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From Ocean to Outflow: Understanding Tropical Cyclone Circulations and Intensification

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LONG-TERM GOALS

1. Identify the relationship between the ocean, eyewall convection, and outflow within tropical cyclones (TCs) to further understand the mechanisms within the TC secondary circulation and the impact of these processes on TC intensification.
2. Improve TC forecast accuracy.

OBJECTIVES

Four principle objectives are designed to achieve the long-term goals:

1. Identify correlations between and investigate the physical mechanisms connecting changes in the upper-ocean thermal structure (i.e. cooling) and the magnitude of the TC outflow.
2. Improve data quality and the proficiency of current airborne ocean observation operations.
3. Quantify the value added by these ocean observations to the accuracy of tropical cyclone intensity forecasts in coupled numerical prediction models.
4. Identify an optimal sensing strategy for ocean observations to increase the accuracy of tropical cyclone intensity forecasts in coupled and statistical numerical prediction models.

APPROACH

This research builds upon the ***T***raining and ***R***esearch in ***O***ceanic and atmospheric ***P***rocesses ***I***n tropical ***C***yclones (TROPIC) program funded by the Office of Naval Research (ONR; Code 32) and supports the ONR Tropical Cyclone Intensity (TCI) Departmental Research Initiative (DRI). The purpose of TCI is to increase understanding of the upper-level TC outflow and the connection between the TC and larger-scale environment. During FY14, atmospheric and oceanographic observations were collected during USAF WC-130J flights into Hurricanes Iselle and Julio in the central North Pacific. During FY15, the first analysis of these storms was completed: an examination of the upper-level outflow through the lifecycle of both TCs. The second analysis is in progress: an investigation of the ocean response to the TC and the relationship between changes in the upper-ocean thermal structure and the

TC outflow. During the field program in FY15, atmospheric and oceanographic observations were collected in hurricanes Guillermo, Hilda, Ignacio, Danny and Joaquin, and Tropical Storm Erika. There were combined operations with the TCI WB-57 during Hurricane Joaquin and Tropical Storm Erika. This ocean/outflow research is divided into two phases: a field phase and a classroom phase. The FY15 classroom phase spanned the 2014-2015 academic year and focused on the Iselle and Julio outflow and ocean analyses. During the summer field phase (July-October 2015), TROPIC personnel, including officers and midshipmen (undergraduate students) from the U.S. Naval Academy and one Coast Guard sailor (a Woods Hole Oceanographic Institute (WHOI) Senior Scientist and ONR-sponsored PI), flew with the USAF 53rd Weather Reconnaissance Squadron (WRS) to collect the data in active tropical systems. In addition to the standard suite of airborne reconnaissance sensors, both Airborne eXpendable BathyThermographs (AXBTs) and Air-Launched Autonomous Micro Observer (ALAMO) profiling floats were deployed from the 53rd WRS WC-130J aircraft over the Atlantic and Pacific Oceans. The 2015-2016 classroom phase began at the U.S. Naval Academy immediately following the FY15 field phase and will continue into FY16. During the classroom phase, the midshipmen will quality control, review, and analyze the data collected during the field phase to address the objectives of this research.

While TROPIC began as a collaborative effort with the Naval Research Laboratory (NRL), Monterey and the USAF 53rd WRS, an opportunity was leveraged to coordinate the field phase of this program with a parallel project undertaken by the Interdepartmental Hurricane Conference (IHC) working group. During the summer of 2011, the IHC working group began a forecast demonstration project in which AXBTs are launched from operational flights into Atlantic Basin TCs, the data are assimilated into coupled air-sea models on a near-real-time basis, and the value added of these AXBTs to the coupled numerical model TC forecast output is evaluated. Operational and logistical support from the 53rd WRS for TROPIC research is substantially enhanced through this partnership, and in return, data from the AXBTs are quality controlled, formatted, and uploaded directly to the Naval Oceanographic Office (NAVO) and to the Global Telecommunication System (GTS) by TROPIC personnel. Data from the ALAMO floats are also uploaded to the GTS via WHOI and the Atlantic Oceanographic and Meteorological Laboratory (AOML). At NAVO, the AXBT and ALAMO observations are assimilated via NCODA and positively impact the Navy's HYCOM and NCOM model forecasts. These ocean models provide initial and/or boundary conditions for other ocean and coupled numerical models, including the Navy Coupled Ocean Atmosphere Mesoscale Prediction System – Tropical Cyclone (COAMPS-TC). Through the GTS, the AXBT and ALAMO observations are available to scientists worldwide, including those at the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) conducting research on the Hurricane Weather Research and Forecast System (H-WRF) coupled mesoscale model to support the IHC Working Group.

Key personnel for the program and subject matter experts for each phase during FY2015 included:

1. Leads:
   CDR Elizabeth R. Sanabia PhD, USN, United States Naval Academy, Annapolis, MD (PI)
   Bradford S. Barrett, PhD, United States Naval Academy, Annapolis, MD (co-PI)
   Peter Black, PhD, Naval Research Laboratory, Monterey, CA
2. Field Phase:
   LtCol Jonathan Talbot, USAF, 53rd WRS, Keesler Air Force Base, Biloxi, MS
   Jeffrey Kerling, Naval Oceanographic Office, Stennis Space Center, Stennis, MS
   Steven Jayne, Woods Hole Oceanographic Institute, Woods Hole, MA

3. Classroom Phase:

Sue Chen, PhD, Naval Research Laboratory, Monterey, CA
James Cummings, PhD, Naval Research Laboratory, Stennis Space Center, Stennis, MS
Midshipmen Anthony Borrego, Sarah Reynolds, and Julie Stapleton, USN, United States Naval Academy, Annapolis, MD

WORK COMPLETED (FY2015)

1. 2014-2015 Classroom Phase (August 2014-June 2015): Research during this FY14-15 phase focused on two primary projects: the Iselle and Julio outflow study and the ocean impact analysis.

A. The outflow study was conducted by three undergraduate Oceanography majors at the U.S. Naval Academy as part of their senior research. Results were presented at the AMS 2015 Annual Meeting and the OFCM 2015 IHC, and a journal article is in preparation. Details are discussed in the Results section.

B. The evolution of the upper-ocean thermal structure beneath hurricanes Iselle and Julio was also analyzed during FY15. Initial results were presented at the AGU 2014 Fall Meeting and work on this topic and the relationship between the ocean and outflow in these TCs will continue into FY16.

During this period, collaborative work continued on two projects:

A. A new technique was developed by S. Chen and J. Cummings (NRL Monterey) to test the sensitivity of the ocean model to AXBT observations in the vicinity of a TC. This effort directly supports Objective 4 of this project: development of an operational ocean sensing strategy for TCs. Initial results based on the Hurricane Isaac (2012) case, using AXBTs collected as part of this project, were presented by S. Chen at the OFCM 2015 IHC and are briefly discussed in the Results section.

B. A data denial study of Hurricane Iselle (2014) was initiated. Work on this project will continue into FY16.

2. 2015 Field Phase (July-October 2015): The FY15 field phase continued 5 days into FY16, and the results for the full field phase are included in this report. The TROPIC team deployed more 225 AXBTs from USAF 53rd WRS WC-130J aircraft during 34 flights over the Atlantic and Pacific Oceans: 20 missions into Hurricanes Guillermo, Hilda, Danny, and Joaquin, 6 into Tropical Storm Erika, and 8 training flights. The team also deployed 25 ALAMO floats during these missions. For the AXBTs, the quality-controlled ocean observations were sent in WMO-approved JJVV format to both the Real-Time Data Handling System (RTDHS) at NAVO for assimilation into the NCOM and HYCOM ocean models and to the National Data Buoy Center (NDBC) for upload to the GTS (for worldwide use). The ALAMO data were sent in near real time to WHOI and AOML for upload to the GTS. Sensor reliability and data transfer statistics are still being analyzed. The NCOM data are used in the coupled COAMPS-TC, which was run in real time during part of the 2015 season and will also be used for data-denial studies of TC forecast accuracy (S. Chen, NRL, personal communication). The coupled COAMPS-TC model is scheduled to be run operationally again in 2016. Both the JJVV and 1-m data were also sent to POCs at URI (for assimilation in the coupled GFDL) and to NCEP/EMC (for assimilation into H-WRF).

Multiple steps were taken to address two of the four research objectives during the 2015 field phase:

A. To improve data quality and operational proficiency, (Objective 2), continued focus was placed on increasing the reliability of the observing system and increasing the temporal and geographic

extent of the ocean observations. The three endeavors begun in FY14 were continued in FY15. Details are briefly described below:

1. Gear maintenance was conducted by Naval Air Systems Command (NAVAIR) prior to the start of the field phase. Signal test equipment was also provided by NAVAIR to enable both in-flight and ground-based troubleshooting. Though the Mobile Oceanographic Observing System (MOOS) was not developed by NAVAIR, subject matter experts were familiar with the system components and conducted preventative maintenance and provided training on test equipment prior to the field phase. Both the maintenance and signal test equipment were significantly helpful throughout the field program.

2. The WHOI ALAMO air-deployed ocean-profiling float (initially developed with ONR funding) was deployed during both operational TC reconnaissance flights as well as training missions. Instruments deployed during Hurricane Guillermo also captured excellent observations during Hurricane Ignacio, which transited the same area about three weeks later. The Naval Oceanographic Office enthusiastically supports development and use of this sensor (C. Szczechowski, NAVO, personal communication), as it provides hundreds of vertical profiles and can last several months, while each AXBT provides a single vertical profile. Cost-benefit, data inter-comparison, and further testing of these sensors are in progress.

3. Joint TC/ocean observation flights with NOAA were planned (E. Uhlhorn, HRD, personal communication) and briefed to the 53rd WRS in the months prior to the season. The current collaborative operations template is based on NOAA conducting ocean observations both ahead of and around the storm and the TROPIC/53rd WRS team conducting the in-storm ocean observation component. The timing of NOAA ocean research and 53rd WRS mission flights did not support in-field collaboration this year, however they remain a viable option in the future.

B. To quantify the value added by the ocean observations to the accuracy of TC intensity forecasts (Objective 3), the impact of the AXBT observations collected during select hurricanes is evaluated. This evaluation is a two-step process, as improvement to the initialization of the ocean in either HYCOM or NCOM must first be shown and then be followed by a data-denial study in COAMPS-TC to determine the impact on the TC forecast.

1. To evaluate the impact on the HYCOM model, the AXBTs deployed during observed TCs are typically compared to the value added by other observations collected in the same ocean basin through an adjoint system (developed by and courtesy of J. Cummings at NRL Monterey). Similar to adjoints in atmospheric systems, the contribution of each observation type to the accuracy of the model forecast can be quantified. However, since there were some challenges in the transition of the COAMPS-TC to real time operation during the field program, assessment of the value added by the AXBTs and ALAMO floats during FY15 is planned for FY16.

2. Data denial studies are in progress for Hurricanes Iselle and Julio from the 2014 field phase (S. Chen, NRL, personal communication). Results, including those determined using the newly developed sensitivity analysis, will be reported when they become available.

<u>3. 2015-2016 Classroom Phase (August 2015-June 2016):</u> Research is currently focused on three projects that address the first two research objectives. Tasks related to these projects include the following:

A. Complete the investigation of the ocean response to Hurricanes Iselle and Julio and the linkages between changes in the upper-ocean thermal structure and the TC outflow in both those storms (Objective 1).

B. Evaluate the response of the upper ocean as measured in the ALAMO floats during the FY15 field program (Objective 2), particularly the noteworthy response observed beneath Hurricane Ignacio (Fig. 1). Also, investigate the physical mechanisms behind the response.

C. Collaborate with other TCI PIs to study the ocean and outflow mechanisms in Hurricane Joaquin (Objective 1).

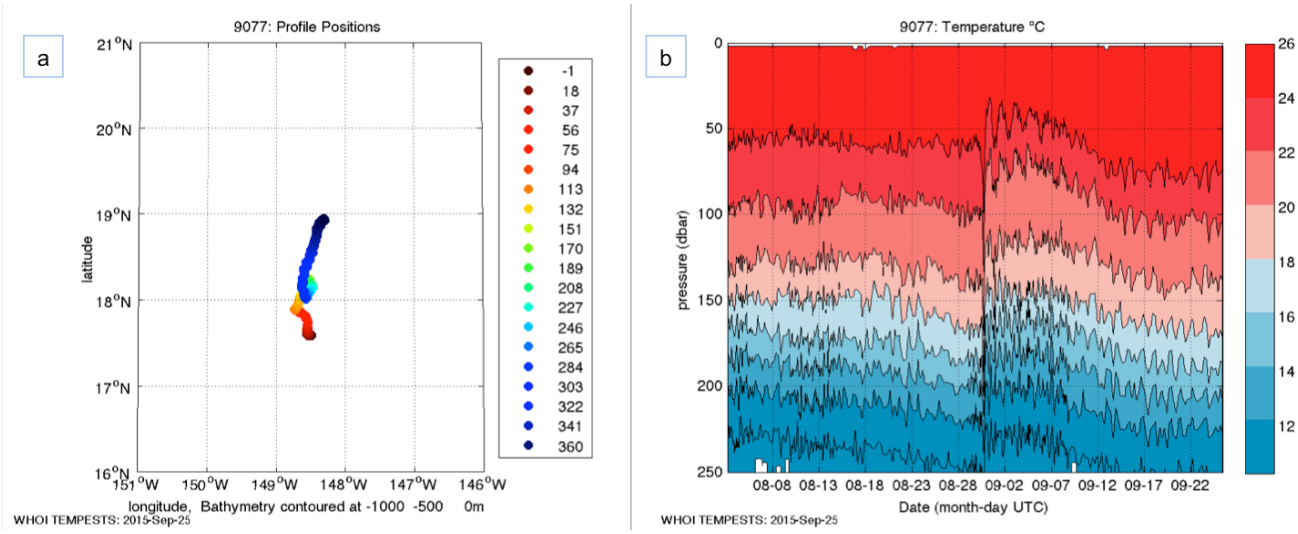

Fig. 1. The (a) positions and (b) upper-ocean temperatures (°C) from ALAMO float 9077. Response from the passage of Hurricane Ignacio is noted in the large depression of the upper 200 m of the water column on 30 August 2015 and the oscillation and cooling present for more than a week afterwards.

RESULTS

Several achievements from the FY2015 TROPIC Ocean-Outflow program are outlined below.

1. Operational results included both "firsts" and continued successes:

A. Sequential ALAMO observations of the upper 300 m of the ocean were taken at about 2-h intervals prior to, during, and after the passage of a major hurricane (Fig. 1), capturing an observation beneath the eyewall of a major hurricane *for the first time*. Maximum surface winds of 81 kts were reported 9 nm southwest of the TC center by a WC-130J about 2 hours after the TC passed 13 nm to the northeast of the closest ALAMO observation location (relevant vortex message available here: http://tropicaleastpacific.com/recon/recon.cgi?basin=ep&year=2015&product=vortex&storm=Ignacio&mission=04&agency=AF&ob=08-30-181050-03-960-79%28107%29-81). This new sensor performed exceptionally well beneath this major hurricane. The continuity of upper-ocean observations under such extreme atmospheric conditions indicates the durability and reliability of the ALAMO profiling float. It is also noteworthy that this sensor had been deployed for a previous TC, and provided a right-place, right-time sequence of observations beneath Hurricane Ignacio.

B. The AXBT observations beneath the 2015 TCs were uploaded to the RTDHS and GTS and often assimilated in near-real-time into the NCODA, operational NCOM, and global HYCOM from operational TC reconnaissance missions for the fifth consecutive year (in Hurricanes Guillermo, Hilda, Danny, and Joaquin, and Tropical Storm Erika). The ALAMO float observations beneath these TCs as well as follow-on systems (like Hurricane Ignacio) were uploaded to the GTS in near-real time for the second straight year, enabling rapid assimilation into both ocean and coupled models.

2. Research results to date include:

A. The analysis of outflow in Hurricanes Iselle and Julio (2014) in the Navy Global Environmental Model (NAVGEM) analyses revealed several findings regarding the outflow location, relationship between the outflow and TC intensity, and relationship between the TC track, jet features, and outflow channels. Those findings are detailed in a manuscript currently in preparation and include the following:

1. The maximum outflow was consistently near 200-hPa (vertically), but the radial location of the maximum outflow varied over time, and was often more than 500 km from the TC center.

2. The TC intensity increased during periods of greater outflow, when the maximum outflow was shifting radially inward toward the TC center (Fig. 2), and when dual outflow channels were present.

3. Outflow channels were greatly impacted by and responded similarly to adjacent large-scale environmental features.

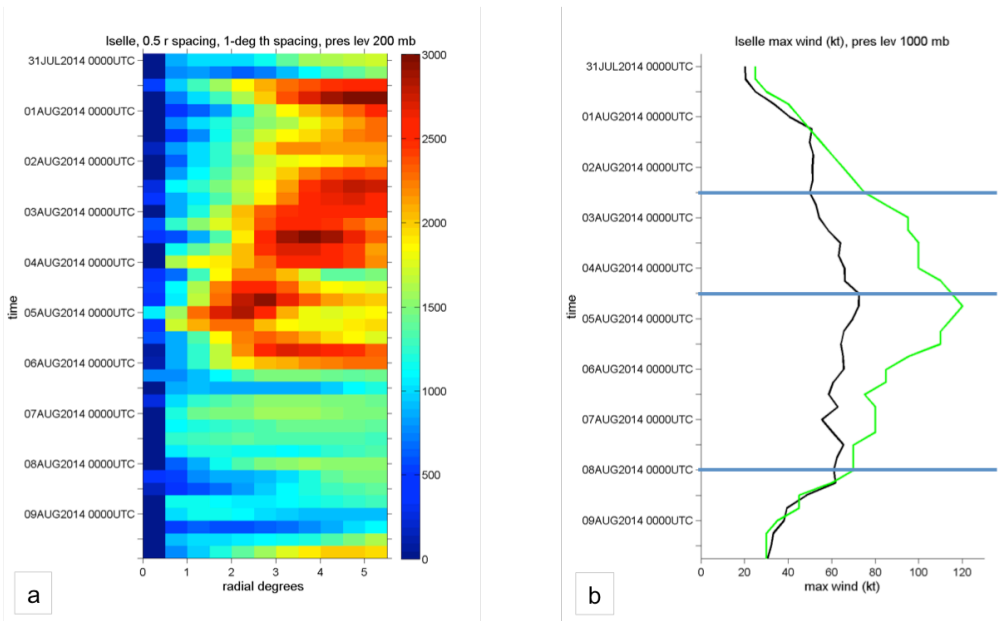

Fig. 2. Radial variation in the (a) total outflow derived from 200-hPa NAVGEM analyses for Hurricane Iselle (shaded, scale at right). (b) Best track intensity (kts) for Hurricane Iselle. Both plots extend from 0000 UTC 31 July 2014 to 0000 UTC 10 August 2014.

B. The significant variability in the ocean beneath Hurricane Ignacio (2015, Fig. 1) was also evident in the ALAMO float observations beneath Hurricane Iselle and Julio (2014). The complexity of those responses necessitated the collection of additional similar observations (which continues), and the focus for the response beneath Iselle and Julio then shifted toward an investigation of the cooling observed at the sea surface through satellite observations. The SST at each TC center location along the storm track (Fig. 3a) was averaged over the 15-day period between 1-15 August 2014. Departures from the average (Fig. 3b) revealed cooling along the TC track of Hurricane Iselle, along with the following details:

1. Cooling was most evident during intensification and maximum intensity (Fig. 3c).

2. Cooling was <u>*greater*</u> when storm speed was <u>*slower*</u>; (note the translation speed increased 2000 km along the storm track, west of 140ºW).

3. Post-TC warming was followed by subsequent cooling as Julio crossed the wake of Iselle.

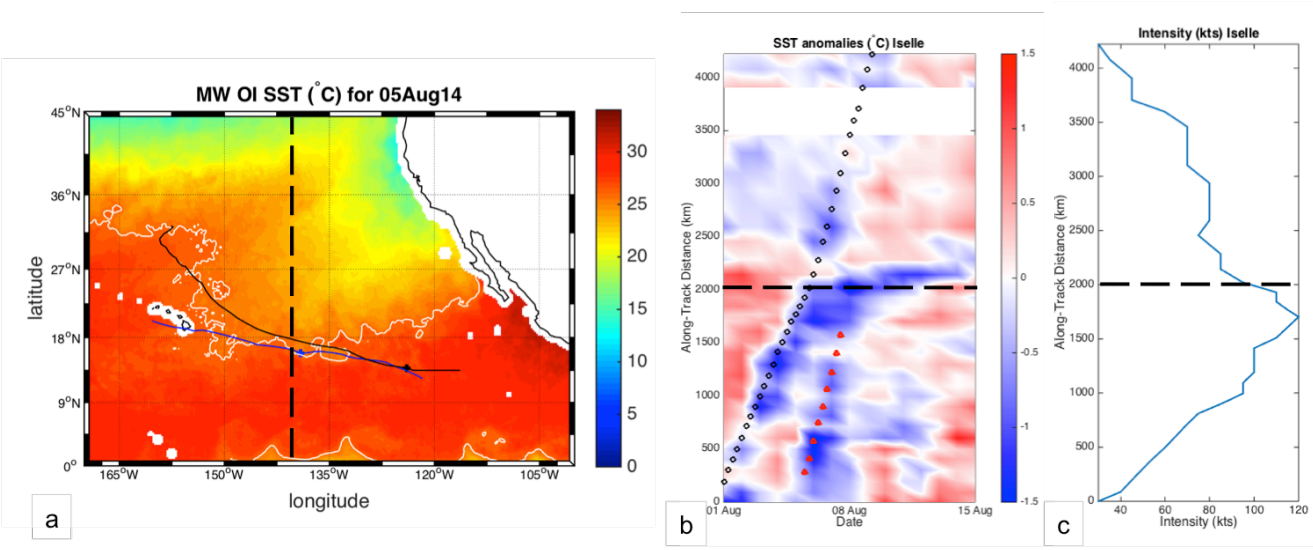

Fig. 3. The (a) Microwave Optimally Interpolated (MWOI) sea surface temperatures (courtesy Remote Sensing Systems) for 05 August 2014 and the (b) SST anomalies (ºC) and (c) TC intensity (kts) along the track of Hurricane Iselle from 1-15 August 2014. Dashed black lines correspond to the eastern edge of the ocean observation area. In (a), the southern track corresponds to Hurricane Iselle and the northern track to Hurricane Julio. The white line bounds the region of SSTs greater than 26ºC. Areas masked by land are blocked out in white (in a-b). The TC center locations are marked with a black circle (Iselle) and red triangle (Julio) (in b-c).

C. A prototype ocean sampling tool was developed by S. Chen and J. Cummings based on AXBT observations collected during Hurricane Isaac (2012) in support of this project. The sampling tool is based on the 3DVAR adjoint method and is designed to establish an optimized ocean data sampling plan. Refinement of this technique (which directly addresses Objective 4 in this research) continues, and will include application toward additional TC cases and possible testing during operational flights during FY16.

IMPACT/APPLICATIONS

1. The lessons learned from this research will impact aircraft-based ocean temperature observation operations beneath tropical cyclones in the following ways:

A. development and refinement of ocean temperature observing systems and procedures, including deployment hardware, data processing software, quality control, and data dissemination;

B. definition of an ocean sensing strategy to support the optimal spatial and temporal distribution of ocean temperature observations within and between reconnaissance flights for assimilation into coupled and statistical TC forecast models;

C. refinement of assimilation schemes and scheduling for coupled TC forecast model runs; and

D. quantification of the impact of AXBT observations on ocean initialization and TC forecasts.

2. Research may indicate that AXBT data consistently improve TC forecast accuracy. If this is the case, the potential impacts on science and systems include:

A. The IHC working group may recommend including AXBT operations become standard during airborne hurricane reconnaissance missions onboard the USAF 53rd WRS WC-130J.

B. The coupled and statistical models including these data may become part of the NHC suite of forecast models.

3. Results from the Ocean/Outflow study will improve understanding of the full secondary circulation of the TC, from heat fluxes at the ocean surface to the anticyclone in the upper troposphere.

A. Lead-lag relationships may show interactions between oceanic heat and upper-atmosphere outflow.

B. Connections between the ocean observations and TC circulation may provide additional considerations to ocean observing strategy development.

RELATED PROJECTS

The "Impact of Target Observations to Tropical Cyclone Structure and Intensity Change" study is currently funded by ONR for work done by PI S. Chen and Co-PIs J. Cummings and J. Schmidt at the Naval Research Laboratory, Monterey.

The "Integrated Rapid-Response Observations and Ocean Ensemble Optimization to Improve Storm Intensity Forecasts in the Northeast U.S." program is currently funded by NOAA under Cooperative Agreement No. NA13OAR4830233 by PI S. R. Jayne and Co-PIs P. Robbins and B. Owens at the Woods Hole Oceanographic Institution.

This TC Ocean-Outflow research builds upon results from the "***T***raining and ***R***esearch in ***O***ceanic and atmospheric ***P***rocesses ***I***n tropical ***C***yclones (TROPIC)" program, funded by ONR for work done by PI E. Sanabia, Co-PIs B. Barrett and W. Schulz at the U.S. Naval Academy from FY11-FY14.

PUBLICATIONS

Sanabia, E. R., B. S. Barrett, Z. D. Cornelius, and N. P. Celone, 2015: Satellite and aircraft observations of the eyewall replacement cycle in Typhoon Sinlaku (2008). *Mon. Wea. Rev.*, **143**, 3406-3420.

Sanabia, E. R., B. S. Barrett, and C. M. Fine, 2014: Relationships between typhoon intensity and eyewall slope as determined by radial profiles of inner-core infrared brightness temperatures. *Mon. Wea. Rev.*, **142**, 4581-4599.