techniques in Defining TC Structure”. This document will represent a current assessment of the topic that will include the measurement of tropical cyclone intensity.

The report is organized as follows: (i) a summary of the changes in satellite instruments since the 2006 IWTC; (ii) a review of current operational practices for measuring structure and intensity, with emphasis on changes and improvements since 2006; (iii) a description of new potential tools being developed; (iv) a listing of upcoming satellite launches and their instruments; and (v) recommendations.

1.4.2 Changes in satellite instruments since the 2006 IWTC

1.4.2.1 Geostationary Satellites

By agreement amongst the satellite operators meeting in the Coordination Group for Meteorological Satellites, the responsibility for regional data coverage by geostationary meteorological satellites is shared amongst the USA, EUMETSAT (for Europe), Japan and Russia. Satellites from other operators are also welcome. India maintains its INSAT satellite for national use and PRC is developing its FY-2 series of experimental geostationary satellites. (from http://www.wmo.int/pages/prog/sat/CGMS/Directoryofapplications/en/im1-5.htm).

![Geostationary satellite coverage diagram](image)

**Figure 1.** Geostationary satellite coverage diagram
Information from internet sources indicates that the Japan Meteorological Agency switched primary earth observing function from MTSAT-1R (Himarwari-6) to MTSAT-2 (Himawari-7) on 1 July 2010 with the MTSAT-2 being located along 145E longitude. MTSAT-2 provides geostationary satellite coverage centered over the Western Pacific Ocean.

GOES-13, launched May 24, 2006, represents the first of the third generation GOES N-P series and has an advanced attitude control system using star trackers, a spacecraft optical bench, and improved Imager and Sounder mountings to provide enhanced instrument pointing performance for improved image navigation and registration to better locate severe storms and other events important to the U. S. NOAA National Weather Service.

1.4.2.2 Microwave Imagery/Polar Orbiting Satellites

Multiple operational microwave imagers have been launched since 2006 and are available for tropical cyclone (TC) monitoring using near real-time digital data sets as outlined in Table 1. The Defense Meteorological Satellite Program (DMSP) has successfully launched two satellites (F-17 and F-18), both including the Special Sensor Microwave Imager Sounder (SSMIS). The SSMIS (Hawkins et al. 2008) is similar to one on F-16, with hardware modifications intended to mitigate temperature anomalies experienced with the F-16 sensor.

Two DMSP microwave imagers are no longer routinely available for TC monitoring: a) F-13 SSM/I, and b) F-14 SSM/I. Some F-13 SSM/I data is available through a limited number of US downlink sites and the Naval Research Laboratory, Monterey (NRL-MRY) is trying to access these data and provide them for Northwest Pacific Ocean TC’s.

Two research and development (R&D) satellites with conically scanning microwave sensors have been launched since 2006. China launched the MicroWave Radiation Imager (MWRI) sensor on FY-3A (May 2008) that has SSMI-like channels. Russia launched an Imaging/Sounding Microwave Radiometer (MTVZA) onboard the Meteor-M spacecraft (2009) with channels ranging from 6-91 GHz and a 2000 km swath. Neither of these instruments are providing real-time data at present and thus will not be discussed further.

The Advance Microwave Sounding Unit (AMSU), which was on many previous NOAA satellites, was launched on the NOAA N-19 (Feb 09) and EUMETSAT MetOp-A (Oct 06). These cross track scanners cover a large swath (2200 km+), though not all of the swath data can be used for TC monitoring due to ground spatial resolution (pixels) becoming too large near the edge of the scan. Additionally, TC intensity algorithms do not utilize the full swath data set.

F-17 and F-18’s SSMIS data are now being reviewed for inclusion in the TC intensity algorithms as these sensors provide important temporal sampling not possible with the NOAA/MetOp-A orbits.

The current constellation of microwave imager satellites occupies four different orbital planes; a) an early morning 0530 orbit with a DMSP satellite, b) one mid morning 0800 orbit with another DMSP satellite, c) a second mid morning 0930 orbit via EUMETSAT’s MetOp-A spacecraft, and d) an afternoon 1330 orbit via NOAA spacecraft. Each has a descending path beginning 12 hours later. This arrangement provides temporal sampling intended to effectively
monitor TC structure and intensity changes, especially rapid intensification or decay, which often occurs within a few hours.

<table>
<thead>
<tr>
<th>Satellite ID</th>
<th>DMSP F-17</th>
<th>DMSP F-18</th>
<th>MetOp-A</th>
<th>NOAA-19</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTAN</td>
<td>1731</td>
<td>2001</td>
<td>2131</td>
<td>1343</td>
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<tr>
<td>Imager</td>
<td>SSMIS</td>
<td>SSMIS</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sounder</td>
<td>SSMIS</td>
<td>SSMIS</td>
<td>AMSU</td>
<td>AMSU</td>
</tr>
</tbody>
</table>

Table 1: List of operational satellite microwave imagers and sounders launched since 2006 that provide global near real-time digital data sets to monitor TCs. LTAN refers to the local time of the ascending node. Descending passes (not shown) begin 12 h later.

1.4.3 Current practices regarding tropical cyclone structure and intensity estimation

1.4.3.1 Surface wind estimation

The primary methods for surface wind estimation involve aerial reconnaissance data and satellite-based scatterometer estimates (the Dvorak method will be discussed in the following section). Reconnaissance data in the Atlantic Basin are obtained from C130 aircraft flown by the U.S. Air Force Reserve, and by NOAA P-3 and Gulfstream IV aircraft. The U.S. National Hurricane Center obtains aerial reconnaissance data approximately 30% of the time in tropical cyclones in the Atlantic Basin, and 5% of the time in the east Pacific. The use of this data will be described first, followed by satellite estimation methods when reconnaissance winds are unavailable.

A major improvement in surface wind estimation from aircraft since 2006 arose from use of the stepped-frequency microwave radiometer (SFMR; Uhlhorn et al. 2007) on all reconnaissance aircraft in the Atlantic Basin. This instrument provides direct estimates of surface wind speed. The U.S. National Hurricane Center uses these estimates, along with dropwindsonde data and reduction of flight-level wind speeds to the surface, to determine maximum surface wind speed and the radii of 34, 50, and 64 knot winds. U. S. Air Force reconnaissance also provides values for eye diameter and radius of maximum winds. Even when aerial
reconnaissance is used, the maximum wind estimate can be in error if, for instance, the aircraft does not sample the region of maximum winds. Nevertheless, it provides the most accurate method currently available.

Limited aerial reconnaissance has also been conducted in the Western North Pacific Ocean around Taiwan since 2003 using an ASTRA aircraft collecting dropwindsonde data. These aerial reconnaissance flights are part of a collaborative effort to provide increased detail on tropical cyclone structure for improved numerical modeling and forecaster understanding of tropical cyclone characteristics. This work involves scientists in Taiwan, partnered with the U. S. National Oceanic and Atmospheric Administration (Hurricane Research Division, National Centers for Environmental Prediction), U. S. Naval Research Laboratory and Meteorological Research Institute/Japan Meteorological Agency. The dropwindsonde data obtained in this effort are transmitted in near real-time for assimilation into numerical models and operational analyses.

Scatterometer winds provide a critical alternative to the accurate but limited aerial reconnaissance data and are used by all international tropical cyclone forecast centers. Scatterometers cannot retrieve the maximum wind values for most TCs, but can represent a “minimum maximum” or the lowest max wind to be used with all other sources (in-situ and remote sensing) in determining the max winds.

Currently, two active microwave scatterometers bear the burden of providing these data: a) ESA’s Active Microwave Instrument (AMI) on the ERS-1 spacecraft (launched 1995), which now provides only a limited amount of data, and b) ESA’s Advanced Scatterometer (ASCAT) on the MetOp-A platform (launched 2006).

Of significant note was the QuikSCAT satellite failure in November 2009 after more than a decade of stellar service providing a 1800 km swath of increasingly reliable ocean surface wind vectors useful for TC applications.

The MetOp ASCAT sensor has a unique swath configuration, with twin 550 km swaths to each side of nadir, separated by a 672 km “hole” or area of no wind retrievals (Fig. 2 below). Routine 50 km oceanic surface wind vectors are being produced now, but 25 km winds are available in an experimental mode. The near real-time digital data set is provided via collaborative agreements with EUMETSAT and NOAA. ASCAT has potential spatial resolution issues, since a TC’s wind field typically includes high gradient zones that can be a mismatch for large scatterometer footprints.

Another developing TC reconnaissance asset is the U.S. Navy’s R&D WindSat polarimetric radiometer onboard the Coriolis spacecraft (2003 launch) which provides near real-time ocean surface wind vectors over its 1000 km swath. The 25 km ground spatial resolution enables WindSat to assist in defining TC gale force winds when rain contamination does not cause wind retrieval issues. Figure 3 illustrates WindSat’s capabilities during Typhoon Yutu in the western pacific on May 20, 2007 at 2108 GMT, with the wind speeds noted by the bottom color table (kt). Note the ability to isolate gale winds as the colors (barbs) change from brown to light purple. No wind retrievals are done in the heavy rain region within the inner core.

1.4.5
Figure 2. Schematic of the ASCAT twin 550-km swaths with the 672-km non-retrieval zone in the middle (left panel) and an example of ASCAT winds for tropical storm 19W (Sinlaku) September 8, 2008 at 1327 UTC. Wind vectors are color coded by the bottom color scale in knots (Hawkins and Velden, 2010).

All operational centers have expressed concern over the loss of QuikScat in November 2009. The ASCAT scatterometer has filled some of the gap, but it has only 60% of the coverage of QuikScat. In addition, the optimum use of ASCAT remains uncertain. The U.S. National Hurricane Center has noted a negative bias for surface wind speeds with ASCAT. RSMC New Delhi uses ASCAT to estimate the center location and intensity only for weak systems. Similarly, RSMC Tokyo uses ASCAT primarily for the determination of tropical storm intensity. TCWC Perth and RMSC Nadi use ASCAT for guidance on the radii of 34 and 50-knot wind speeds. JTWC also uses ASCAT winds, but for 34, 50, and 64-knot wind radii they also make use of the CIRA multi-platform wind distribution (CIRW) available on the Regional and Mesoscale Meteorology Branch (RAMMB) web site. This latter tool has been added since 2006.

1.4.3.2 Dvorak method

It is a tribute to Vern Dvorak that his subjective method for estimating tropical cyclone intensity from satellite images devised during a time of primitive satellite tools (Dvorak 1975) has continued to serve as the primary method of determining tropical cyclone intensity in real time. Every forecast center makes use of the Dvorak method. The Dvorak method has some known weaknesses and biases, especially for weaker storms. These have been described recently by Knaff et al. (2010). JMA uses a modification of the original Dvorak method for early-stage storms by K. Kishimoto (see: http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-
based in part on earlier work by Tsuchiya et al. (2001). The Dvorak technique has historically been done subjectively, but CIMSS has developed objective digital analysis of satellite images based on Dvorak’s rules that do not require a subjective interpretation. One benefit of this approach is that objective methods for including microwave information can potentially be added. These will be described in detail later in the discussion of the CIMSS Advanced Dvorak Technique (ADT; Olander and Velden 2007; Sears and Velden 2010). The U.S. National Hurricane Center uses the ADT when aircraft reconnaissance is unavailable.

![Figure 3. WindSat ocean surface wind vectors for Typhoon Yutu on May 20, 2007 at 2108 GMT overlaid on a GMS-6 visible satellite image. Wind speeds are colored according to the bottom scale (kts).](image)

1.4.3.3 Current operational use of intensity estimation tools (primarily microwave data)

Microwave data have a fundamental advantage: the ability to see underneath the central dense overcast in tropical cyclones in order to detect eyewall formation, secondary eyewall development and eyewall cycles, and annular structure before they are detectable in visible and
infrared images. For instance, JTWC has noted in the western Pacific that an eye is often seen on microwave when the maximum winds are less than 55 knots. The disadvantage of microwave information is that the relatively small swath width associated with this data can miss part or the entire tropical cyclone core. Furthermore, microwave data are available only intermittently due to polar-orbiting satellite orbit characteristics. The multiple current polar-orbiting satellite configuration, however, mitigates the orbit issue and allows fairly high frequency of coverage at any given location. This multiple satellite configuration will likely be degraded over time due to the demise of current satellites and the cancellation of the U. S. National Polar-orbiting Operational Environmental Satellite System (NPOESS) program in February 2010.

Operational centers all expressed a desire to more formally add microwave methods to their process of intensity estimation. A number of tools are being developed in research settings that are becoming available to operational centers. These will be discussed further in the following section. In this section we will summarize the current use of such tools.

RSMC New Delhi currently examines microwave estimates from CIRA and CIMSS, but because these have not been verified for the Indian Ocean using ground truth, they continue to use the Dvorak technique for estimating intensity. RSMC Nadi operationally uses vertical shear trends from CIMSS and the FSU phase space diagrams, as well as AMSU intensity estimates. TCWC Perth supplements Dvorak estimates with microwave-based tools: ADT, AMSU-based values from CIMSS and CIRA, and SATCON from CIMSS (see next section). JTWC considers SATCON and microwave imagery as a supplement to the Dvorak technique. CIRA and CIMSS AMSU cross-section data are also used at JTWC to provide evidence of middle and upper level warm cores and as structure change determination tools. JTWC also uses the CIRA Multi-platform satellite tropical wind analysis system (Knaff 2006) data in TC wind field analyses.

1.4.4 New products for intensity estimation

1.4.4.1 Google Earth

Tropical cyclone satellite products have typically been posted on web pages in standard image formats such as jpeg or gif that facilitate quick access and serving due to the relatively small file sizes. However, no geolocation information is embedded in the products other than the latitude/longitude lines and any geopolitical boundaries noted with overlays. Users are often forced to “guess” at TC center locations using crude eyeball or divider estimates. The US Navy Research Laboratory (NRL), Monterey has partially mitigated this problem by creating MTIF files to optimize use of tropical cyclone satellite products within the Automated Tropical Cyclone Forecasting System (ATCF). This MTIF capability provides the National Hurricane Center (NHC, Miami), Central Pacific Hurricane Center (CPHC, Honolulu) and the Joint Typhoon Warning Center (JTWC, Pearl Harbor, HI) with the capability to extract accurate location data points and utilize these data to evaluate numerical analyses and subjectively enhance or refine Dvorak intensity determinations.
In addition to the ATCF MTIF data, NRL has created and is distributing Google Earth compatible kml files since 2008. This Google Earth venue was developed to provide a framework for data fusion (Turk et al (2010)).

Figure 4 below displays a sample Google Earth rendition for Typhoon Jangmi, sampled during the Tropical Cyclone Structure 2008 field experiment with both MTSAT visible (left frame) and SSMIS 91 GHz Tb (right frame) imagery products. Near real-time flight tracks from the WC-130J (blue) and NRL P-3 (yellow) are overlain. Additionally drifting buoys deployed before these flights are evident and greatly aided planning for dropping more buoys to study air-sea interaction.

Google Earth was also used extensively to track multiple aircraft during the NASA GRIP experiment in 2010. These flight tracks were easily overlaid on various satellite images and other data sources. Numerical weather prediction model fields were overlaid in order to better intercompare storm structure for both initial conditions and forecast verification.

![Google Earth presentation with MTSAT visible (left) and F-16 SSMIS 91 GHz brightness temperature (right) images of Typhoon Jangmi on Sept. 24, 2008 overlain with WC-130J (blue) and NRL P-3 (yellow) real-time flight track.](image)

**Figure 4:** Google Earth presentation with MTSAT visible (left) and F-16 SSMIS 91 GHz brightness temperature (right) images of Typhoon Jangmi on Sept. 24, 2008 overlain with WC-130J (blue) and NRL P-3 (yellow) real-time flight track.

1.4.4.2 Tropical cyclone products for structure and intensity estimation

New products that have been developed since 2006 will be reviewed in this section. References at the end of this chapter will provide more complete information.

Two processes developed by the Japan Meteorological Agency (JMA), Meteorological Institute are being refined for operational implementation within the next few years by the RSMC Tokyo. The first JMA development is the estimation of tropical cyclone intensity by multi-channel microwave imager data based upon research by Hoshino and Nakazawa (2007). The second JMA intensity determination tool slated for operational implementation is based upon research done by Bessho et al. (2010), whereby TC central pressure estimations will be made from AMSU data.

The Advanced Dvorak Technique has been described by Olander and Velden (2007) and Sears et al. (2010). The most recent version of the ADT (version 8.1.2) addresses one of the
traditional areas of difficulty in assessing TC intensity with IR-based Dvorak techniques, the Central Dense Overcast (CDO) scene type. Changes in TC structure can occur beneath the cold and blanketing cirrus of the CDO, leading to changes in intensity. This cirrus overcast masks changes in the TC structure and intensity, primarily in the development stages of the TC eyewall. The resulting impact on the ADT is that the estimated intensity will plateau during the CDO phase (when IR temperatures change little) until an eye becomes visible in the IR imagery, at which time the ADT logic uses the eye scene to intensify the TC.

In order to address the limitation in the IR-based identification of an eye, microwave imagery is used. The new approach makes use of the CIMSS Automated Rotational Center Hurricane Eye Retrieval (ARCHER; Wimmers and Velden 2010) method for estimating tropical cyclone structure and position information from available passive microwave channels in the 85-92 GHz frequency range. ARCHER computes two scores which are combined into a final score for estimating current intensity. The first score is based on the completeness of the eyewall. ARCHER evaluates each “ring” of cold Tb’s surrounding the TC. The innermost ring which meets the criteria of having a $T_B$ differential ($T_B_{\text{eye}} - T_B_{\text{eyewall}} > 20K$) and a completeness of > 85% is designated the eyewall. In addition, the fraction of pixels in the eyewall < 232K is estimated. The higher of these two values ($T_B$ differential and number of pixels < 232K) is chosen as the completeness score. In addition to computing the score for the eyewall, ARCHER also produces an estimate of the eye size. Once the innermost ring is established, the diameter of the ring is computed. Because the 85-92 GHz ring best represents a level in the middle of the troposphere, 10 km is subtracted from the diameter to get an estimate of the surface diameter (an eyewall slope of 45 degrees is assumed).

The second component of the ARCHER score is similar to the Dvorak EIR method. Each pixel in the eyewall is compared to the warmest Tb within the eye. For each 1 K difference between the eyewall Tb and eye Tb, 1 point is added to the initial ARCHER score. The final ARCHER score is a sum of the eyewall completeness score and the eyewall intensity score.

This microwave information from ARCHER is passed to the ADT algorithm, and can be employed prior to the emergence of an eye scene in the ADT. The details of this process will not be described here. An independent validation of ADT 8.1.2 during the 2008 season showed a significant improvement in skill compared to the previous version (see table 2 below). Figure 5 below shows an example of the results. Intensity estimates are improved in the period just prior to eye formation.
Table 2: Validation statistics for the ADT-MW intensity technique using an independent 2008 Atlantic season aircraft recon data set with 299 matchups.

<table>
<thead>
<tr>
<th></th>
<th>MSLP (units: hPa)</th>
<th>Bias</th>
<th>RMSE</th>
<th>Abs. Err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADT – Version 7.2</td>
<td>4.09</td>
<td>11.61</td>
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<td>ADT – Version 8.1</td>
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<table>
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<td>-2.98</td>
<td>7.78</td>
<td>5.84</td>
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</table>

**299 matches – Independent Test Sample**

Table 2: Validation statistics for the ADT-MW intensity technique using an independent 2008 Atlantic season aircraft recon data set with 299 matchups.

**Figure 5:** Example of the ADT performance with the addition of microwave information (black – JWTC best track, blue – ADT IR-based values, and red – ADT microwave intensity estimates.

The SATellite CONsensus (SATCON; Herndon et al. 2010) algorithm developed at CIMSS objectively combines TC intensity estimates analyzed from satellite infrared and microwave-based methods to produce a consensus estimate which is more skillful than the individual members. Current members of SATCON include the CIMSS ADT along with the CIMSS and CIRA AMSU algorithms (e.g., Herndon and Velden 2006). SATCON provides the TC forecaster with the ability to quickly reconcile differences in objective intensity methods thus decreasing the amount of time spent on the analysis of current intensity. Real-time SATCON
estimates were made available to interested TC analysis and forecast centers during the 2008 and 2009 hurricane seasons.

Each member of SATCON has strengths and weaknesses. For example, the ADT method tends to perform best when there is a clear eye present in the IR imagery. However, the performance can be degraded when the TC encounters strong wind shear. Both of the AMSU-based methods suffer from varying degrees of sub-sampling and perform best when the TC eye is greater than 50 km in diameter. SATCON makes use of this information to optimally combine the estimates into a single estimate that maximizes the strengths while minimizing the weaknesses. The actual weights used in the SATCON algorithm are derived from the RMSE errors for the individual members in a given situation. Figure 6 on the following page shows an example of RMSE errors for different scenarios for the three members.

![Figure 6: RMSE errors for different scenarios: CDO, eye, and shear cases.](image)

Each SATCON member contains parametric information which can be used by the other members. For example, the ADT produces estimates of TC eye size when a clear eye is present. Because both AMSU methods suffer from sub-sampling issues when the TC eye is less than 50 km, the ADT eye size can be used to adjust the AMSU estimates. The CIMSS AMSU method uses AMSU-B information to determine TC position offset and this can be shared with CIRA AMSU. CIRA AMSU outputs estimates of cloud liquid water (CLW) and max Tb anomaly that can be used to adjust the ADT. TC eye size estimates from ARCHER can be used by both AMSU methods to account for sub-sampling (in the absence of IR eye information).
Tables 3 and 4 show SATCON performance compared to the individual members (Table 3) and the subjective Dvorak technique (Table 4). A homogenous sample of cases including all three members from 1999-2009 makes up a dataset of N=460. Validation consisted of reconnaissance measured MSLP and Best Track MSW coincident with reconnaissance. Table 3 shows that SATCON outperforms the individual members. Another measure of skill is that SATCON must perform better than a simple average of the three members as illustrated in Table 5. This is an important result because it indicates that the weighting logic is making an impact.

<table>
<thead>
<tr>
<th>(Knots)</th>
<th>CIMSS AMSU</th>
<th>CIMSS ADT</th>
<th>CIRA AMSU</th>
<th>SATCON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>-4.0</td>
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<td>-8.6</td>
<td>-1.0</td>
</tr>
<tr>
<td>Ave err</td>
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<tr>
<td>RMS err</td>
<td>10.2</td>
<td>13.5</td>
<td>14.6</td>
<td>8.3</td>
</tr>
</tbody>
</table>

**Table 3.** Accuracy of maximum sustained winds (MSW) estimates derived from satellite-based methods compared to 3-member SATCON and individual members verified against reconnaissance-coincident best track MSW. Negative method bias indicates underestimate.

<table>
<thead>
<tr>
<th>(hPa) (Knots)</th>
<th>SATCON MSLP</th>
<th>Dvorak MSLP</th>
<th>SATCON MSW</th>
<th>Dvorak MSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
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<td>-3.0</td>
</tr>
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<tr>
<td>RMS err</td>
<td>6.4</td>
<td>9.1</td>
<td>8.3</td>
<td>9.0</td>
</tr>
</tbody>
</table>

**Table 4.** Accuracy of minimum sea level pressure (MSLP) and maximum sustained wind (MSW) estimates (N = 460). Verification for MSLP is reconnaissance measured MSLP. MSW verification is best track MSW coincident with reconnaissance. Dvorak is average of TAFB and SAB.
In 2008, the TPARC/TCS-08 field project conducted in the western North Pacific permitted the opportunity to validate satellite-based TC intensity methods in a basin other than the Atlantic. Aircraft reconnaissance was flown into three TC’s during the study for the purposes of getting intensity estimates using flight level winds, SFMR, and dropsondes. One component of the experiment was to verify the subjective Dvorak technique in a double blind experiment where the Dvorak experts were blind to the aircraft data. This also allowed an unbiased comparison with the objective intensity methods including SATCON. While the number of cases is small, the TC intensities sampled during the experiment spanned the range of 35 -140 knots. Table 6 reveals the results of this experiment and shows a similar trend to the Atlantic verification where SATCON is comparable in skill and perhaps more skillful on average than the operational Dvorak method. Figure 7 below gives an example from a particular storm.

<table>
<thead>
<tr>
<th>(hPa)</th>
<th>SATCON MSLP</th>
<th>Simple MSLP</th>
<th>SATCON MSW</th>
<th>Simple MSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>0.3</td>
<td>-2.5</td>
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<tr>
<td>Ave err</td>
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<td>RMS err</td>
<td>6.4</td>
<td>7.7</td>
<td>8.3</td>
<td>9.3</td>
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</table>

Table 5. Comparison of SATCON with a simple average of the three members for both MSLP (hPa) and MSW (kts).

<table>
<thead>
<tr>
<th>(Knots)</th>
<th>“Blind” MSW</th>
<th>OPer MSW</th>
<th>SATCON MSW</th>
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<tbody>
<tr>
<td>Bias</td>
<td>3.6</td>
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<tr>
<td>Ave err</td>
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<tr>
<td>RMS err</td>
<td>11.9</td>
<td>14.9</td>
<td>10.1</td>
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</table>

Table 6. TCS-08 validation experiment for Typhoons 13W, 15W and 19W (N = 14). “Blind” is average of five independent Dvorak analysts. “Oper” is the operational center Dvorak average.
Eyewall cycles represent a major influence on tropical cyclone intensity (e.g., Sitkowski et al. 2010). Not only can rapid weakening and later re-intensification occur, but the weakening itself can produce a substantial broadening of the region of strong winds, thereby increasing the risk of damaging storm surge at landfall. Recently Kossin and Sitkowski (2009) have developed an objective technique for predicting secondary eyewall formation using geostationary satellite data plus information on the surroundings of the storm from the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria and Kaplan 1999). This empirical model provides forecasters with a probability of imminent secondary eyewall formation. This provides an additional tool for evaluating tropical cyclone structure and its role on future intensity.

### 1.4.5 Future satellite instrument plans

Future plans for microwave imagers are highlighted in Table 7, with the big question pertaining to near real-time access for the Chinese (FY-3B, FY3C) and Russian (METEOR-3) sensors. Both space programs are making strides forward with R&D microwave sensors that will then become operational on subsequent spacecraft and thus could join a constellation of TC monitoring sensors. The major US effort is geared to the launch of two Advanced Temperature...
and Moisture Sounders (ATMS) onboard the NPOESS Preparatory Program (NPP) satellite in late 2011 (now deemed an operational spacecraft) and the first satellite in the newly created Joint Polar Satellite System (JPSS) which represents the NOAA portion of the redirected NPOESS project. ATMS holds promise for continuing the TC intensity applications now applied using AMSU data.

The future also holds promise with two non sun-synchronous R&D satellites planned for the next several years: a) Megha-Tropiques (MT), and b) GPM-Core. The French/Indian Megha-Tropiques MADRAS conical microwave imager has channels from 18-89 GHz and a 1700 km swath, but the satellite is in a tropical inclination of 20 degrees. The combination of the orbital slot and the sensor swath will provide the TC community with a maximum of five views/day at 14 N and S and a minimum of three views/day anywhere from 29S to 29N. Thus, Megha Tropiques has a non sun synchronous orbit like TRMM and will provide ~ 10 km 89 GHz brightness temperature imagery over the entire swath. This represents a major TC monitoring asset. In addition, the Global Precipitation Mission (GPM) will carry two sensors when launched in 2013; 1) GPM Microwave Imager (GMI) and the Dual frequency Precipitation Radar (DPR). The GMI will have a 904 km swath (larger than TMI) with frequencies ranging from 10-89 GHz for standard imagery and include channels at 165 and 183 for enhanced rain retrievals while the DPR will operate at 13.6 and 35.5 GHz with swaths of 245 and 120 km respectively (in between the swath range for the TRMM PR).

<table>
<thead>
<tr>
<th>Satellite ID</th>
<th>NPP</th>
<th>DMSP F-19</th>
<th>DMSP F-20</th>
<th>JPSS1</th>
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<tr>
<td>LTAN</td>
<td>1330</td>
<td>0800</td>
<td>2000</td>
<td>1330</td>
</tr>
<tr>
<td>Imager</td>
<td>X</td>
<td>SSMIS</td>
<td>SSMIS</td>
<td>X</td>
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<tr>
<td>Sounder</td>
<td>ATMS</td>
<td>SSMIS</td>
<td>SSMIS</td>
<td>ATMS</td>
</tr>
</tbody>
</table>

**Table 7:** Current plans for US “operational” microwave imager and sounder launches over the next five years that are applicable to the TC reconnaissance mission globally. NPPS is now considered an operational satellite by the US.
<table>
<thead>
<tr>
<th>Satellite ID</th>
<th>FY-3C</th>
<th>METEOR-3</th>
<th>MetOp-B</th>
<th>GCOM-W1</th>
<th>GCOM-W2</th>
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<td>LTAN</td>
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<td>0930</td>
<td>1330</td>
<td>1330</td>
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<tr>
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<td>MTVZA</td>
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<td>MWTS/HS</td>
<td>MTVZA</td>
<td>AMSU</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 8: Current plans for non-US “operational” microwave imager and sounder launches over the next five years that are applicable to the TC reconnaissance mission globally. Note, several of these efforts are “joint” projects with US satellite missions.

<table>
<thead>
<tr>
<th>Satellite ID</th>
<th>Megha-Tropiques</th>
<th>FY-3B</th>
<th>METEOR-M2</th>
<th>GPM-Core</th>
<th>GPM-GMI</th>
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<td>Changes</td>
<td>0930?</td>
<td>Changes</td>
<td>Changes</td>
<td>Changes</td>
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<tr>
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<td>MWRI</td>
<td>MTVZA</td>
<td>GMI</td>
<td>GMI</td>
</tr>
<tr>
<td>Sounder</td>
<td>SAPHIR-WV only</td>
<td>MWTS/HS</td>
<td>MTVZA</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 9: Current plans for “R&D” microwave imager and sounder launches over the next five years that are applicable to the TC reconnaissance mission globally. GPM-GMI is currently not fully funded.
1.4.6 Recommendations

1. Aircraft reconnaissance

All international tropical cyclone forecast centers other than the U.S. NHC noted the hardships produced by lack of aircraft reconnaissance of tropical cyclones, and even NHC has it available only 30% of the time in the Atlantic. It remains the best means of estimating current tropical cyclone intensity, and it provides ground truth for evaluating all of the forecast methods being developed. Everyone understands the large cost of reconnaissance, but its value is equally large. Possibly unmanned aircraft could fill the gap in the future, but that is likely years away.

2. Satellite instrumentation

With the loss of the QuikScat scatterometer, a sensor that had evolved to be a very useful tool over its lifespan, the ASCAT now plays a critical role. Additional scatterometer information, however, should be strongly supported as additional intensity estimations are needed at all stages of tropical cyclone development. Continued degradation in the current constellation of microwave satellite coverage appears to be imminent. As such, it is recommended that planned microwave launches be held to their current schedule, and that new satellites are planned to make the upcoming loss of time resolution be as brief as possible.

3. Forecaster training and collaborations among operational centers

Most operational centers expressed the importance of good forecaster training. JTWC has instituted a formal Personal Qualification Standard to insure that every forecaster is trained in the latest techniques. Several of the smaller centers expressed a desire for partnerships and collaborations with larger centers. A strong recommendation is to enlarge and develop such programs.

4. Basin specific Dvorak validation

Several operational forecast centers stated need for “ground truth” of the Dvorak technique for specific geographical areas.

5. Objective use of microwave data

A majority of the operational centers noted the subjective use of microwave data to determine current intensity and intensity change. Further development of an objective technique for intensity and intensity change determination is recommended based on these inputs.
4.7 References


