Final Report

Satellite-Based Applications to Benefit Navy Tropical Cyclone Analysis and Numerical Model Forecasts

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14. ABSTRACT

This 3-year award (with a 1-year NCE) granted to the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison Space Science and Engineering Center (UW-SSEC) supported applied research directed towards advancing the use of satellite data and products in tropical cyclone (TC) analysis and forecasting relevant to the DoD mission and operations. Algorithms were created and enhanced that exploit inherent advantages from satellite-based imagers and sounders, and new methodologies were designed as advanced satellite sensors came on line. We employed our extensive experience in satellite data interrogation and product development to the project's proposed goals and tasks. Only about half of the requested funding was received during the period of performance, so not all of the originally-proposed tasks were investigated. However, many of the research goals were accomplished, resulting in enhanced satellite-based TC analysis algorithms and data products that were improved after careful calibration and evaluation. This Final Report for research conducted under NRL BAA-N00173-16-R-BA01 broadly summarizes the research accomplishments and milestones achieved.

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Executive Summary

This 3-year award (with a 1-year NCE) granted to the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison Space Science and Engineering Center (UW-SSEC) supported applied research directed towards advancing the use of satellite data and products in tropical cyclone (TC) analysis and forecasting relevant to the DoD mission and operations. Algorithms were created and enhanced that exploit inherent advantages from satellite-based imagers and sounders, and new methodologies were designed as advanced satellite sensors came on line. We employed our extensive experience in satellite data interrogation and product development to the project's proposed goals and tasks. *Only about half of the requested funding was received during the period of performance, so not all of the originally-proposed tasks were investigated.* However, many of the research goals were accomplished, resulting in enhanced satellite-based TC analysis algorithms and data products that were improved after careful calibration and evaluation. This Final Report for research conducted under NRL BAA-N00173-16-R-BA01 broadly summarizes the research accomplishments and milestones achieved. Further information and details of the research results can be obtained through the publications and web sites listed in the report, as well as the monthly progress reports provided to NRL-MRY grant managers during the period of performance.

Brief Study Background

Recent studies have indicated that space-based remote sensing can be employed to help fill meteorological data gaps over oceanic regions in order to provide more accurate forecasts for fleet operations. Advances in space-based technology are providing improved sensor capabilities with associated opportunities to better observe the 3-D atmosphere. In addition, progress in computer resources and numerical techniques have enabled the research community to expand the development of computer-based, automated algorithms capable of transforming real time measurements into useful information. Taking advantage of these emerging technologies has the potential to provide optimal satellite data coverage and quality. The resulting datasets, products and diagnostic derivatives can be used to enhance the forecasting capabilities of naval weather prediction centers (e.g. the Joint Typhoon Warning Center, JTWC) and favorably impact global fleet operations.

UW-CIMSS has pioneered the development of many techniques designed to efficiently extract meteorological information from weather satellite measurements. Some of these methods were specifically developed for Naval applications under NRL support, leading to promising new algorithms, data sets and capabilities. The JTWC relies heavily on satellite-based guidance for their TC analysis and forecast processes. Already, objective methods developed jointly by NRL and CIMSS to analyze TC intensity and structure are being demonstrated. Some of these include the Advanced Dvorak technique (ADT, Olander and Velden 2012), a microwave sounder-based intensity estimation technique (Herndon and Velden, 2012), a consensus intensity estimation method (SATCON, Velden and Herndon 2020), a microwave imager-based eyewall replacement

cycle product (M-PERC), and an objective TC center and structure diagnostic tool called ARCHER (Wimmers and Velden, 2012a). All of these techniques benefited from the additional research and development performed under this grant, which included the incorporation of new science modules, adaptation to new sensors, further validation/demonstration studies, and readiness for operational transition.

Project Scope

The completed research accomplished under this grant is directed at advancing the use of satellite data and products to enhance TC analysis. The resulting research and development will be summarized to include 1) upgrades to the satellite-based, automated algorithms to objectively estimate TC intensity and adaptation of these methods to emerging new sensors, and 2) upgrades to passive microwave imager-based products and algorithms for assessing TC position and structural behavior. The CIMSS team worked with NRL-Monterey research partners to build, improve, test, and adapt the algorithms and methodologies, while at the same time interacting with JTWC forecasters as part of demonstration 'proving grounds' to get feedback on product value.

Research Objectives and Summary of Accomplishments

Overarching Objective: Advance the use of meteorological satellite data and products to improve tropical cyclone analysis and forecasting to benefit DoD operations.

1) Refinements to the Advanced Dvorak Technique (ADT), an automated objective tropical cyclone intensity estimation algorithm using satellite data,

Background: A prototype, computer-based, objective TC intensity estimation algorithm was developed and tested at UW-CIMSS under previous NRL-sponsored research (Velden et al. 1998; Olander and Velden 2007). The technique is based on objective IR cloud pattern recognition and statistical matching procedures, with enhancements from microwave inputs. The ADT is now an operational algorithm at NOAA/NESDIS and is an integral part of the JTWC TC intensity estimation toolbox.

Approach/Accomplishments: Further ADT algorithm modifications were necessary in order to address user feedback from JTWC. These modifications included: 1) Adjustments to operate more efficiently on systems designated as Sub-Tropical, and TCs undergoing Extratropical Transition; 2) Implementation of the latest version of the ARCHER objective center-fixing routine; 3) Incorporation of a scheme to estimate critical TC surface wind field radii; 4) Adaption to the new Himawari and GOES-R satellites as they came online. All modifications were tested both in research mode and in real-time trials and incorporated into the latest publically-available version (V9.0; Olander and Velden 2019) that JTWC now accesses TC estimates from.

2) Further exploration of satellite-based microwave information as TC intensity and structure tools

Background: Passive microwave sensors offer a unique view of TC structure owing to their relatively low sensitivity to cloud contamination. Microwave sounders such as the Advanced Microwave Sounding Unit (AMSU), Advanced Technology Microwave Sounder (ATMS), and the Special Sensor Microwave Imager Sounder (SSMIS) are good examples. Under previous NRL funding, microwave sounder information was employed

to exploit the relationship between TC warm core structures and intensity (Brueske and Velden 2003; Herndon and Velden 2012). Algorithms based on this relationship were developed that are now used operationally at TC analysis centers.

In addition to the sounders, microwave imagers offer an important perspective on TC structure and evolution. The signatures in passive microwave imagery from instruments such as the DMSP Special Sensor Microwave Imager (SSMI) and the GPM Microwave Imager (GMI) have been used extensively in a qualitative mode by satellite analysts to infer TC convective organization. CIMSS researchers developed an algorithm to objectively and quantitatively assess TC center-fix and structure information (ARCHER, Wimmers and Velden 2016), which now provides information to the microwave sounder-based and ADT intensity estimates, as well as microwave imager-based TC structure analysis algorithms.

Approach/Accomplishments:

- The microwave sounder-based TC warm core retrieval technique as an intensity estimation algorithm continued by refining and adapting it to work with the new NPP ATMS and METOP AMSU scan geometry and antenna patterns. The resultant performance was characterized and documented, and the results of this work are now incorporated into the operating algorithm.
- A microwave imager-based approach to estimate and forecast TC eyewall replacement cycles (ERC) was developed. Using organization signatures and structure scores determined by ARCHER, a scheme was developed that produces probabilities of a TC ERC. These ERCs can be linked to TC intensity changes. The

M-PERC (Microwave-Probabilities of Eyewall Replacement Cycle) algorithm is now in demonstration mode with JTWC typhoon duty officers via ATCF data feeds.

3) Continued development and refinement of a consensus satellite-based TC intensity estimation approach

Background: An ensemble approach to satellite-based TC intensity estimation is being investigated by examining the properties and error characteristics of the available objective satellite-based intensity estimation methods and then creating a weighted consensus. A latest version of such an objective algorithm (SATCON – SATellite CONsensus; Velden and Herndon 2020) is currently in demonstration mode at CIMSS. The ultimate goal is to take advantage of the strengths of each independent method towards an ensemble approach that yields superior collective intensity estimates.

Approach/Accomplishments: Experiments have been performed to optimize the weighting of the individual methods in the consensus approach in order to achieve reduced TC intensity estimation errors. Combining methods through information sharing (e.g., providing our AMSU/ATMS technique with eye sizes from ARCHER or ADT) was explored, and further work has been done to optimize the member weights and add new members to the consensus as they are made available. An extensive validation effort shows SATCON significantly reduces satellite-based TC intensity estimation errors. The results of this study were recently published (Velden and Herndon, 2020), and the SATCON algorithm was tested in a real-time “proving ground” trial with JTWC during the 2019 TC season. The SATCON estimates are now frequently mentioned by JTWC TC analysts in their real-time TC discussions.

Specific Task/Milestone Accomplishments

1) Further refinement of the Advanced Dvorak Technique (ADT) resulted in the latest version release (V9.0), which is now the operating algorithm with TC intensity estimates being made available to JTWC via the ATCF. The modifications included: 1) Adjustments to operate more efficiently on systems designated as Sub-Tropical, and cyclones undergoing Extratropical Transition; 2) Implementation of the latest version of the ARCHER objective center-fixing routine; 3) Incorporation of a scheme to estimate critical TC surface wind field radii; and 4) Adaption to the new Himawari and GOES-R satellites. A scientific journal article was published (Olander and Velden, 2019) with performance results, and more info and intensity estimates can be found at: http://tropic.ssec.wisc.edu/real-time/adt/adt.html.

2) Continued development of an advanced VIS/IR and passive microwave imager-based algorithm for TC center fixes (ARCHER). The capabilities of ARCHER were enhanced to include probability distributions for position error and multi-platform assimilations of storm track. An extensive cal/val effort was reported in Wimmers and Velden (2016) for an array of operating microwave and VIS/IR satellite sensors, and is presented concisely in real-time on the ARCHER demonstration website (http://tropic.ssec.wisc.edu/real-time/archerOnline/web/index.shtml) as concentric rings of 50% and 95% probability locations. The ARCHER center-fix estimates are also now provided in near real-time to JTWC forecasters via the ATCF, and the algorithm has been ported to the GeoIPS processing environment developed at NRL-MRY in anticipation of transition to operational processing.

3) Advanced the development of microwave sounder-based algorithms to estimate TC intensity. Specifically:

- METOP-B AMSU and NPP ATMS were added to the microwave sounder TC intensity algorithm. Post-processing of passes was completed for storms with coincident aircraft ground truth data for calibration and tuning of the resulting sounder TC intensity estimates. These recent instruments are now incorporated into the operating algorithm (http://tropic.ssec.wisc.edu/real-time/amsu/).
- ARCHER-based TC structure information (e.g. RMW) has been updated and improved for input into the microwave sounder algorithm with good results on positively impacting the TC intensity estimates. This element is now incorporated into the operating sounder algorithm.

4) The M-PERC (Microwave-Probabilities of Eyewall Replacement Cycles) algorithm has been tested and evaluated for Atlantic and East Pacific TCs, and is in testing mode for West Pacific TCs. Training on interpretation of the product was conducted with JTWC personnel, and MERC ERC information is being provided via ATCF. A science journal manuscript is in preparation. The real-time M-PERC site is here: http://tropic.ssec.wisc.edu/real-time/archerOnline/web/index_erc.shtml

5) The end-product for many of the satellite-based TC algorithm outputs discussed above is by providing inputs to the satellite consensus (SATCON) algorithm for estimating TC current intensity (expressed as maximum sustained surface winds and minimum sea-level pressure). An extensive validation effort shows SATCON significantly reduces satellite-based TC intensity estimation errors by up to 10-20% over individual members

and standard Dvorak technique estimates. The results of this study and further details on the SATCON methodology were recently published (Velden and Herndon, 2020). Based on these promising results, the SATCON algorithm was demonstrated in a real-time "proving ground" trial with JTWC forecasters during the 2018-19 TC seasons. As a result, the SATCON estimates are now frequently mentioned by JTWC TC analysts in their real-time TC situational awareness discussions. The SATCON algorithm is planned for operational transition via the NRL GeoIPS platform in the near future. Further information and real-time TC intensity estimates can be found on the SATCON web site: http://tropic.ssec.wisc.edu/real-time/satcon/

Operational Implications and Transitions

As noted above, several of the satellite-based TC analysis algorithms developed and tested under this research initiative are being made available for transition into operational environments. The ADT is now operational at the NOAA/NESDIS Satellite Analysis Branch, with the latest V9.0 expected to go public next TC season. The ADT TC intensity estimates are also made available to Naval (and other) operational users through the Automated Tropical Cyclone Forecast (ATCF) conduit. The objective satellite-based TC center fix application (ARCHER) has been successfully ported to the NRL GeoIPS processing platform, setting the stage for operational processing. Other algorithms such as the consensus intensity estimation method (SATCON) and the Microwave-Probability of Eyewall Replacement Cycle (M-PERC) are targeted for the same GeoIPS platform in the near future.

New Publications and Presentations related to this research

2021

Journal Literature

Kossin, James P., Derrick C. Herndon, Anthony J. Wimmers, Xi Guo, and Eric S. Blake, 2021: **The M-PERC and E-SHIPS Models: New Tools for Hurricane Intensity Forecasting During Eyewall Replacement Cycles**. To be submitted to *Weather and Forecasting*.

2020

Journal Literature

Velden, Christopher S. and Herndon, Derrick. **A consensus approach for estimating tropical cyclone intensity from meteorological satellites: SATCON**. *Weather and Forecasting*, Volume 35, Issue 4, 2020, pp.1645-1662. Link to PDF

2019

Journal Literature

Olander, Timothy L. and Velden, Christopher S., **The Advanced Dvorak Technique (ADT) for estimating tropical cyclone intensity: Update and new capabilities**. *Weather and Forecasting*, Volume 34, Issue 4, 2019, pp.905-922. Link to PDF

Wimmers, Anthony; Velden, Christopher and Cossuth, Joshua H., **Using deep learning to estimate tropical cyclone intensity from satellite passive microwave imagery**. *Monthly Weather Review*, Volume 147, Issue 6, 2019, pp.2261-2282. Link to PDF

2018

Journal Literature

Knapp, Kenneth R.; Velden, Christopher S. and Wimmers, Anthony J., **A global climatology of tropical cyclone eyes**. *Monthly Weather Review*, Volume 146, Issue 7, 2018, pp.2089-2101. Link to PDF

2017

Journal Literature

Velden, Christopher; Olander, Timothy; Herndon, Derrick and Kossin, James P., **Reprocessing the most intense historical tropical cyclones in the satellite era using the Advanced Dvorak Technique**. *Monthly Weather Review*, Volume 145, Issue 3, 2017, pp.971-983. Link to PDF

Conference presentations

Herndon, Derrick and Velden, C. S., **An update on the CIMSS SATellite CONsensus (SATCON) tropical cyclone intensity algorithm**. Conference on Hurricanes and Tropical Meteorology, 33rd, Ponte Vedra, FL, 16-20 April 2018**.** Boston, MA, American Meteorological Society, 2018, Abstract 284.

Olander, T., A. Wimmers and C. Velden, 2021: **Employing AI-Machine Learning Techniques to Enhance TC Intensity Information from the Advanced Dvorak Technique (ADT).** 34th AMS Hurricane Conf., virtual.

Olander, Timothy and Velden, C., **The UW-CIMSS Advanced Dvorak Technique (ADT) - current status and future upgrades**. Conference on Hurricanes and Tropical Meteorology, 33rd, Ponte Vedra, FL, 16-20 April 2018**.** Boston, MA, American Meteorological Society, 2018, Abstract 247.

Velden, Christopher S.; Olander, T.; Burton, A.; Courtney, J.; Ritchie, E. A.; Stark, C. and Tyo, S. J.. **A reanalysis of Australian region tropical cyclones in the geostationary satellite era. Part 1: Intensity, using the objective Advanced Dvorak Technique (ADT)**. 33rd Conf. on Hurricanes Tropical Meteorology, Ponte Vedra, FL, 16-20 April 2018**.** Boston, MA, American Meteorological Society, 2018, Abstract 246.

Wimmers, Anthony; Cossuth, J. H. and Velden, C. S., **Application of a deep learning neural network to remotely-sensed TC intensity**. Conference on Hurricanes and Tropical Meteorology, 33rd, Ponte Vedra, FL, 16-20 April 2018**.** Boston, MA, American Meteorological Society, 2018, Abstract 248.

Wimmers, Anthony; Kossin, J. P. and Herndon, D. C., **Improved eyewall replacement cycle forecasting using a modified microwave-based algorithm**. Conference on Hurricanes and Tropical Meteorology, 33rd, Ponte Vedra, FL, 16-20 April 2018**.** Boston, MA, American Meteorological Society, 2018, Abstract 10D.2.

Wimmers, Tony; Kossin, Jim and Herndon, Derrick. **Improved eyewall replacement cycle foreasting using a modified microwave-based algorithm (ARCHER)**. Interdepartmental Hurricane Conference, 71st, Miami, FL, 14-16 March 2017.

Wimmers, Tony; Kossin, Jim and Herndon, Derrick. **Improved eyewall replacement cycle forecasting using a modified microwave-based algorithm (ARCHER)**. Tropical Cyclone Operations and Research Forum, Working Group for Disaster Impact Assessments and Plans, Weather and Water Data (WG/DIAP) Meeting, Miami, FL, 14-16 March 2017. Silver Spring, MD, National Oceanic and Atmospheric Administration (NOAA), Office of the Federal Coordinator for Meteorology (OFCM), Abstract 9.2.

Additional Report References

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Olander, T. and Velden, C., 2012: The Advanced Dvorak Technique (ADT) - Current status and latest advancements**.** Conference on Satellite Meteorology, Oceanography and Climatology, 18th, and Joint AMS-Asia Satellite Meteorology Conference, 1st, New Orleans, LA, 22-26 January 2012**.** Boston, MA, American Meteorological Society.

Velden, C.S., T. Olander and R. Zehr, 1998: Evaluation of an objective scheme to estimate tropical cyclone intensity from digital geostationary satellite infrared imagery. *Wea. and Forecasting*, **13**, 172-186.

Wimmers, A. and *C.* Velden, 2012*:* Advances in objective TC center fixing using multispectral satellite imagery**.** Conference on Hurricanes and Tropical Meteorology, 30th, Ponte Vedra Beach, FL, 15-20 April 2012**.** Boston, MA, American Meteorological Society.