LONG-TERM GOALS

To understand tropical cyclone (TC) structure (center location, inner core organization, size, and intensity) and the time evolution from genesis to a mature storm while focusing on environmental conditions that impact rainband and inner core changes that are directly related to a storm’s intensity changes and associated wind and rain fields.

OBJECTIVES

Develop accurate, automated, satellite remote sensing techniques to derive TC location, inner core characteristics, size, intensity and intensity changes under all conditions (e.g., 24 hr/day, any global location, and strengths ranging from tropical depression to Category 5). Create demonstration products that enable the TC community to more accurately assess a storm’s location, track and intensity via the exploitation of multiple satellites via sensor data fusion.

APPROACH

Satellite sensors represent the only viable observing platform that can provide the geographic coverage, and spatial, spectral, and temporal sampling required to monitor TC parameters in a near real-time mode globally. This project will focus on developing new satellite-based tools that assist the TC community in mapping storm structure (location, inner core characteristics, size, and intensity). Long term efforts have focused on visible/infrared (vis/IR) imagery that provide 30-minute refresh within the tropical oceanic basins. This effort will exploit the data fusion possible by combining microwave imagers and sounders with the more traditional vis/IR sensors and take advantage of the inherent capabilities to view storm characteristics in all-weather conditions.

Combining digital data from a suite of geostationary (GEO) and low earth orbiting (LEO) satellites for near real-time applications on 5-8 ongoing storms (typical for the Joint Typhoon Warning Center (JTWC, Pearl Harbor, HI) can create chaos in an operational setting when multiple products need to be queried from different computer systems and visualization platforms. Thus, one goal is to simplify the GEO-LEO data fusion, while extracting the best traits from each digital data set and thus enhance Navy/DOD’s ability to accurately monitor global TCs.
Previous efforts utilizing microwave imager data have outlined the ability to view storm structure generically, but have only recently delved into the more difficult quantitative analyses. Our project will enable the next step by recalibrating multiple sensors to a “standard” frequency that will permit advances in storm signals not feasible earlier. In addition, we plan to significantly add to the temporal sampling of TC intensity by incorporating new microwave sounders that will be in the operational constellations for years to come.

**WORK COMPLETED**

1. Completed initial version of microwave sounder-based ATMS TC intensity estimate algorithm ATMS TC intensity estimates and compared to multiple other satellite and in-situ data sets.
2. Completed ARCHER v3.0 which incorporates relative sensor-weighting based on the sources’ respective confidence measures and transitioned to a Joint Hurricane Testbed (JHT) funded project (collaboration with U. of Wisconsin-CIMSS),
3. Recalibrated SSM/I and TMI 85 GHz and SSMIS 92 GHz brightness temperatures to 89 GHz in order to mitigate large frequency dependent impacts encountered within tropical cyclone inner core convection (frozen hydrometeors) and thus enable consistent TC structure details using multi-sensor data sets, resulting in > 100,000 TC data samples (collaboration with Josh Cossuth, FSU PhD student),
4. Remapped SSM/I and SSMIS microwave imager data using Backus-Gilbert resampling that permits the user to take full advantage of the nyquist sampling and extract the full information content for TC structural details (collaboration with Josh Cossuth, FSU PhD student).
5. Created remapping tool to handle 37 GHz microwave imagery Tb to assist in creating higher resolution digital data sets to be added to the ice scattering channel data (collaboration with Josh Cossuth, FSU PhD student and Song Yang),

**TECHNICAL RESULTS**

**Section 1: NPOESS Preparatory Program (NPP) Advanced Technology Microwave Sounder (ATMS) TC Intensity Estimates (CIMSS Collaboration)**

NPP-ATMS passes over TCs in all basins over the last three years (2012-2014) were used to develop an automated intensity algorithm by extracting ATMS-derived upper-level warm core details. Storms in the sample vary in intensity from tropical depression (25 kts) to Category 5 (155 kts). The basic approach used is similar to the CIMSS AMSU and SSMIS algorithms that leverage the high correlation between storm intensity and the magnitude of the upper-level warm core temperature anomaly created by the TC heat engine. Brightness temperature (Tb) anomalies are calculated for ATMS channels 7-10, and ancillary data consisting of environmental pressure (via the Automated Tropical Cyclone Forecasting system, ATCF) and TC eye size (derived from the CIMSS Automated Rotational Center Hurricane Eye Retrieval [ARCHER] and the Automated Dvorak Technique, [ADT, IR-based method that follows the general rules created by Dvorak to associate storm intensity with cloud structure and organization] were then matched to the ATMS TC overpass times. All cases where the estimated TC eye size was smaller than the respective ATMS field of view (FOV) resolution were initially removed (N=45) to first eliminate sub-sampling issues (inability to adequately view the
storm’s warm core signature). Regressions for TC minimum sea level pressure (MSLP) anomaly were then developed using the remaining cases for each channel (see Figure 1 below). Cases where the TC eye size was smaller compared to the ATMS FOV resolution were then used to develop bias corrections for the MSLP estimates. The bias corrections are channel-dependent in order to account for the typical TC eyewall slope (weighting function peak at varying altitudes as the eyewall slopes upward).

![ATMS Channel 8 Tb Anomaly Compared to TC Pressure Anomaly](image)

**Figure 1:** ATMS channel 8 Tb anomalies regressed against the operational “Best Track” TC pressure anomaly for all cases where the estimated size of the TC eye is larger than the ATMS FOV horizontal resolution (i.e. fully resolved).

The TC maximum sustained wind (MSW) is then estimated using a linear regression of the ATMS-derived pressure anomaly matched to “Best Track” TC MSWs. Table 1 below shows the results for the dependent 2012-2014 sample. Additional cases will be added during 2014 and an independent validation of the algorithm will be done at the end of the season when all aircraft reconnaissance penetration (vortex message) data is quality controlled and made available.
Table 1. ATMS algorithm performance compared to subjective manual Dvorak operational intensity estimates based on dependent sample. The Dvorak numbers are derived from an average of coincident agency estimates.

<table>
<thead>
<tr>
<th></th>
<th>N =110</th>
<th>ATMS MSLP</th>
<th>ATMS MSW</th>
<th>Dvorak MSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>0.0</td>
<td>0.0</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Avg Abs Error</td>
<td>5.6</td>
<td>7.7</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>7.3</td>
<td>10.2</td>
<td>11.4</td>
<td></td>
</tr>
</tbody>
</table>

Section 2: Automated Tropical Cyclone Center Location Identification (CIMSS Collaboration)

Detecting the “surface or low-level circulation center”, LLCC, routinely is difficult at best using IR-based imagery due to upper-level cloud obscuration and is often complicated by human subjectivity. Microwave sensors can mitigate many of the IR sensor limitations, but analysts must be trained on proper interpretation of microwave imagers and sounders, otherwise inaccuracies can result. In addition, attempting to keep track of center fixes on 5-8 TCs simultaneously with 15 minute GEO temporal sampling and 5-10 microwave imager overpasses/storm currently overwhelms the available satellite analyst manpower. This will become even more as GOES-R and Himawari-8 come online and 5-10 minute full disk scans become operational. Accurate, automated center finding methods are highly desired to complement the human analysts.

During FY-14 we have incorporated the ARCHER multi-satellite algorithm into an automated, real-time, online demonstration for tracking TCs globally. The website is a testing ground for new methods of visualization that can present ARCHER as an objective guidance tool for TC center fixes (Figure 2). Satellite inputs include visible, longwave and shortwave infrared from five geostationary satellites (GOES-East/West, MTSAT-2, Meteosat-7 and Meteosat-10); ice scattering channel [85-92 GHz] imagery from the current constellation of passive microwave imagers (SSM/I (F-15), SSMI/S (F-16/17/18), TRMM TMI, GCOM AMSR-2 and GPM GMI); high resolution 37 GHz imagery from three R&D microwave imagers (TRMM TMI, GCOM AMSR-2 and GPM GMI); and scatterometer ocean surface vector winds (OSVW) data from MetOp-A/B’s Advanced Scatterometers (ASCAT). Usage of scatterometer data required the development and calibration of an innovative new algorithm based on the ARCHER gradient-analysis method, and the resulting framework produces center-fix and expected error data that is totally compatible with the output from other image-based sources (Figure 3).

Algorithm validation showed that the ARCHER center-fix was more accurate than human forecasters (from the SAB and TAFB database) in 35% to 40% of cases in the critical tropical depression (TD) and tropical storm (TS) stages of development. This level of accuracy is consistent with our goal of a center-fixing tool that does not substitute for a skilled forecaster, but rather serves to complement and accelerate the forecasting process. In particular, the automated and objective center-fixing system can organize large amounts of visual information with objective metrics for evaluation, and allow forecasters to deduce trends such as deviations from the forecast track and/or a need to “rebest track” recent data once new imagery indicates that older positions were incorrect. In addition, the objective location of the center of rotation in LEO microwave and geostationary imagery can allow other algorithms (i.e. AMSU) to estimate TC parameters such as intensity. The ARCHER tool is now being
run as an operational testbed algorithm at NHC as part of a Joint Hurricane Testbed (JHT) project as a direct result of the ground breaking work accomplished within this program.

Figure 2. Automated ARCHER-derived “track” result for Super Typhoon Neoguri (2014). Position estimates are spaced at three-hour intervals. Satellite data sources are indicated in the color coded legend. Colored circles indicate the 50% certainty range for the associated center-fixes, and the light shaded zone indicates the combined 95% certainty range. The JTWC operational track, for independent reference, is shown as white disks.

Note there are various stages during the TCs lifespan when the confidence in the center fix fluctuates widely as some combination of upper-level cloudiness and poor microwave temporal sampling deny the analysts with suitable accurate data sets. Inaccurate center fixes cannot only directly impact near real-time storm warnings, but also negatively impact multi-day mesoscale and global model forecasts needed to set conditions of readiness (COR) for DOD bases and airfields. It should be noted that this effort includes for the 1st time the scatterometer data that provides a unique view of the LLCC when compared to microwave imagery Tb. A creative adaption of ARCHER was developed to deal with accurately finding circulation centers in ocean surface vector winds, which can be difficult to do manually with satellite analysts.
Figure 3. A graphic of the ARCHER scatterometer-based center-fix for Super Typhoon Halong (2014) during the early tropical depression stage. The vector field is the ASCAT ambiguity (all potential solutions) retrieval; colored contours are the center-fix scores (where the bulls-eye is the estimated center of rotation), the square is the ARCHER-derived center-fix position, the cross is the JTWC operational forecast position at this time, and the magenta circle is the area of 50% certainty. In this case, ARCHER indicates with high confidence that the true center of rotation is ~100 km north of the operational track.

Section 3: Tropical Cyclone Structural Evolution

TC structural evolution from genesis to peak intensity and subsequently during decay is difficult to monitor, but vital to better comprehend how TC’s form, morph into storms reaching Category 5 and then decay. We simply do not fully understand the various pathways during a TC’s lifespan since we have not had a consistent all-weather 24/7 observing tool.

A standardization of satellite microwave imager observations of tropical cyclones (TCs) is currently underway. This work will facilitate easier subjective analysis by operational meteorologists and foster robust objective analysis techniques by researchers. A beta version of this process has been completely and produced the following results:

- All microwave data from 1987-2012 gathered from SSM/I, SSMIS, TMI, AMSR-E, and WINDSAT observations
- Best track data from NHC, CPHC, and JTWC used for climatological TC information
- Hourly interpolated positions used to find all data with 10° of TC location
- Ice scattering channels recalibrated to 89 GHz from 85 GHz for SSM/I and TMI, 91 GHz for SSMIS (Yang et al. 2014).
- Backus-Gilbert optimal interpolation enhances the relatively coarse resolution of the recalibrated 89 GHz channels for SSM/I and SSMIS (Poe 1990).
- The interpolated TC center is relocated using ARCHER analysis (Wimmers and Velden 2010).
- Approximately ~100,000 standardized digital images in netCDF format produced.

An example of the recalibration effort is outlined in Figure 4, where both original ice scattering digital imagery is displaced along with the recalibrated 89 GHz Tbs. When viewed one beneath the other, analysts can clearly see there are major Tb changes that could be confused when carrying out intensity trend analyses. A consistent 89 GHz Tb data set will mitigate both manual analysis confusion as well as permit automated analyses to create consistent structural evolution morphology.

**Figure 4:** Temporal evolution of typhoon Jangmi microwave imagery using the ice scattering channel from multiple sensors using 85, 89, and 91 GHz. The top panels are the recalibrated Tb, the 2nd panel are the original 89 GHz Tbs. The 3rd panel is the next set of recalibrated Tb, while the 4th panel is the original 89 GHz Tb for the 3rd panel. Direct comparisons are difficult at this spatial scale, but note the 2nd example on Sept. 25, 2008 at 2050Z, where the top or recalibrated example clearly shows dramatically “cooler” Tbs that would have been incorrectly analyzed as too weak in the original 85 GHz TMI data set. This is also true for the SSM/I and TMI example seen in sample #4 and #6 respectively on the top row, where recalibration significantly alters the Tbs. Subjective manual analyses would have led to inaccurate intensity trend estimates if the original data was only used.
This unique digital data set now provides the capability of viewing both individual storms as well as creates storm composites from which we can extract fundamental structural features associated with intensification, decay, inner core variations, etc. Figure 5 provides the temporal evolution from genesis in the Caribbean Sea to Cat 5 for hurricane Wilma and then eventual very large eye and wind field that caused major damage to the entire south Florida region. Note the inner core structure variations that include the formation of double eyewalls and the eventual decay of the inner eye into one very large eyewall. Concentric eyewall structure changes are also mapped in multi-sensor composites in Fig. 6 for hurricane Ike as it rapidly intensified just NE of Cuba.

Figure 5. Chronological sampling of ice scattering channel 89 GHz horizontal polarization Tb imagery for hurricane Wilma from Oct 17-24, 2005, using recalibrated SSMI 85 GHz and SSMIS 92 GHz digital data in concert with AMSR-E and TRMM TMI data sets.
Figure 6. Chronological sampling of ice scattering channel 89 GHz horizontal polarization $T_b$ imagery for hurricane Ike from Sept. 2-13, 2008, using recalibrated SSMI 85 GHz and SSMIS 92 GHz digital data in concert with AMSR-E and TRMM TMI data sets. Note the development of concentric eyewalls while the storm is near Cuba and Haiti.

This dataset facilitated preliminary TC structure analyses of the inner-core and its relationship with intensity (e.g. Cossuth 2014). During the dataset creation and analysis, several additional goals were identified to expand the dataset utility based on other concurrent research as well as to help real-time applications benefit from this standardization. The following represents the current and future efforts:

Current:

- Applying the recalibration, Backus-Gilbert interpolation, and ARCHER analysis to the NRL TC webpage for a transition to 6.4 real-time demonstrations.

- Expanding the SSM/I and SSMIS Backus-Gilbert interpolation to the 37 GHz frequencies which permits higher resolution images to take advantage of the nyquist sampling (Figure 7).
Future:

- Reprocess the previous data using the additional Backus-Gilbert analysis as well as the latest version of ARCHER (2.8), which provides greater capability to analyze re-centering confidence.
- Perform ARCHER at both 89 GHz and 37 GHz to help mitigate the effects of parallax and/or storm tilt on miss-centering.
- Expand the dataset through 2014, add data from AMSR-2, GMI, as well as MADRAS (potentially), and begin archiving the standardized data analyzed in real-time through the NRL TC webpage.
- Carry out extensive analysis of TC rainband and inner core structural evolution, outlining the pathways to storm intensity changes and precursors to change that may identify to analysts events such as rapid intensification, TC candidates more likely for concentric eyewall formation, and events leading to inner eyewall decay and the formation of very large single eyewalls where the radius of max winds radically enlarges and potentially causes major damage. The data set will permit discoveries not earlier possible on the potential multiple “pathways” TCs possess; a) eyewall formation, b) secondary eyewall formation, cycles, and inner eyewall decay, c) new insight into rainband and inner core impacts due to shear, cool sea surface temperatures and dry air intrusions (such as Saharan Air Layer or mid-latitude sources). Coincident digital data sets depicting shear, SSTs and ocean surface wind vectors (QuikSCAT, ASCAT scatterometer, and WindSat) will be available for analysis.
IMPACT/APPLICATIONS

The frequent, high quality, remapped and frequency corrected digital data set covering microwave imager overpasses from 1987 to the present will provide the team and the community with the first ever digital data set needed to study storm inner core evolution. While microwave imager data has proven useful for near real-time warning applications, the full potential of gleaning storm evolution has not been realized due in part to the lack of a consistent high resolution data set covering multiple decades and oceanic basins.

TRANSITIONS

The ATMS derived TC intensity estimate algorithm is being transitioned to a corresponding 6.4 work unit funded by PEO C4I PMW-120, where an ongoing near real-time demo is underway with validation in concert with JTWC. The automated microwave center finding method (ARCHER) is now funded as a NOAA Joint Hurricane Testbed program at NHC and has great potential to mitigate the data overload coming with the advent of GOES-R 5 minute imagery. The recalibration and Backus Gilbert resampling are both being transitioned to a 6.4 PEO C4I PMW-120 work unit to be incorporated into a demonstration on the NRL TC web page (http://www.nrlmry.navy.mil/TC.html) and will be transitioned to operations at FNMOC upon successful feedback from JTWC and NHC.

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, the National Hurricane Center and the Central Pacific Hurricane Center and serves as the conduit to new products at FNMOC. Feedback from JTWC, NHC, CPHC and the TC research community has been extremely positive at multiple technical conferences and via email sent directly to NRL-MRY.

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

PUBLICATIONS & PRESENTATIONS


Wimmers, A. J. and C. S. Velden, 2014:: Improvements and validation of the ARCHER automated TC center-fixing algorithm, AMS 31st conference on Hurricanes and Tropical Meteorology, San Diego, CA.