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 Training and Research in Oceanic and atmospheric Processes In tropical Cyclones (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. The original approach for the first year of the ocean/outflow research component was twofold: first, to conduct a baseline ocean/outflow study using COAMPS-TC model and AXBT observation data from Hurricane Irene (2011); then, to participate in the TCI field phase between July-September 2014, flying with the USAF 53rd Weather Reconnaissance Squadron (WRS) to collect the ocean data upon which this research would be based (in conjunction with outflow data collected by other assets). Due to sensor readiness challenges, this approach was reconfigured. The field program was conducted in two parts, with ocean observations from the WC-130J taking place between July and September 2014, and outflow observations from the B-57 taking place in October.
The modeling and ocean observation components were streamlined into a single study, focused on Hurricanes Iselle and Julio. Combined ocean/outflow field programs are planned for FY15 and FY16.

This ocean/outflow research is divided into two phases: a field phase and a classroom phase. During the field phase in year one of the project, TROPIC personnel, including officers and midshipmen from the U.S. Naval Academy (undergraduate students) and one Coast Guard sailor (Assistant Scientist and ONR-sponsored PI), flew with the USAF 53rd 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 between July-September 2014. The classroom phase began at the U.S. Naval Academy immediately following the field phase and will continue through the academic year in FY15. 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 3-5 year forecast demonstration project in which AXBTs are launched from operational flights into Atlantic Basin TCs, the data are input 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 logistics support from the 53rd WRS for TROPIC research is substantially enhanced through this partnership, and in return, data from the AXBT drops are quality controlled, formatted, and uploaded to the Global Telecommunication System (GTS) by TROPIC personnel. The data are then available to the Navy Coupled Ocean Atmosphere Mesoscale Prediction System – Tropical Cyclone (COAMPS-TC) model and 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 FY2014 include:

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 (FY2014)

1. 2014 Field Phase (July-September 2014): The TROPIC team deployed 257 AXBTs from USAF 53rd WRS WC-130J aircraft during 38 flights over the Atlantic and Pacific Oceans: 28 missions into Hurricanes Bertha, Iselle, Julio, and Cristobal and Tropical Storm Dolly, 1 mission into a non-developing TC, and 9 training flights (Fig. 1). The quality-controlled ocean observations were sent in WMO-approved JJVV format to both the Real-Time Data Handling System (RTDHS) at the Naval Oceanographic Office (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). Sensor reliability and data transfer statistics are still being analyzed. The NCOM data are used in the coupled COAMPS-TC, which was not run in real time during the 2014 season, but will be used for data-denial studies of TC forecast accuracy for Hurricanes Iselle and Julio (S. Chen, NRL, personal communication). The coupled COAMPS-TC model is on schedule to be run operationally in 2015. 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).

Fig. 1. The AXBT and ALAMO float deployment locations during July-September 2014.

Multiple steps were taken to address two of the four research objectives during the 2014 field phase:

A. To improve data quality and operational proficiency (Objective 2), emphasis was focused on increasing the reliability of the observing system and increasing the temporal and geographic extent of the ocean observations. Details on each of those endeavors are briefly described below:

1. Gear maintenance was transitioned from a private contractor to Naval Air Systems Command (NAVAIRSYSCOM). 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 through the field program.

2. The WHOI ALAMO air-deployed ocean-profiling float (initially developed with ONR funding) was introduced into operations this year for testing and evaluation. 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 operations were conducted with NOAA (although on a limited scale) to collaborate in the collection of ocean observations over a wider geographical area than either organization could accomplish alone. Planned (E. Uhlhorn, HRD, personal communication) and briefed to the 53rd WRS in the months prior to the season, these collaborative operations may provide a template from which to build future endeavors where NOAA can conduct ocean observations both ahead of and around the storm and TROPIC/53rd WRS can conduct the in-storm ocean observation component. While implemented on a smaller scale than originally planned, data collected from Hurricanes Bertha and Cristobal will be analyzed, and lessons learned will be applied in future years.

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 Hurricanes Iselle and Julio was 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 of the TC forecast.

1. To evaluate the impact on the HYCOM model, the AXBTs deployed during Iselle and Julio were first compared to the value added by other observations collected in the Pacific Ocean 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. This analysis showed greater improvement to the HYCOM 48-h forecast was provided by the AXBTs during Iselle and Julio than by any other sensor type in the Pacific Ocean. Details are included in the results section.

2. Data denial studies are planned during the 2014-2015 Classroom Phase (S. Chen, NRL, personal communication).

2. 2014-2015 Classroom Phase (August 2014-June 2015): Research during the FY14-FY15 TROPIC classroom phase will address each research objective noted previously. Initial tasks include:


B. Conduct ocean/outflow model-based study of Hurricanes Iselle and Julio to addresses Long-Term Goal 1 and Objective 1 listed previously. This will be the primary focus of the FY15 Classroom phase and analysis period. Some of the relevant questions to be addressed include:

1. Is there a correlation between changes in the upper-ocean thermal structure (i.e. cooling) and the magnitude of the TC outflow?
2. Is there a lead/lag relationship within the secondary circulation? i.e. Do changes in the magnitude of the outflow precede or follow changes in updraft magnitude and/or changes in the rate of cooling in the upper ocean?
3. Is there a lead/lag relationship between the primary and secondary circulations?
4. Are coupled models capturing these lead/lag relationships?

C. Quantify and evaluate the impact of AXBT observations on coupled COAMPS-TC forecast accuracy in Hurricane Isaac from 2012. Examine the impact of variations in horizontal, vertical and temporal AXBT observation density on ocean model improvement (in progress with S. Chen and J. Cummings; carryover from 2012-2013 research objectives; see Related Projects section).

D. Quantify and evaluate the impact of AXBT observations on coupled and uncoupled COAMPS-TC forecast accuracy in Hurricanes Iselle and Julio (collaboration with S. Chen and J. Cummings for the coupled COAMPS-TC and J. Doyle, NRL, for the uncoupled COAMPS-TC).
RESULTS

Several achievements from the FY2014 TROPIC Ocean-Outflow program are outlined below.

1. Operational results included both “firsts” and continued successes:
   A. Aircraft-based ocean observations beneath tropical cyclones were conducted during operational 53rd WRS missions over the central Pacific Ocean for the first time.
   B. The ALAMO profiling floats were deployed into a hurricane for the first time (2 floats from a WC-130J aircraft during a mission into Hurricane Iselle on 07 August 2014; both were successful).
   C. Two TROPIC ensigns contributed to the successful search and recovery (SAR) of three civilian mariners in distress during Hurricane Julio. During a routine TC reconnaissance mission north of Hawaii on 10 August 2014, the WC-130J crew was diverted to initiate SAR efforts for the sailing vessel WALKABOUT. As the aircraft descended to 1000 ft, Ensign Cornelius located the small craft from among the 50-ft seas and 80-100-kt winds, which greatly facilitated subsequent rescue efforts.
   D. The AXBT observations beneath TCs were assimilated in near-real-time into the NCODA, operational NCOM, and global HYCOM from operational TC reconnaissance missions for the fourth consecutive year (in Hurricanes Bertha, Iselle, Julio, and Cristobal, and Tropical Storm Dolly).
   E. For the fourth consecutive year, the TROPIC AXBT observations from beneath TCs were uploaded to the GTS, frequently in near-real time.

2. Research results to date include:
   A. The real-time assimilation of AXBT observations collected beneath Hurricane Iselle (Fig. 2, courtesy J. Cummings) reduced the error in the 48-h sea temperature forecast in the HYCOM model (Fig. 3, courtesy J. Cummings) more so than any other sensor in the entire Pacific Ocean. The data were assimilated on 09 August 2014 and the forecasts were valid on 11 August 2014. This result is similar to that found during Hurricane Isaac (2012) in the Gulf of Mexico; however, it extends the value added to a different ocean basin and over a much larger geographical area.
   B. The real-time assimilation of AXBT observations collected during both Hurricanes Iselle and Julio between 06-10 August 2014 (not shown) further strengthened the hypothesis that these AXBTs observations significantly improve the initialization and forecasts of the upper-ocean thermal structure in Navy ocean models (NCOM and HYCOM). These results (also courtesy J. Cummings, NRL) again indicated that the AXBTs had the greatest positive impact of any sensor type on the 48-h sea temperature forecast, this time in the central North Pacific. In the vertical, the greatest impacts were in the layer between 200-300-m depth, which corresponds to the base of the permanent thermocline in the region. The impacts of the Argo and altimeter data were much smaller and were confined to depths within the thermocline. These results imply a strong sensitivity in the model to the strength of the gradient below the thermocline as well as to the depth of the thermocline, both features that AXBTs measure well.
   C. The extension of these error reductions to atmospheric TC track and intensity forecasts is anticipated following the analyses of ocean/outflow relationships during these storms during the classroom phase.
Fig. 2. Data map of AXBT impact to HYCOM 48-h sea temperature forecast during the pre-operational run of HYCOM (v3.1) at the Naval Oceanographic Office. Data were assimilated 09 August 2014, and the forecast was valid on 11 August 2014. Negative values (cool colors) indicate a beneficial impact (reduction of the 48-h forecast error in deg C). A positive value (warm color) indicates assimilation of the AXBT increased forecast error (not applicable). (Courtesy: J. Cummings).

Fig. 3. Impact (at left, in degrees C) of each observation type for the analysis in Fig. 2. Number of each observation type is depicted at right. (Courtesy: J. Cummings).
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, in FY14 and FY15.

This TC Ocean-Outflow research builds upon results from the “Training and Research in Oceanic and atmospheric Processes In tropical Cyclones (TROPIC)” program, funded by ONR for work done by E. Sanabia and PIs B. Barrett and W. Schulz at the U.S. Naval Academy from FY11-FY14.

PUBLICATIONS