

Real-Time Upper-Ocean Temperature Observations from Aircraft during Operational Hurricane Reconnaissance Missions: AXBT Demonstration Project Year One Results

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ABSTRACT

Thousands of aircraft observations of upper-ocean thermal structures have been obtained during hurricane and typhoon research field experiments in recent decades. The results from these experiments suggest a strong correlation between upper-ocean thermal variability and tropical cyclone (TC) intensity change. In response to these results, during the Office of the Federal Coordinator of Meteorology (OFCM) 2011 Interdepartmental Hurricane Conference (IHC), the Working Group for Hurricane and Winter Storms Operations and Research (WG/HWSOR) approved a 3-yr project to demonstrate the usefulness of airborne expendable bathythermographs (AXBTs) in an operational setting. The goal of this project was to initialize and validate coupled TC forecast models and was extended to improve input to statistical intensity forecast models. During the first season of the demonstration project, 109 AXBTs were deployed between 28 July and 28 August 2011. Successes included AXBT deployment from WC-130J aircraft during operational reconnaissance missions tasked by the National Hurricane Center (NHC), real-time onboard and postflight data processing, real-time data transmission to U.S. Navy and NOAA hurricane numerical prediction centers, and near-real-time assimilation of upper-ocean temperature observations into the Naval Research Laboratory Coupled Ocean–Atmosphere Mesoscale Prediction System–Tropical Cyclones (COAMPS-TC) forecast model. Initial results showed 1) increased model accuracy in upper-ocean temperatures, 2) minor improvements in TC track forecasts, and 3) minor improvements in TC intensity forecasts in both coupled dynamical and statistical models [COAMPS-TC and the Statistical Hurricane Intensity Prediction Scheme (SHIPS), respectively].

1. Introduction

a. Project motivation and background

Results from recent field experiments, including The Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign

(T-PARC), Tropical Cyclone Structure 2008 (TCS-08), and the Impact of Typhoons on the Ocean in the Pacific (ITOP), as well as feature-based modeling studies (e.g., Yablonsky and Ginis 2008), have strongly suggested that the inclusion of upper-ocean temperature observations in coupled numerical models can improve tropical cyclone (TC) track and intensity forecast accuracy (e.g., Black et al. 2010; Chen et al. 2011). In light of these results, the Working Group for Hurricane and Winter Storms Operations and Research (WG/HWSOR) approved a multiyear Airborne Expendable Bathythermograph

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(AXBT) Demonstration Project beginning in the 2011 North Atlantic hurricane season (WG/HWSOR 2011). The primary objectives of the first year of the demonstration project were 1) to determine whether AXBT measurements made during operational reconnaissance flights could be routinely assimilated on a near-real-time basis in coupled prediction models and 2) to assess the impact of the AXBT data on modeled upper-ocean temperature and TC track and intensity predictions. Implicit in the first objective is the demonstration that (i) the AXBTs could be launched on a not-to-interfere basis with standard reconnaissance tasks; (ii) the signals could be recorded and processed on board the aircraft in real time; (iii) the data could pass the initial quality control (QC) on the aircraft via despiking and smoothing routines; (iv) the data could be formatted for real-time transmission, including coding in BATHY format for transmission in real time to the world via the Global Telecommunications Service (GTS); and (v) the observations could be sent off the aircraft in real time to modeling centers, including the Naval Research Laboratory via the Naval Oceanographic Office and the National Oceanic and Atmospheric Administration's (NOAA) Environmental Modeling Center. Implicit in the second objective is the demonstration that the data (i) would not only pass the QC but (ii) also improve the representation of the ocean in the initialization, and that (iii) this improvement would impact the coupled model forecasts of TC forecast track and intensity. Through significant interagency coordination and support from the U.S. Air Force (USAF) 53rd Weather Reconnaissance Squadron (WRS), 109 AXBTs were deployed between 28 July and 28 August 2011 on a not-to-interfere basis with normal operations. A total 84 of these AXBT observations passed an initial quality control check at the Naval Oceanographic Office (Fig. 1).

The upper ocean has been periodically sampled in the vicinity of TCs by ships and aircraft for nearly four decades. Originally, AXBTs were deployed from U.S. Navy WC-121 aircraft during Project Stormfury in 1971 and shortly thereafter from National Hurricane Research Project (NHRP) DC-6 and C-130H aircraft (Black 1983). Beginning in 1978, AXBTs were deployed from the new (at the time) WP-3D aircraft and were followed by extensive expendable profiler deployments including AXBTs, airborne expendable conductivity-temperature-depth sensors (AXCTDs), and airborne expendable current profilers (AXCPs) that were deployed before, during, and after Atlantic hurricanes from WP-3D hurricane research flights conducted jointly by the NOAA Aircraft Operations Center (AOC), the NOAA/Hurricane Research Division (HRD), and the University of Miami (e.g., Shay et al. 1989; Shay and Brewster 2010).

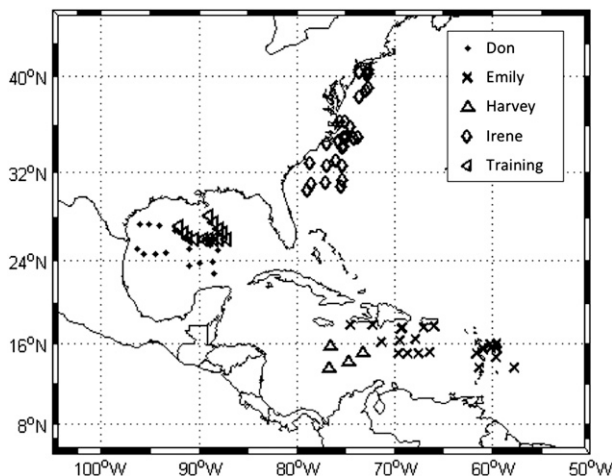


FIG. 1. Locations of 2011 AXBT Demonstration Project observations taken between 28 Jul and 28 Aug 2011 that passed the initial quality-control check for further assimilation into coupled models at the Naval Oceanographic Office.

The 2011 AXBT Demonstration Project was the first to incorporate AXBT drops into routine operational WC-130J flights, which have composed an average of 75% of the total operational TC reconnaissance flights over the past 3 years. The purpose of this paper is 1) to give the background and purpose of the AXBT Demonstration Project; 2) to explain the operational methodology, including drop patterns, processing procedure, data path, and interagency coordination employed during the 2011 North Atlantic hurricane season; 3) to present an initial set of results from the inclusion of AXBT data in both statistical and dynamical numerical prediction models; and 4) to outline plans for a future operational AXBT program.

b. Theoretical basis

The ocean provides the heat energy required for the development and maintenance of TCs (Riehl 1950). The warmer the sea surface is beneath a tropical cyclone, the more heat energy is available to the TC (Emanuel 1986, 1999). The amount of heat energy available to a TC from the upper ocean has, in the past, been parameterized in numerical models using sea surface temperatures (SSTs) in an attempt to quantify the direct effect on TC intensity (e.g., Brand 1971). Within the past decade, however, ocean heat content (OHC) has been shown to be another valuable measure of the energy available to a TC at any given time (e.g., Shay and Brewster 2010). Defined by Leipper and Volgenau (1972) as the integration of the thermal structure of the upper ocean from the 26°C isotherm to the surface, OHC quantifies the energy available to indirectly affect TC intensity (e.g., Brand 1971; Price

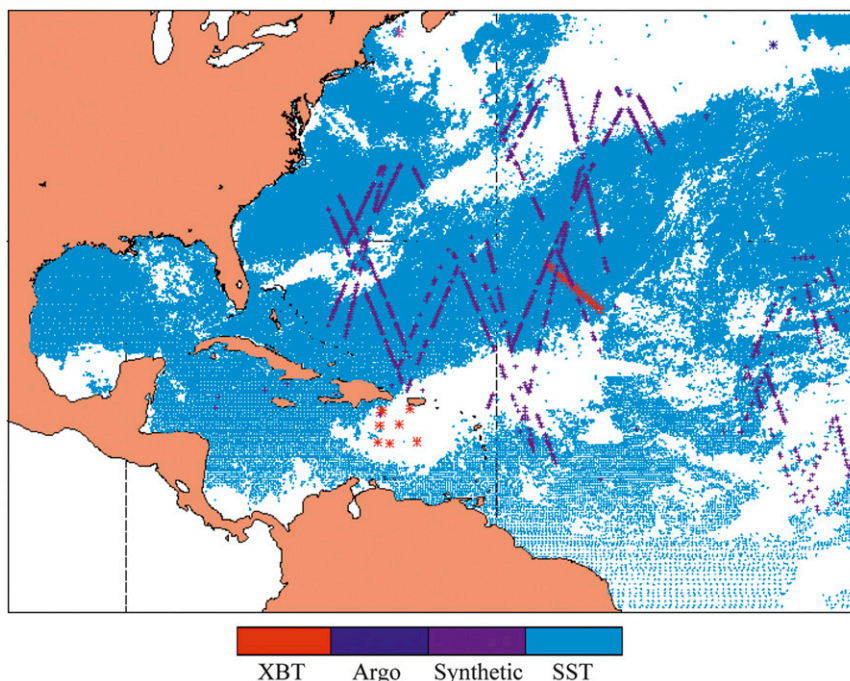


FIG. 2. Locations of ocean temperature observations (colors indicate observation source) assimilated by the NCOA system at 1200 UTC 3 Aug 2011. Grid spacing is 6 km. Eight of the 11 AXBTs deployed beneath TS Emily as part of the 2011 AXBT Demonstration Project filled the data-void region southeast of the Dominican Republic in near-real time.

2009). An example of the importance of OHC and the upper-ocean thermal structure to numerical simulations of a developing TC comes from Hurricane Opal (1995), which underwent rapid, unexpected intensification in the Gulf of Mexico (Shay et al. 2000; Bosart et al. 2000). Opal was found to deepen 14 mb more in model simulations that included a Gulf of Mexico warm-core ring (WCR) than in those that did not (Hong et al. 2000).

One of the challenges confronting the operational TC community is to use observations of the upper ocean to improve TC predictions in coupled numerical models, a feat complicated by the scarcity of in situ temperature measurements in the data-sparse ocean. While SST can be derived from satellite measurements and upper-ocean thermal structure and OHC can be estimated using satellite-derived sea surface height anomalies (SSHAs) from satellites carrying radar altimeters (Goni et al. 2009), neither of these remote measurements is available in regions of heavy rain (Tournadre and Morland 1997; Jayne et al. 2003; Guan and Kawamura 2003; Levitus et al. 2009; Nagamani et al. 2012). For example, during Tropical Storm (TS) Emily, the only near-real-time measurements available in the vicinity of the TC for the 1200 UTC 3 August 2011 ocean model initialization were those made during this demonstration project (Fig. 2).

Current TC intensity prediction methods include both statistical and dynamical models. On the statistical modeling side, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) forecast model (DeMaria and Kaplan 1994; DeMaria and Kaplan 1999) uses parameters taken from climatology, persistence, the local atmospheric environment, sea surface temperature, and brightness temperatures from operational geostationary satellites to predict TC intensity out to 120 h. Since 2002, SHIPS has also included values of OHC, taken from daily analyses, as an intensity predictor. In 2002–03, the SHIPS intensity forecasts improved by up to 3.5% through 72 h as a result of including OHC as a predictor (DeMaria et al. 2005). Calculations of OHC from measurements taken during the 2011 AXBT Demonstration Project were input into the SHIPS model, and the methodology and results from including the observations are presented in the next sections.

On the dynamical modeling side, coupled ocean–atmosphere models are able to predict not only the ocean response to hurricane passage (e.g., Price 1981; Sanford et al. 1987; Shay et al. 1992; Price et al. 1994; D’Asaro 2003) but also the atmospheric response to the ocean structure below (Shay et al. 2000; Hong et al. 2000; Lin et al. 2005; Walker et al. 2005; Wu et al. 2007; Shay 2009; Chen et al. 2010). Numerical modeling studies have shown

that high values of upper-ocean heat content are associated with intensifying TCs (Hong et al. 2000; Emanuel et al. 2004; Lin et al. 2005). Similar studies have shown that TCs passing over regions of low values of heat content correspondingly weaken (e.g., Walker et al. 2005; Sun et al. 2006; Shay 2009). These results, while important, were primarily obtained using coupled models running in research mode, without the constraints of real-time and operational deadlines. As coupled numerical models are transitioned from primarily a research mode to an operational mode, initialization will require real-time measurements of the ocean to produce consistent, physically realistic intensity predictions. The value of real-time observations to TC forecasts has been well documented for the atmospheric component, with dropsonde observations contributing to improvements in TC forecasts in both the Atlantic (Aberson and Franklin 1999; Aberson and Etherton 2006; Aberson 2010) and the western Pacific (Wu et al. 2009; Jung et al. 2012) basins. Despite their importance, however, upper-ocean observations in the vicinity of a TC remain scarce (Fig. 2). Furthermore, oceanic mesoscale features—including the Loop Current, warm- and cold-core eddies in the Gulf of Mexico, and rings along the Gulf Stream and the Kuroshio—cannot be captured accurately by climatology-based analyses (Yablonsky and Ginis 2008). One way to mitigate the lack of remotely sensed data in the near-TC environment is to use in situ AXBT measurements. The benefit of in situ measurements, particularly AXBT observations, was confirmed during the recent T-PARC, TCS-08, and ITOP experiments, which found that changes in intensity of existing TCs depended on subsurface eddy conditions (Black 2012). Results from these field programs provide support for sampling the upper ocean as part of routine TC observations. Measurements of upper-ocean temperature made during the 2011 AXBT Demonstration Project were successfully input into the global Hybrid Coordinate Ocean Model (HYCOM; Bleck 2002) and the Navy Coastal Ocean Model (NCOM; Barron et al. 2006) forecasts for use in two coupled dynamical prediction models: the Hurricane Weather Research and Forecasting (HWRF) model (Rappaport et al. 2009; Gopalakrishnan et al. 2010) and the Coupled Ocean–Atmosphere Mesoscale Prediction System–Tropical Cyclone (COAMPS-TC; see the appendix). The potential value of these AXBT observations also extends to a range of other dynamical prediction models, including the Geophysical Fluid Dynamics Laboratory model (Bender et al. 2007) and the Advanced Hurricane WRF (AHW; Cavallo et al. 2013). The methodology and results from assimilating the AXBT data into these model analyses are presented in the next sections.

A detailed description of the logistics pathway needed to ensure operational, near-real-time availability of quality-controlled AXBT data to the Naval Oceanographic Office (NAVO) and the National Centers for Environmental Prediction's (NCEP) Environmental Modeling Center (EMC) is provided in section 2. Results from the 2011 AXBT Demonstration Project, which show small but positive impacts of including AXBT data on intensity predictions from both the coupled COAMPS-TC model and the statistical SHIPS model, will be discussed in section 3. Concluding remarks and suggestions for a future operational AXBT program are presented in section 4.

2. Methodology

Both the operational and computational methodologies described in this section evolved throughout the 2011 AXBT Demonstration Project. The end state for the season is described below.

a. Equipment technical configuration

More than 100 Hermes and Sparton AXBTs (military designation AN/SSQ-36) were utilized for the 2011 AXBT Demonstration Project from stocks at the Naval Research Laboratory (NRL) in Monterey, California. Released manually from a tube in the rear of the pressurized interior of the WC-130J aircraft, the AXBT descends beneath a parachute to the ocean. Upon impact with the ocean surface, a saltwater battery is activated, which turns on the VHF transmitter, activates a wire squib, and, in turn, releases the temperature probe. Signal modulation begins the transmission of a frequency that is proportional to the temperature as the probe descends to approximately 800-m depth. Temperature data are transmitted from the probe to a surface float via a copper wire and from the float to the aircraft via one of three very-high frequency (VHF) radio frequency channels chosen by the project team and programmed into the AXBT by the loadmaster just before deployment from the aircraft. The equipment and system configuration used on board the aircraft during the 2011 AXBT Demonstration Project were identical to those deployed for the T-PARC, TCS-08, and ITOP field programs in 2008 and 2010. Also, a nonmobile system using the same components and similar configuration was recently installed on board the NOAA WP-3D for use by the HRD and University of Miami investigators (Shay et al. 2012), and this system was used during the Dynamics of the Madden–Julian Oscillation (DYNAMO) field program in late 2011.

For each reconnaissance mission in which AXBTs were to be deployed, the NRL Mobile Ocean Observing

System (MOOS) was brought aboard the WC-130J and connected to the airframe in two places. First, a power cable connected the aircraft power to the MOOS Nova Electric power converter in which the 400-cycle aircraft power was converted to a 60-cycle, 120-V signal to power the components of the observing system. Second, a communication wire connected the aircraft VHF2 antenna to the MOOS input, a Sippican MK10 receiver within one of two MOOS portable cases. The demodulated audio output from the MK10 was then split with one branch connected to a Marantz PMD560 audio recorder to record the raw audio signal and the other branch connected to the Sippican MK21 data acquisition system for real-time processing. The digital output from the MK21 processor and system computer was then displayed on the MOOS system video monitor for visual inspection in real time by the equipment operator.

b. Data path

After transmission of AXBT data from the ocean to the aircraft was complete, the digital data were transferred to the MOOS system laptop and processed by the project team on board the aircraft using the Johns Hopkins University Applied Physics Laboratory (JHU/APL) System for At-Sea Environmental Analysis (SASEA) program. Raw temperature data were first despiked to remove data dropouts and were then smoothed. Significant-level data points denoting changes in the profile slope were detected and encoded in JJVV (BATHY) messages, similar to dropsonde TEMP DROP messages (however, only significant levels rather than both mandatory and significant levels are reported in the JJVV format), for transmission off the aircraft following the format defined in Annex VI of the Intergovernmental Oceanographic Commission and World Meteorological Organization Guide to Operational Procedures for the collection and exchange of JCOMM Oceanographic Data (UNESCO 1999).

The JJVV messages were passed to the aerial reconnaissance weather officer (ARWO) via an external hard drive and transmitted as an ADMIN message via SATCOM from the aircraft to either the ground station at Keesler Air Force Base (AFB), Mississippi, or the portable ground station at the forward deployment base on St Croix, U.S. Virgin Islands. The message was received by project personnel on the ground, and quality control of AXBT data was conducted in a manner patterned after that provided by the Chief, Aerial Reconnaissance Coordination All Hurricanes (CARCAH) for the quality control of atmospheric data. Similar to the treatment of atmospheric data, the degree of quality control of the ocean data was suitable for operational use and an operational timeline.

Following quality control, the JJVV-formatted AXBT observations were sent via e-mail to the NAVO Real-Time Data Handling System (RTDHS). The RTDHS receives more than 60 000 observations each day from XBTs, CTD sensors, ship observations, drifting buoys, fixed stations, profiling floats, and ocean gliders, and these data are pushed to multiple databases and numerical models at 2-h intervals (J. Illich, NAVO, 2012, personal communication). One challenge uncovered during the course of the 2011 project was an inadvertent delay in the submission of AXBT observations e-mailed to the RTDHS during the 2200–0000 UTC time period. This problem was detected in mid-August, and for the remainder of the 2011 season, any data transmitted between 2200 and 0000 UTC had to be input manually into the RTDHS by NAVO personnel (J. Illich, NAVO, 2011, personal communication). Most often, the time for the AXBT data to proceed along the pathway from deployment from the W-C130J to arrival at the RTDHS ranged between 1 and 10 h.

From the RTDHS, the AXBT observations from the 2011 Demonstration Project were input, along with all other ocean observations, into the Navy Coupled Ocean Data Assimilation (NCODA; Cummings and Smedstad 2013) system, the data assimilation system for NCOM in COAMPS and global HYCOM. The NCODA assimilation system is tightly coupled to an ocean data quality system, where the data received from the RTDHS undergo further quality-control procedures as described in Cummings (2011).

An additional pathway was also developed and automated for these AXBT data from the RTDHS to the National Data Buoy Center (NDBC). The NDBC developed and automated a procedure by which the AXBT data were uploaded to the GTS to ensure both receipt at NCEP/EMC for inclusion in the HWRF model and unrestricted, worldwide access (Fig. 3).

c. AXBT data in the COAMPS-TC model

Of the 109 AXBTs deployed during the 2011 demonstration project, data from 84 passed operator QC and were successfully included in the RTDHS at NAVO (Table 1) for further use by NCOM, HYCOM, and COAMPS-TC and transmission to NDBC for upload to the GTS and further use by HWRF (Fig. 3). Data from the other 25 were not included because of equipment malfunction, signal processing errors, or quality control concerns. Of the 84 AXBTs that were successfully included in the RTDHS, data from 75 passed NCODA QC and were used in the real-time coupled COAMPS-TC model forecasts for four landfalling TCs (Tropical Storms Don, Emily, and Harvey, as well as Hurricane Irene), two training flights, and one transit flight (see the

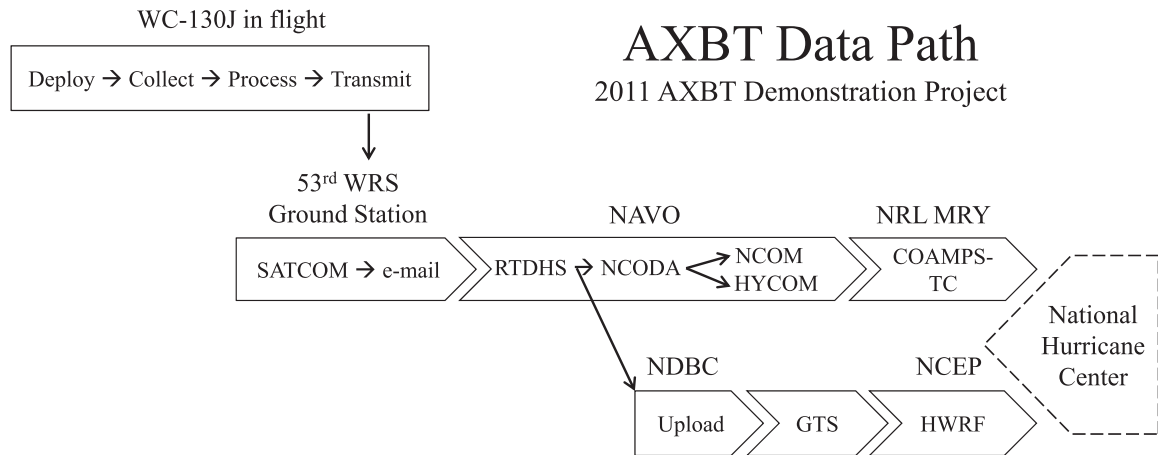


FIG. 3. Data path for 2011 AXBT Demonstration Project observations from the WC-130J aircraft to coupled numerical models. Solid lines and arrows indicate capabilities; dashed lines indicate that NHC is the intended beneficiary of the improved model output.

appendix for COAMPS-TC model description). Data from the remaining nine AXBTs were rejected by the NCODA preprocessing program because of inconsistencies in vertical sampling, for example, when the AXBTs did not sample deep enough due to deployment either in shallow water or a had limited number of sampling levels. These rejected AXBTs were, however, able to be included in hindcast experiments by relaxing the profile selection criteria for the maximum depth sampled in NCODA.

To assess the impact of AXBT temperature observations on COAMPS-TC track and intensity forecasts, multiple hindcast experiments were carried out for Tropical Storms Don and Emily and for Hurricane Irene. The two 5-day forecast experiments that were carried out for Tropical Storm Emily are examined in section 3. The control experiment included data from 10 AXBTs (8 assimilated in real time and 2 included only in the

hindcast), while the data-denial experiment excluded the AXBT observations. Both model runs started at 1200 UTC 3 August 2011 when the center of Emily was about 200km southeast of the Dominican Republic. Similar experiments were carried out for Hurricane Irene as the TC neared Cape Hatteras on 27 August 2011. The control experiment included data from 17 AXBTs (13 assimilated in real time and 4 included only in the hindcast), while the data-denial experiment excluded the AXBT observations. Both model runs began at 1200 UTC 27 August 2011, and were a warm start from the 0000 UTC 27 August 2011 forecast. An additional data-denial study was also conducted for a training flight on 11 August 2011 over the Gulf of Mexico, and this case is also examined in section 3. Data from 11 AXBTs deployed during that flight were included in the control experiment (10 that were assimilated in real time and 1 included only in the hindcast), while the

TABLE 1. Summary of AXBT deployments during the 2011 AXBT Demonstration Project.

2011 AXBT flight No.	TC name	Takeoff time (UTC)	Takeoff date (2011)	Duration (h)	Mission type	No. of AXBTs deployed	No. of AXBTs in RTDHS	No. of AXBTs in COAMPS-TC in near-real time	
1	Don	1000	28 Jul	8.8	Fix	10	7	7	
2	Don	1000	29 Jul	8.8	Fix	11	8	8	
3	Pre-Emily	1550	1 Aug	9.0	Invest	11	10	10	
4	Emily	0400	3 Aug	8.5	Fix	11	10	8	
5	Emily	1550	4 Aug	5.5	Fix	3	3	3	
6	Training 1	1437	10 Aug	2.5	Training	3	3	3	
7	Training 2	1454	11 Aug	3.4	Training	13	11	10	
8	Pre-Harvey	1520	17 Aug	6.2	Invest	4	4	4	
9	Transit	1955	19 Aug	5.1	Transit	3	0	0	
10	Irene	1820	26 Aug	10.7	Fix	14	10	5	
11	Irene	1200	27 Aug	11.0	Fix	16	10	10	
12	Irene	0630	28 Aug	9.5	Fix	10	8	7	
Total						AXBTs:	109	84	75

data-denial experiment excluded the AXBT observations. Since there was no TC present during the training flight, the focus of this analysis was solely on the impact of the AXBT observations in assessing the upper-ocean thermal structure.

The COAMPS-TC setup for the 2011 AXBT Demonstration Project used a triple-nest configuration with horizontal resolutions of 45, 15, and 5 km and a 60-level, terrain-following, stretched vertical coordinate system that had 20 levels below 2 km. The coarse mesh covered an area from 9.1°S to 51.8°N and from 17.5° to 102°W. The atmospheric boundary conditions were provided by the Global Forecast System (GFS). In addition to the atmospheric physics improvements described in Doyle et al. (2012), a new generalized microphysics scheme (J. Schmidt, NRL, 2012, personal communication) and the Eta Model Kain–Fritsch scheme were used. While NCOM has a nesting capability, the nest feature was not enabled. Instead, a single domain was used that spanned from 1.5° to 44.7°N and from 30.4° to 99.6°W with a 6-km horizontal resolution. The vertical sigma– Z coordinate system consisted of 50 vertical levels with 29 sigma levels and 24 Z levels in the upper 100 m of the ocean. For the atmospheric area outside the NCOM domain, the sea surface temperature (SST) was updated at the coupled time step using the global NCOM (gNCOM) SST. The coupling interval was every 10 min. The lateral boundary conditions for NCOM were also provided by gNCOM. The COAMPS-TC system was run with a 12-h data assimilation cycle for both the atmosphere and ocean.

d. Use of AXBT data in SHIPS

During each mission, OHC was calculated on board the aircraft using the method of Leipper and Volgenau (1972):

$$\text{OHC}(x, y) = \rho c_p \int_{z_{26}}^0 [T_i(x, y, z) - 26] dz,$$

where T_i is the three-dimensional temperature (°C), ρ is the density (kg m^{-3}) calculated using the United Nations Educational, Scientific and Cultural Organization (UNESCO) 1980 International Equation of State for Seawater (Millero and Poisson 1981) with salinity held constant at 35 psu, c_p is the specific heat of water at constant pressure ($4200 \text{ J kg}^{-1} \text{ K}^{-1}$), and z_{26} is the depth (m) of the 26°C isotherm (Price 2009). While in flight, these in situ OHC values were compared to the NRL Intra-Americas Sea Ocean Nowcast/Forecast System (IASNFS; Ko et al. 2003, 2008) OHC analyses (Fig. 4a) to enhance situational awareness and make slight adjustments to release points along the flight track.

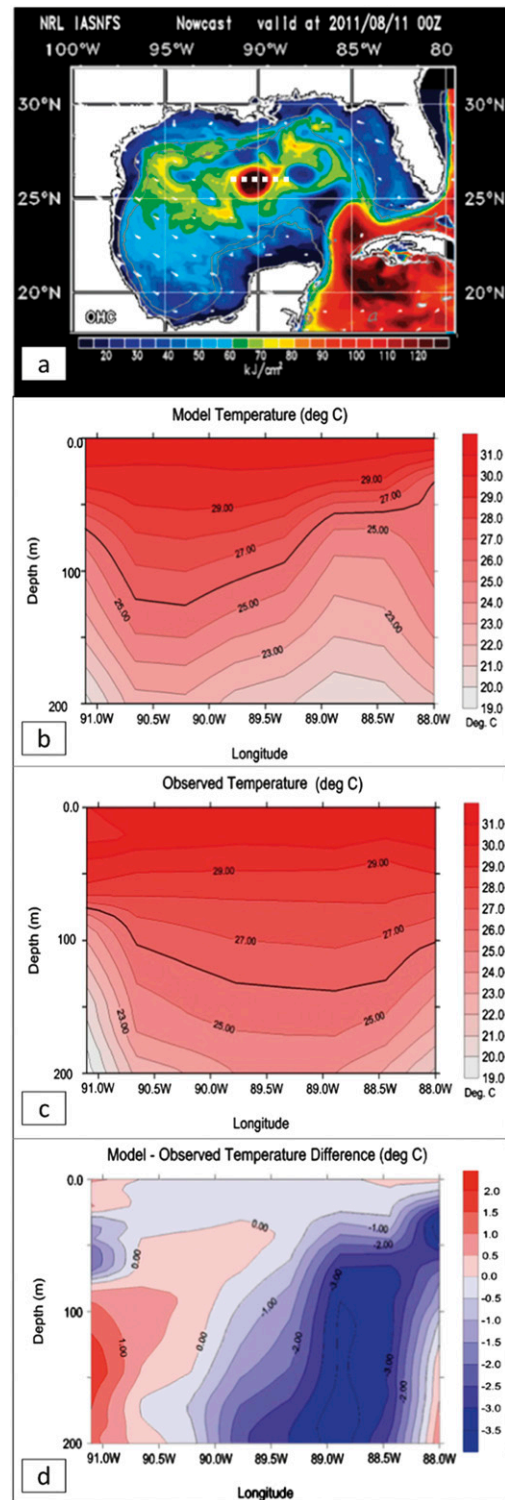


FIG. 4. (a) Ocean heat content (kJ cm^{-2}) from the IASNFS nowcast at 0000 UTC 11 Aug 2011 (courtesy D. Ko). The dashed white line indicates position of cross sections in (b)–(d). Ocean temperature from 0- to 200-m depths along 26°N between 88.0° and 91.1°W for the (b) IASNFS model, (c) AXBT observations, and (d) temperature difference (IASNFS model minus AXBT observed).

To assess the impact of AXBT temperature observations on SHIPS intensity forecasts for Tropical Storm Emily, multiple hindcast experiments were carried out. The OHC values used as predictors in the SHIPS model are taken from a satellite-enhanced climatology database (DeMaria et al. 2005). Using OHC values from this database at points along the forecast TC track, the operational SHIPS model reports an OHC intensity adjustment (IA), using the following formula (M. DeMaria, NOAA/NESDIS, 2012, personal communication):

$$IA = \frac{(O_p - \bar{O}_p)}{\sigma_{O_p}} (c \times \sigma_d),$$

where IA is the adjustment (kt) to the TC intensity arising from the inclusion of OHC as a predictor, O_p is the measured OHC value, \bar{O}_p the OHC predictor mean, σ_{O_p} the OHC predictor standard deviation, c the OHC coefficient, and σ_d the standard deviation of the intensity change. Since AXBTs were not normally deployed along the forecast track during the 2011 demonstration project, a direct sensitivity study replacing the SHIPS OHC with the AXBT OHC at the analysis and forecast positions was not possible. It was possible, however, to evaluate the accuracy of the SHIPS OHC database at the AXBT deployment locations and to identify the associated errors in forecast IA that would result at each point. To do this, first, both SHIPS (model) and in situ (observed) IA values were calculated using database and AXBT OHC values for O_p . Then, a “forecast intensity discrepancy” was identified at each time step by subtracting the SHIPS IA value from the AXBT IA value through the 36-h forecast. Examining the forecast intensity discrepancies that resulted from differences in SHIPS and AXBT OHC values at multiple AXBT deployment locations gave a range of uncertainties at each forecast time. An “intensity uncertainty range” was then determined from the maximum and minimum differences in IA at each forecast time or until the TC made landfall. Thus, the intensity uncertainty range quantified the potential impact of AXBT data on SHIPS performance. Finally, even though Tropical Storm Emily made landfall 30 h after the mission, the potential impact on TC intensity was analyzed only for the SHIPS model rather than switching to the version of SHIPS with the inland decay component (Decay-SHIPS) upon landfall. The impact at each time step was small and compared favorably in magnitude to that observed within the COAMPS-TC studies.

e. Flight and drop geometry

Unlike research field programs, where flight patterns are routinely designed to optimize observations and

data collection, the USAF WC-130J flight patterns during hurricane reconnaissance are determined by the mission of each flight. During the 2011 AXBT Demonstration Project, reconnaissance missions fell into two categories: invest flights and fix flights. Invest missions are typically flown near 1000 ft to search for a closed circulation pattern near the ocean surface. During these low-level missions, flight-level and surface winds are the primary observation tools used to assess the circulation, and dropsondes are not often deployed. There were AXBT operations during two invest flights in 2011 (in pre-TS Emily and pre-TS Harvey). In these cases, AXBTs were deployed from 1000 ft at time increments that would ensure relatively even horizontal spacing and placement near boundaries of ocean features as indicated by the IASNFS OHC analysis when feasible.

Once a low-level center is identified, systems are either numbered or named (depending on intensity), and reconnaissance flights shift to fix missions. The principal goals of a fix mission are to locate the geographic center of the TC circulation and to observe the central pressure and a maximum surface wind. The National Hurricane Operations Plan (NHOP) requires these centers to be fixed at prescribed intervals and times: every 6 h based on synoptic times and at 3-h increments when the TC approaches land (OFCM 2011). The flight level for fix flights can range between 1000 and 10 000 ft and the pattern (known as an “alpha pattern”) resembles the shape of the Greek letter alpha, with radial legs typically extending 105 n mi from the TC center on intercardinal headings (OFCM 2011), and cross legs of nearly 150 n mi connecting the outermost points. During fix flights, dropsondes are deployed at the circulation center and may also be released in the eyewall during each pass through the eye of the storm. There were AXBTs deployed during seven fix flights in 2011, with release points at the outermost point of each radial leg, the midpoints of each cross leg, and occasionally at other locations (e.g., at previous AXBT drop locations, or while inbound on a radial leg), as feasible.

The manning, structure, and equipment configuration on board the WC-130J aircraft resulted in two constraints to AXBT operations. First, one loadmaster is typically assigned to each hurricane reconnaissance mission. In flight, one of the loadmaster’s primary tasks is to deploy atmospheric dropsondes and to process the incoming data, both of which are done from a work station toward the front of the aircraft, adjacent to the ARWO station. During the 2011 AXBT flights, the loadmaster deployed both the dropsondes as well as the AXBTs (which were released near the rear of the aircraft). In the current WC-130J configuration, there is no remote AXBT launch capability, so the loadmaster must physically move

to the rear of the aircraft to launch each AXBT. Therefore, concurrent dropsonde and AXBT launches usually were not feasible, and AXBT deployments were not conducted during dropsonde-intensive sections of the flight. When possible, the 53rd WRS did support the AXBT missions with an extra loadmaster, which eased this constraint; however, particularly during forward-deployed operations, a second loadmaster was not always available. If AXBT launches are adopted as an operational mission, augmenting the crew with a second loadmaster is recommended to facilitate the concurrent deployment and processing of both atmospheric and ocean profilers.

The second constraint resulted from the current AXBT launch tube configuration. While AXBTs frequently and successfully were deployed from altitudes in excess of 30 000 ft during T-PARC and TCS-08 (Black 2009), increased use of the launch tubes caused wear that degraded launcher reliability at high altitudes and precluded AXBT deployment from altitudes above 10 000 ft during the 2011 AXBT Demonstration Project. Since transit to and from the TC region is typically conducted at high altitudes (often near 24 000 ft) for maximum fuel economy, this launch-tube constraint limited the AXBT deployment area to locations where the aircraft was near or below 10 000 ft, usually within a 100-n mi radius of the TC center. Since cloud cover can extend several hundred nautical miles from the TC center and prevent measurement of SST by remote sensors, there remains a data gap between the outer reaches of the radial flight pattern and the satellite coverage area. Flight plans to facilitate AXBT deployment in this data-sparse region are being investigated for future seasons. Also, a new AXBT launch tube has been developed by the 53rd WRS and is in the process of being approved by the Air Force Reserve Command.

f. 2011 summary

During the 28 July–28 August 2011 test period, 109 AXBTs were deployed during 12 missions into four TCs (Hurricane Irene, Tropical Storms Don and Emily, and pre-TS Harvey), two training flights, and one transit flight (Table 1). Of the 109 AXBTs, 84 were included in the RTDHS at NAVO (Table 1, Figs. 1 and 3) and were available for inclusion in the global NCOM, HYCOM, COAMPS-TC, and HWRF. The remaining 25 either failed the RTDHS quality control check or were not forwarded off the aircraft to the RTDHS due to equipment malfunction, signal processing errors, or quality control concerns. This initial success rate of 77% compared reasonably well to the U.S. Navy standard success rate of 87% for AXBTs within their prescribed 5-yr shelf lives. Of the 84 that passed the RTDHS quality control

check, 75 (89%) were included in real-time NCOM and HYCOM forecasts, and the remaining 9 observations were assimilated during COAMPS-TC hindcast experiments.

3. Results

Data collected during the 2011 AXBT Demonstration Project provided the basis for several case studies, three of which are presented here. The first is an analysis of data collected during a squadron training flight on 11 August 2011 over the Gulf of Mexico. While there was no TC present, an examination of upper-ocean temperatures in NCOM, HYCOM, and IASNFS revealed the variability in upper-ocean thermal structure and the adjustments made to both the HYCOM and NCOM forecasts by including the AXBT data in the initialization. The second and third are analyses of data collected during operational flights into Tropical Storm Emily in the eastern Caribbean Sea on 3 August 2011 and Hurricane Irene along the U.S. east coast on 26–27 August 2011. In both TC cases, the inclusion of AXBT data not only improved the representation of the upper-ocean thermal structure, but also resulted in small improvements in track and intensity forecasts in the COAMPS-TC model (for Emily) and small improvements in intensity forecasts (for Irene).

a. Gulf of Mexico training flight

The Gulf of Mexico Loop Current was sampled by 13 AXBTs deployed during a loadmaster training flight on 11 August 2011, including 9 AXBTs that were deployed along an east–west line along 26°N at near 0.5°-longitude increments between 91.1° and 87.2°W. This region was selected for the training flight because it contained the northern portion of the Loop Current and featured a pronounced mesoscale WCR flanked to its east by a smaller mesoscale cold-core ring (CCR) (illustrated in Fig. 4a as rings of high and low OHC, respectively).

The AXBT temperature measurements along 26°N were compared to the IASNFS model values. A horizontal cross section of temperatures along the flight path from the surface to 200-m depth in the model analysis indicated the 26°C isotherm was located at 65-m depth at 91°W, 120-m depth at 90.25°W, and between 40 and 50 m deep from 89.0° to 88.0°W (Fig. 4b). Interpolated AXBT data, however, revealed that the 26°C isotherm was actually located deeper than indicated by the IASNFS along much of the flight path, averaging 125 m deep between 89.5° and 88°W (Fig. 4c). Temperature differences between the IASNFS model and the AXBT observations (Fig. 4d) indicated that the model analysis was between +2° and –3°C different from the observations. The model analysis had a warm bias between

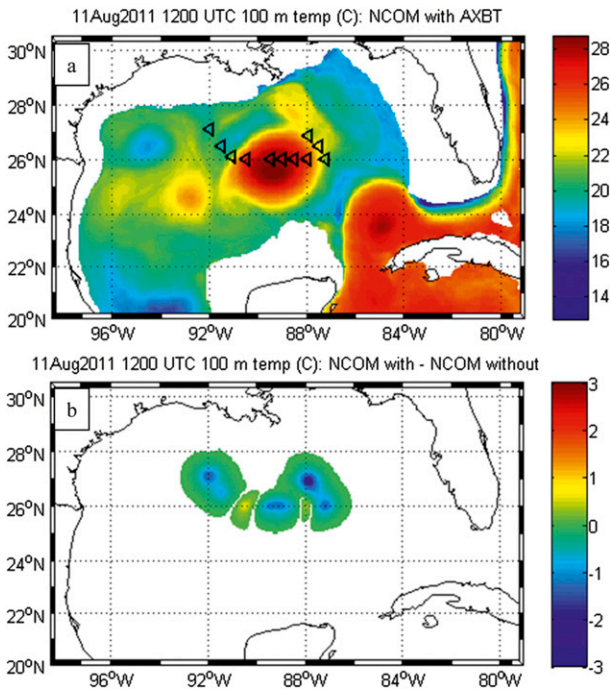


FIG. 5. (a) Ocean temperatures ($^{\circ}\text{C}$) at 100-m depth from the 1200 UTC 11 Aug 2011 NCOM analysis (including AXBT data). Black triangles indicate AXBT deployment locations. (b) Difference ($^{\circ}\text{C}$) in NCOM ocean temperature at 100 m after assimilating AXBT data (analysis with AXBT data minus analysis without AXBT data).

100- and 200-m depths at 91.0°W and a cold bias from 20- to 200-m depths between 90.0° and 88.0°W . This suggests a position error of the eddy by the model and a general underestimation of its intensity.

While the AXBT data were not assimilated into the IASNFS model, 10 of the 13 AXBT temperature profiles were assimilated into the 1200 UTC 11 August 2011 NCOM ocean model in real time, and 1 of the 13 profiles was included only in the hindcast study. A data-denial rerun of the COAMPS-TC model revealed the impact of the AXBT data on the upper-ocean thermal structure. At 100-m depth, the upper ocean was characterized by a pronounced WCR south of Louisiana (Fig. 5a) that was flanked on either side by cooler regions. The AXBTs were deployed across the center of this WCR during the training flight. Inclusion of the AXBT data resulted in the reduction of the temperature in the center and at the northeast and northwest edges of the WCR, cooling these areas by up to 1.5°C . On the southwest edge of the WCR, however, temperatures increased, warming by up to 0.5°C (Fig. 5b). These differences indicate that in the original NCOM analysis, the WCR core was too warm and its geographic extent was too large and displaced to the east at 100-m depth. This

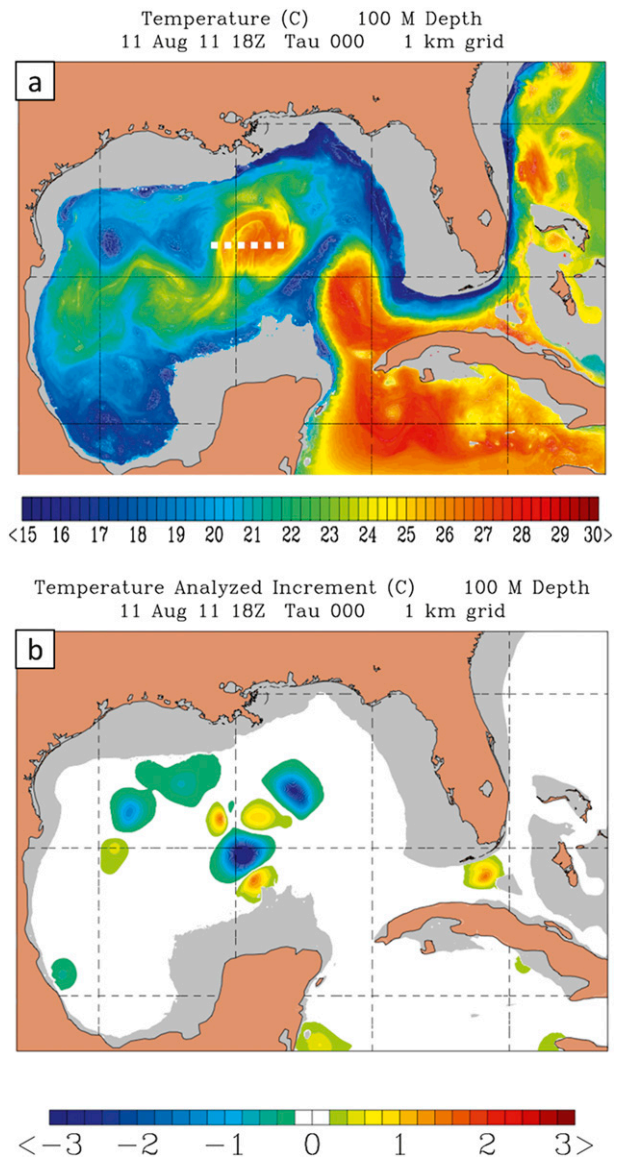


FIG. 6. (a) Ocean temperatures ($^{\circ}\text{C}$) at 100-m depth from the 1800 UTC 11 Aug 2011 HYCOM analysis (including AXBT data). White dashed line highlights the AXBT deployment locations along 26°N . (b) Increment ($^{\circ}\text{C}$) in HYCOM ocean temperature at 100 m, which is the AXBT observation temperature minus the model background. The pattern suggests the AXBT data both strengthened the magnitude (along 26°N) and reduced the NE-SW extent of the WCR in the model.

result was opposite of the IASNFS (Fig. 4), where the AXBT data showed the WCR representation to be too cold on the eastern edge and too large on the western edge in the IASNFS analysis.

In addition to NCOM, 11 AXBT temperature profiles were assimilated into a 24-h HYCOM forecast valid at 1800 UTC 11 August 2011. The resulting analysis field is shown in Fig. 6a. The model increment (defined as the

observation minus the model background field) indicated that without the AXBT data, the 100-m temperature at the center of the mesoscale WCR was up to 1.5°C too cold, while the peripheral regions to the northeast and south were nearly 2.0°C too warm (Fig. 6b). The effect of the AXBTs (at 100-m depth) was to shrink the NE–SW horizontal scale and warm the core of the WCR. These two corrections—adjustments to the location and intensity of the WCR—were the same two types of corrections made in the NCOM model. The results in Figs. 4–6 reveal notable differences in upper-ocean thermal structure between three ocean models (IASFNS, NCOM, and HYCOM) and AXBT observations. In particular, the AXBT data highlighted the spread between the representations of the Gulf of Mexico WCR in the three models, ranging from +2.0° to –1.5°C from the surface down to 100-m depth. They also documented the improvement in the upper-ocean thermal structure representation in two different ocean models (NCOM and HYCOM) that came directly from the inclusion of the AXBT data in the analyses.

b. Tropical Storm Emily

In addition to the training flight on 11 August 2011, AXBT measurements were also made and assimilated in real time into NCOM during a fix flight into Tropical Storm Emily on 3 August 2011. At 1200 UTC 3 August 2011, Emily was located south of Puerto Rico with a central pressure of 1003 hPa and maximum sustained winds of 45 kt (Kimberlain and Cangialosi 2012). Visible and microwave satellite imagery confirmed that Emily was disorganized, consisting of a large cloud mass south and southwest of Puerto Rico (Fig. 7a) and a small region of cold cloud tops near 15°N, 68°W (Fig. 7b). The fix mission was flown in an alpha pattern, and 11 AXBTs were deployed between 0429 and 1120 UTC at the corners of the pattern and along each cross leg (Fig. 7c). Given the flight pattern and Emily's northwest motion (Fig. 7d), some AXBTs were deployed 150 km ahead of, and others 150 km behind, the developing TC. Data from one AXBT failed the QC check on board the aircraft; however, data from eight AXBTs were successfully sent from the aircraft to the HF ground station at the St Croix 53rd WRS and forwarded to the RTDHS. Data from the remaining two AXBTs were processed as the aircraft returned to St. Croix and were submitted to the RTDHS after landing. Data from 8 of the 10 temperature profiles passed both the RTDHS and NCODA quality control filters and were used in real time for the 1200 UTC COAMPS-TC model cycle, and the remaining two were included only in the hindcast study.

The 1200 UTC 3 August 2011 COAMPS-TC ocean model with AXBTs indicated that the upper ocean in

the vicinity of Emily was characterized by several relatively warm and cool regions. The SSTs varied between 27° and 31°C, with the warmest waters generally located south and east of Emily as well as between Cuba and Jamaica and west of Haiti (Fig. 7c). At 100-m depth, the warmest waters (26°–27°C) were located around and south-southeast of Hispaniola, between 14° and 18°N and 66° and 70°W (Fig. 7e). A region of cooler water (23.5°–24.5°C) at 100-m depth was located immediately south of Puerto Rico (Fig. 7c). Ocean heat content showed similar variability, with three areas of OHC above 100 kJ cm⁻² in the same locations as the warm 100-m temperatures, and the remainder of the Caribbean Sea generally less than 80 kJ cm⁻² (Fig. 7g). A data-denial sensitivity run of COAMPS-TC without the AXBT data showed that the inclusion of AXBT data resulted in changes in SSTs between –0.15° and +0.3°C (Fig. 7d). At 100-m depth, the AXBT observations resulted in a 0.2°–0.8°C temperature increase south of Puerto Rico (Fig. 7f). Additionally, COAMPS-TC with the AXBT data initialized the 100-m ocean temperatures 0.3°C cooler near 15°N, 66.5°W (Fig. 7f). A similar pattern was seen in OHC, where values were 5–15 kJ cm⁻² greater ahead of Emily, and 5 kJ cm⁻² less behind Emily (Fig. 7h) in the COAMPS-TC analysis with the AXBT data. The shape and “spotty” structure of the results of the data-denial experiment is a function of the radius of influence used by COAMPS-TC when assimilating the AXBT observations.

These changes can be seen in both the depth of the 26°C isotherm (Fig. 8a) and the OHC (Fig. 8b) at the AXBT deployment locations. Without including AXBT data, the depth of the 26°C isotherm in the NCOM model used in COAMPS-TC was too shallow for 9 of 10 AXBT profiles (Fig. 8a), with an average underprediction of –16.8 m and a range of –46.3 to 15.7 m (negative values indicate that the 26°C isotherm was located closer to the surface in the NCOM model than in the AXBT observation). When AXBT data were included in the NCOM, however, the 26°C isotherm moved deeper, closer to observed values, with an average difference between the NCOM model and AXBT observations of –10.4 m and range of –28.9 to 8.9 m. Ocean heat content in the NCOM model was also lower than AXBT observations for 9 of 10 AXBT profiles (Fig. 8b), with an average difference of –21.2 kJ cm⁻² and a range of –34.8 to 9.8 kJ cm⁻² (negative values indicate the NCOM model OHC was lower than the AXBT observed OHC). Similar to the 100-m temperatures, when AXBT data were included in the initialization, differences in OHC values between the NCOM model and AXBT observations decreased, with an average difference of –13.9 kJ cm⁻² and a range of –26.0 to 4.4 kJ cm⁻². These comparisons

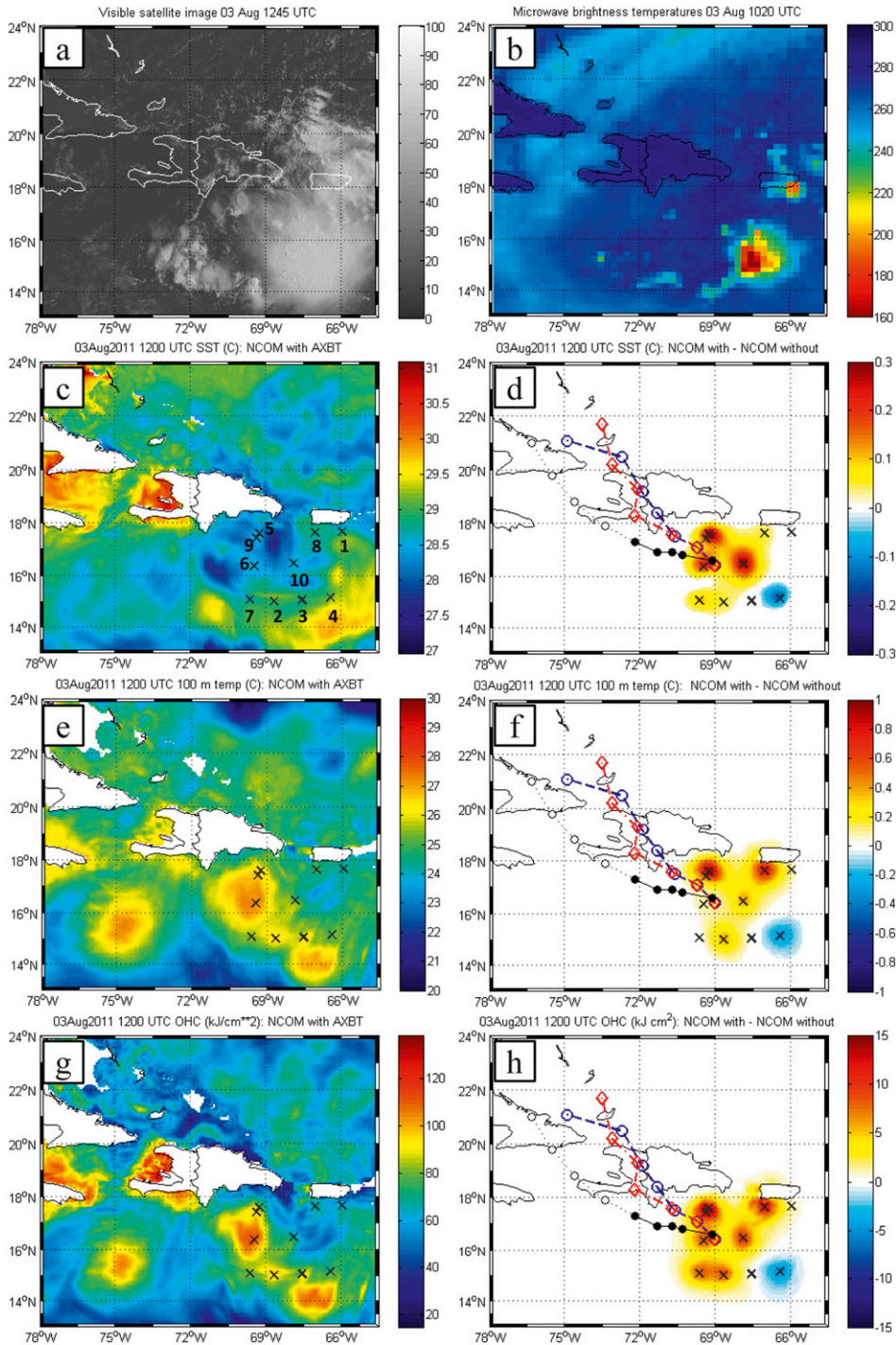


FIG. 7. (a) Visible *Geostationary Operational Environmental Satellite-13 (GOES-13)* imagery [in units of GOES Variable Format (GVAR), scaled] of TS Emily from 1245 UTC 3 Aug 2011. (b) Brightness temperatures (K) from the Defense Meteorological Satellite Program *F-17* Special Sensor Microwave Imager/Sounder (SSM/IS) at 1020 UTC 3 Aug. Ocean temperatures (°C) at (c) the sea surface and (e) 100-m depth from the 1200 UTC 3 Aug initialization of COAMPS-TC (including AXBT observations). The numbered AXBT drop locations are denoted by black exes. Temperature differences (°C) at (d) the sea surface and (f) 100-m depth that resulted from the inclusion of AXBT observations in the 1200 UTC 3 Aug COAMPS-TC initialization. The TS Emily best-track positions are denoted by black circles (unfilled when below depression intensity); COAMPS-TC track with (blue circles) and without (red diamonds) AXBT data. (g),(h) As in (c),(d), but for OHC (kJ cm⁻²).

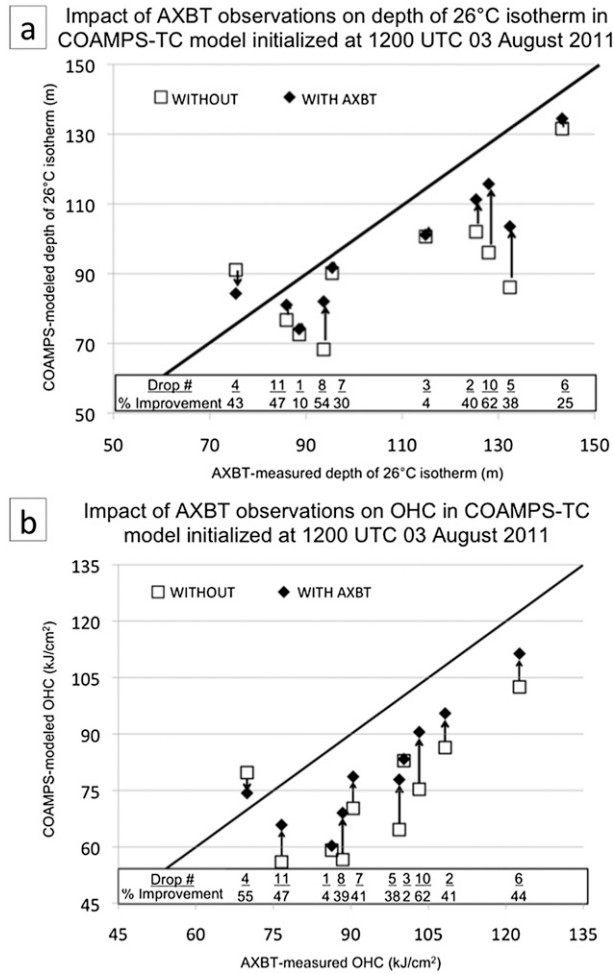


FIG. 8. Comparison of COAMPS-TC (modeled) vs AXBT (observed) (a) depth of 26°C isotherm and (b) OHC for the COAMPS-TC model analyses without (clear squares) and with (black diamonds) AXBT data. The black diagonal lines mark the location where the model value equals the observed value. Black arrows indicate the change in the model following initialization with the AXBT data. The percent improvement for each drop is noted in the text box.

reveal that including the AXBT observations in COAMPS-TC resulted in substantial improvements in the model representation of the upper-ocean thermal structure.

Even though Emily was a relatively weak TC during the mission on 3 August 2011 and despite its interaction with the Hispaniola landmass 30 h after the flights, slight improvement in both the 1200 UTC COAMPS-TC track and intensity forecasts resulted from assimilating the AXBT temperature observations into the NCOM analysis (Fig. 9). For example, the track forecast errors at 12, 18, 24, and 36 h were 10, 16, 9, and 84 km lower, respectively, as a result of including AXBT observations in

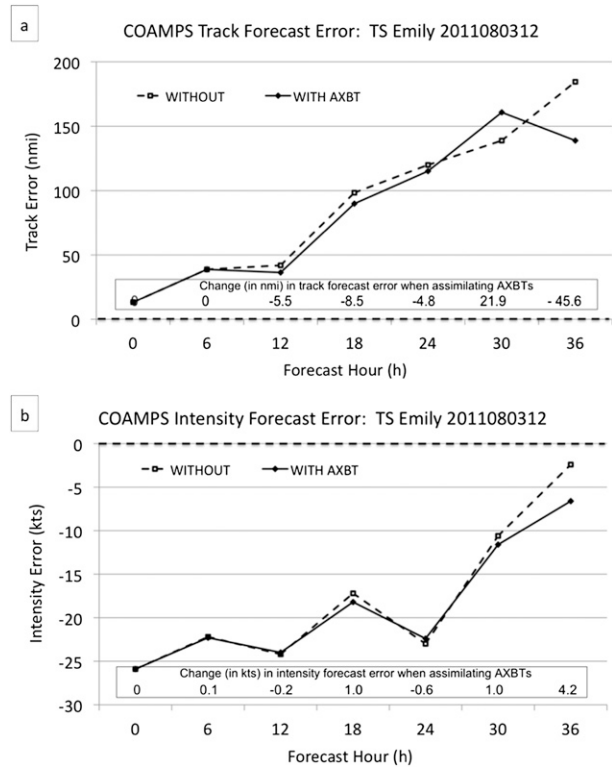


FIG. 9. (a) Track and (b) intensity forecast errors for the COAMPS model run initialized at 1200 UTC 3 Aug 2011 with (black diamonds) and without (squares with clear centers) AXBT data. The improvement (reduced error) or degradation (increased error) at each time step is noted above the x axis in each plot.

COAMPS-TC (Fig. 9a). The track error at 6 h was unchanged, and the track error at 30 h was degraded by 40 km. Relative forecast improvements were 13.2%, 8.6%, 4.0%, and 24.7%, respectively, at 12, 18, 24, and 36 h. Intensity forecast results were mostly unchanged, with five of six forecast time steps varying by 1 kt or less. Two of the four forecast hours prior to landfall showed small (but statistically insignificant) improvements. The intensity forecast was 0.2 and 0.6 kt better at 12 and 24 h, respectively, and was degraded by between 0.1 and 1 kt at 6 and 18 h, respectively. Following landfall, however, (the 30- and 36-h forecast times), intensity errors were degraded by 1 and 4.2 kt, respectively (Fig. 9b). Perhaps the intensity forecast showed little sensitivity to the inclusion of AXBT data because of the weak initial intensity of Emily (45 kt), compounded by an even weaker initialization in the model (only 25 kt in the COAMPS-TC initialization). Weak wind speeds may have reduced the potential for surface fluxes to have a significant influence on the circulation of Emily. Another possible complication could have been the approach and crossing of Emily over the southern coast of Hispaniola.

TABLE 2. Impact of database (SHIPS) and observed (AXBT) OHCs on the 36-h SHIPS forecast initialized at 1200 UTC 3 Aug 2011 for 10 of the 11 AXBTs deployed during the 3 Aug 2011 WC-130J fix mission in TS Emily. (Data from one AXBT failed the QC check on board the aircraft.) The minimum and maximum IA differences (in bold) define the intensity uncertainty range at this 36-h forecast time.

Drop No.	SHIPS	AXBT	SHIPS IA (kt)	AXBT IA (kt)	IA difference (kt)
	OHC (kJ cm^{-2})	OHC (kJ cm^{-2})			
1	80.6	86.3	1.67	2.22	0.55
2	92.6	108.3	2.83	4.35	1.52
3	104.4	100.3	3.98	3.58	-0.40
4	100.2	69.9	3.57	0.63	-2.95
5	90.0	99.4	2.58	3.49	0.91
6	104.7	122.6	4.01	5.75	1.74
7	77.2	90.4	1.34	2.62	1.29
8	74.9	88.4	1.11	2.42	1.31
9	93.2	103.2	2.89	3.86	0.97
10	85.9	76.6	2.18	1.28	-0.90

In addition to coupled dynamical models, the impact of AXBT observations on intensity forecasts of Tropical Storm Emily was also examined using the statistical SHIPS model. During each flight, an IA value was calculated for each in situ OHC observation, and then compared to the corresponding IA value calculated using OHC from the SHIPS database at each AXBT observation location. Maximum and minimum differences between IAs at each of the 10 deployment locations on 3 August 2011 (Table 2) were used to determine the intensity uncertainty range at 6-h increments, out to 36 h. Intensity differences ranged from near zero at the initial time to +1.7 and -3.0 kt at 36 h (Fig. 10). The SHIPS and AXBT intensity adjustments for the 36-h forecast time step are summarized in Table 2. While small, the 4.7-kt range at the 36-h forecast agrees reasonably well with the magnitude of impact the AXBT data had on the COAMPS-TC forecasts of Emily (Fig. 9b). This range also agrees with the impact OHC had on other TCs of similar intensity (DeMaria et al. 2005).

c. Hurricane Irene

Hurricane Irene made landfall as a category 1 hurricane over Cape Lookout, North Carolina, at 1200 UTC 27 August 2011 (Avila and Cangialosi 2011). In the 16 h prior to landfall and in the 8 h that followed, 30 AXBTs were deployed during two WC-130J operational hurricane reconnaissance missions (Table 1). Of these, 20 were forwarded to the RTDHS, and data from 15 passed both the RTDHS and NCODA quality control filters and were used in the COAMPS-TC model runs in real time. For the data-denial study, the COAMPS-TC was run using a 12-h data assimilation window. Nine AXBT

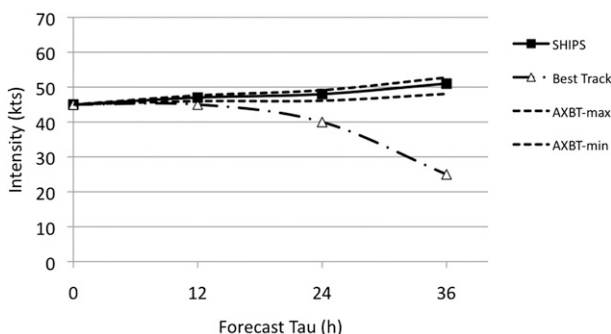


FIG. 10. The TS Emily intensity (kt) based on the operational SHIPS model forecast initialized at 1200 UTC 3 Aug 2011 (solid line). The intensity uncertainty range outlined by the maximum and minimum IA differences (two dashed blue lines) realized by including AXBT (observed) OHC values in the SHIPS analysis, and the actual intensities denoted in the NHC best track (dot-dashed line with diamonds).

observations were assimilated in the 0000 UTC 27 August 2011 ocean model, and eight AXBT observations were assimilated in the subsequent 1200 UTC 27 August 2011 ocean model, which used a warm start from the previous run.

The data-denial experiments examined here were initialized using the warm-start run from 1200 UTC 27 August 2011. At 100-m depth, the primary impact of the 0000 UTC AXBT observations was to cool the ocean behind the storm by 0.5° – 1.5°C in the region between 30° and 35°N near 76°W (Fig. 11). Downstream impacts were most evident to the east and northeast of the initial drop locations and varied in both sign and magnitude. The initial corrections resulting from the 1200 UTC 27 August 2011 AXBT observations were more limited in geographic extent at the analysis time, but also propagated downstream through the forecast cycle (not shown). At the analysis time, these corrections to the upper-ocean thermal structure were reflected in the improved representation of the depth of the 26°C isotherm at the seven AXBT locations (Fig. 12), where temperatures exceeded 26°C . In every case, the depth of the 26°C isotherm was too shallow in the model. Assimilation of the AXBT data in the COAMPS-TC model deepened the isotherm in each case and reduced the error by between 17% and 99%.

Unlike the Emily data-denial study in which the assimilation of AXBTs impacted track more than intensity, in the Irene case, the AXBT data had little impact on the TC track forecasts (Fig. 11), but made slight improvements to TC intensity forecasts over multiple time steps (Fig. 13). The improvements ranged between -0.6 and 1.6 kt between the 18- and 48-h forecasts. The overall improvement, while slight, was noteworthy because it

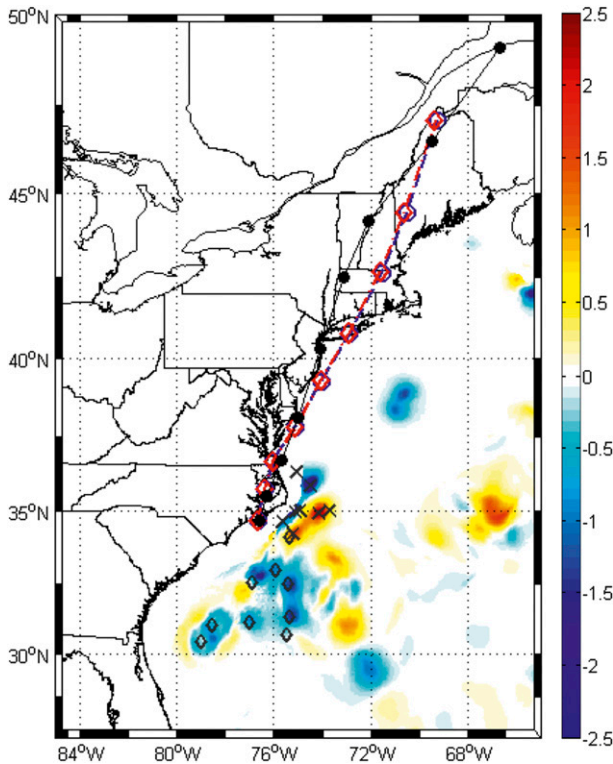


FIG. 11. Temperature differences ($^{\circ}\text{C}$) at 100-m depth resulting from the inclusion of AXBT observations at 0000 UTC (clear black diamonds) and 1200 UTC 27 Aug 2011 (black exes) COAMPS-TC initialization. The 0000 UTC simulation was used as a warm start for the 1200 UTC simulation. Hurricane Irene best-track positions are denoted by black circles; COAMPS-TC track forecasts denoted by a blue dashed line with clear circles (with AXBT data) and a red dashed line with clear diamonds (without AXBT data).

resulted only from changes to the upper-ocean thermal structure just prior to landfall and not from differences in TC track. Additionally, the eight AXBTs assimilated in the 1200 UTC 27 August 2011 run were all deployed to the east and south of the storm center, as the TC had already made landfall. Finally, the range of impact of AXBT data on COAMPS-TC intensity changes in both the Emily and Irene cases matched the range of impact of AXBT data seen in the SHIPS model.

4. Conclusions and future work

The 2011 AXBT Demonstration Project met both of its first-year objectives. Data from AXBTs deployed during operational aircraft reconnaissance were routinely assimilated on a real-time basis into two ocean models, NCOM and HYCOM, and one coupled model, COAMPS-TC. Furthermore, the assimilated data directly resulted in the improved representation of upper-ocean temperatures in both the NCOM and HYCOM models and had several

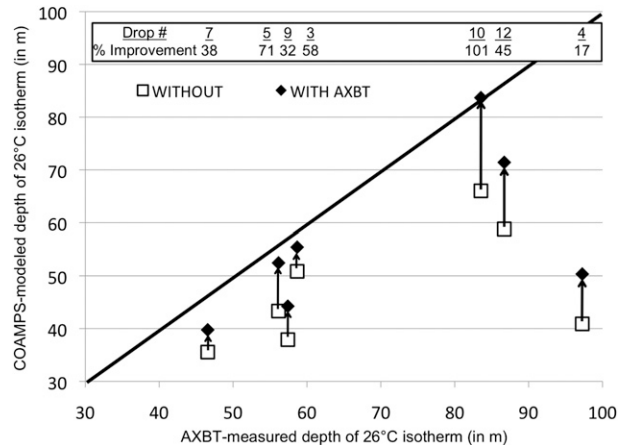


FIG. 12. Comparison of COAMPS-TC (modeled) vs AXBT (observed) depths of 26 $^{\circ}\text{C}$ isotherm for the COAMPS-TC 1200 UTC 27 Aug 2011 analyses without (clear squares) and with (black diamonds) AXBT data. The black diagonal line marks the location where the model value equals the observed value. Black arrows indicate the change in the model following initialization with the AXBT data. Percent improvement for each drop is noted in the text box at the top.

positive impacts on COAMPS-TC track and intensity forecasts prior to landfall. When incorporated into the SHIPS model, the impact of the AXBT data on TC forecast intensity compared well to that observed in the corresponding COAMPS-TC forecast. The data also were uploaded to the GTS in near-real time for worldwide availability and were archived for HWRP hindcast studies (H.-S. Kim, NCEP/EMC, 2011, personal communication).

Between 28 July and 28 August 2011, 109 AXBTs were deployed in the Gulf of Mexico, Caribbean Sea, and North Atlantic Ocean. Of these, 84 passed the initial quality control check at the RTDHS and 75 were assimilated into real-time NCOM forecasts. Comparisons between AXBT observations and IASNFS analysis temperatures in the Gulf of Mexico on 11 August 2011 revealed temperature differences between -4° and $+2.5^{\circ}\text{C}$ within the warm-core ring between the surface and 200-m depth. By assimilating AXBT data into the 1200 UTC 11 August 2011 NCOM and 1800 UTC 11 August 2011 HYCOM forecasts, 100-m temperatures near the WCR were adjusted between -2° and $+0.5^{\circ}\text{C}$ in both modeling systems. The temperature differences between the AXBT data and the IASNFS, NCOM, and HYCOM model forecasts support the need for near-real-time data to improve the analysis of upper-ocean temperatures in air-sea coupled hurricane models such as coupled COAMPS-TC. If coupled models are to be the new standard in the future, real-time corrections from in situ observations will be important in improving ocean component model predictions.

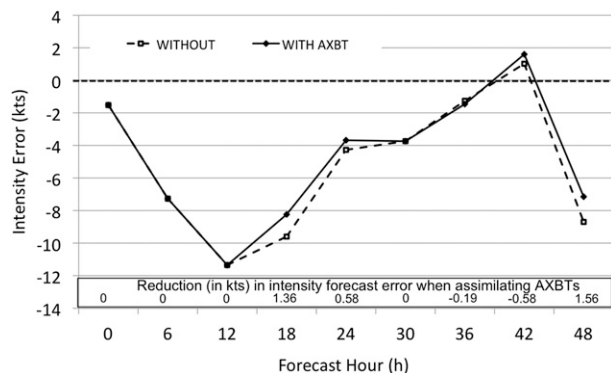


FIG. 13. Intensity forecast errors for the COAMPS-TC model run initialized at 1200 UTC 27 Aug 2011 with (black diamonds) and without (clear squares) AXBT data. The improvement at each time step is noted above the x axis. Positive values indicate reduced error (improvement) and negative values increased error (degradation).

In a similar manner, AXBT data from the WC-130J mission on 3 August 2011 for Tropical Storm Emily were assimilated into the COAMPS-TC model and resulted in changes in SST between -0.15° and $+0.3^{\circ}\text{C}$, in 100-m temperature between -0.3° and $+0.9^{\circ}\text{C}$, and in OHC between -6 and $+16\text{ kJ cm}^{-2}$. As a result of including AXBT data, COAMPS-TC track forecasts improved at most forecast hours, including an 84-km improvement (24% relative improvement) at 36 h. Intensity forecast improvements were smaller, generally less than 1 kt (0.8%–2.6% relative improvement) and occurred in two of the four forecasts prior to landfall. Despite the small intensity improvements, however, the magnitude of improvement was in line with the range of potential improvement (-4 to $+3$ kt) from sensitivity studies using the SHIPS statistical model and occurred while the storm was within 36 h of landfall.

The improvement to the intensity forecast for Hurricane Irene resulted from the assimilation of AXBT data in consecutive model runs and suggests the potential utility of AXBT observations in consecutive operational TC reconnaissance missions, particularly over the open ocean. Assimilation of nine AXBT observations in the initial model run resulted in a cooler TC wake as well as multiple downstream impacts at 100-m depth in the subsequent analysis. Assimilation of eight AXBT observations to the east and south of the TC center improved the representation of the upper-ocean thermal structure at the analysis time, reducing the error in the depth of the 26°C isotherm by an average of more than 50% at the AXBT deployment locations. Together, even though all 17 AXBTs were deployed within 16 h of landfall, these observations improved the COAMPS-TC intensity forecasts for Hurricane Irene at three time

steps between 18 and 48 h. Though the reduction in intensity error was slight (less than 2 kt in each case), the improvement was on the same order of magnitude as that in Emily as well as the range given by the SHIPS model. Furthermore, the improvements in upper-ocean temperature structure found for all three cases examined here were on the same order of magnitude as those found by other field campaigns to be associated with substantial improvements in intensity forecasts of strong TCs (Lin et al. 2012), suggesting the potential for utility in an operational setting.

The proximity in time and space of these observations to landfall highlights the need to conduct future AXBT operations in consecutive operational reconnaissance missions over TCs in the open ocean to further assess potential improvement in coupled model forecasts of TC track and intensity. Future AXBT missions could focus on increasing and optimizing model input through improved horizontal data resolution, for example, deploying AXBTs farther ahead of the storm, along the storm track, and in locations sampled on previous flights. Further, increased standardization and automation should enhance the quality control process. Finally, point intercomparisons between thermal profiles from AXBTs and other in situ sensors were not conducted during the operational flights; however, opportunities for intercomparison with buoy and ARGO float data will be sought in coming years.

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APPENDIX

COAMPS-TC Model Description and Setup

The fully air–ocean coupled COAMPS-TC system consists of two independent data assimilation systems (Daley and Barker 2001; Cummings and Smedstad 2013)

and forecast models for the atmosphere (Hodur 1997; Chen et al. 2003) and ocean (Martin 2000). The atmospheric data assimilation uses the Navy Atmospheric Variational Data Assimilation System-Tropical Cyclones (NAVDAS-TC) that relocates the background model TC to the observed location prior to initializing a TC circulation using 49 synthetic atmospheric wind, temperature, and moisture profiles (Liou and Sashegyi 2011). The location of TC and radius of gale force winds are based on the real-time warning message issued by the Joint Typhoon Warning Center (JTWC) and National Hurricane Center (NHC). Similar to NAVDAS, NCODA uses the three-dimensional variational method to assimilate in situ and remotely sensed ocean observations of temperature, salinity, sea surface height, and currents. For the forecast models, the atmospheric component uses a different suite of improved atmospheric physics specifically calibrated for TC prediction (Doyle et al. 2012). The ocean component is NCOM, which is a hydrostatic model with a stretched sigma- Z vertical coordinate. The two-way coupling between the atmosphere and ocean is accomplished through the Earth System Modeling Framework (Chen et al. 2010). The momentum, heat and salt fluxes, sea level pressure, and sea surface temperature are exchanged between the atmospheric and ocean model at the user-specified time intervals. The coupled COAMPS-TC system is relocatable to any ocean basin. To improve the real-time efficiency, the coupled COAMPS-TC has the inner two meshes automatically following the tropical cyclone (TC). If there is more than one TC active in a given basin and at a given time, then multiple coupled COAMPS-TC runs are initialized for each TC.

REFERENCES

- Aberson, S. D., 2010: 10 years of hurricane synoptic surveillance (1997–2006). *Mon. Wea. Rev.*, **138**, 1536–1549.
- , and J. L. Franklin, 1999: Impact on hurricane track and intensity forecasts of GPS dropwindsonde observations from the first-season flights of the NOAA Gulfstream-IV jet aircraft. *Bull. Amer. Meteor. Soc.*, **80**, 421–427.
- , and B. J. Etherton, 2006: Targeting and data assimilation studies during Hurricane Humberto (2001). *J. Atmos. Sci.*, **63**, 175–186.
- Avila, L. A., and J. P. Cangialosi, 2011: Tropical cyclone report: Hurricane Irene. National Hurricane Center Rep., 45 pp. [Available online at http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf.]
- Barron, C. N., A. B. Kara, P. J. Martin, R. C. Rhodes, and L. F. Smedstad, 2006: Formulation, implementation and examination of vertical coordinate choices in the global Navy Coastal Ocean Model (NCOM). *Ocean Modell.*, **11**, 347–375.
- Bender, M. A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL coupled hurricane–ocean prediction system and a summary of its performance. *Mon. Wea. Rev.*, **135**, 3965–3989.
- Black, P. G., 1983: Ocean temperature change induced by tropical cyclones. Ph.D. dissertation, The Pennsylvania State University, University Park, PA, 278 pp.
- , 2009: Western Pacific tropical cyclone adaptive observing of inner core life-cycle structure and intensity change. Office of Naval Research Rep. 20785 (0001409WX), 15 pp.
- , 2012: Tropical cyclone unusual intensity and structure change in the western North Pacific observed by reconnaissance aircraft during TPARC/TCS08 and ITOP/TCS10. *Trop. Cyclones Res. Rev.*, **1**, 75–88.
- , and Coauthors, 2010: Observational and modeling comparison of Super Typhoon Jangmi (2008) and Hurricane Katrina (2005). Preprints, *29th Conf. on Hurricanes and Tropical Meteorology*, Tucson, AZ, Amer. Meteor. Soc., 8C.5. [Available online at <https://ams.confex.com/ams/pdfpapers/169216.pdf>.]
- Bleck, R., 2002: An oceanic general circulation model framed in hybrid isopycnic–Cartesian coordinates. *Ocean Modell.*, **4**, 55–88.
- Bosart, L., C. S. Velden, W. E. Bracken, J. Molinari, and P. G. Black, 2000: Environmental influences on the rapid intensification of Hurricane Opal (1995) over the Gulf of Mexico. *Mon. Wea. Rev.*, **128**, 322–352.
- Brand, S., 1971: The effects on a tropical cyclone of cooler surface waters due to upwelling and mixing produced by a prior tropical cyclone. *J. Appl. Meteor.*, **10**, 865–874.
- Cavallo, S. M., R. D. Torn, C. Snyder, C. Davis, W. Wang, and J. Done, 2013: Evaluation of the Advanced Hurricane WRF Data Assimilation System for the 2009 Atlantic hurricane season. *Mon. Wea. Rev.*, **141**, 523–541.
- Chen, S., and Coauthors, 2003: COAMPS version 3 model description. NRL Rep. NRL/PU/7500-04-448, 143 pp.
- , T. J. Campbell, H. Jin, S. Gaberšek, R. M. Hodur, and P. J. Martin, 2010: Effect of two-way air–sea coupling in high and low wind speed regimes. *Mon. Wea. Rev.*, **138**, 3579–3602.
- , J. Doyle, R. Hodur, H. Jin, J. Cummings, and J. Schmidt, 2011: An overview of COAMPS-TC forecasts and targeting for ITOP. *65th Interdepartmental Hurricane Conf.*, Miami, FL, Office of the Federal Coordinator for Meteorological Services and Supporting Research. [Available online at <http://www.ofcm.gov/ihc11/Presentations/Session09/s09-07-2011%20ihc%20itop%20chen.ppt>.]
- Cummings, J., 2011: Ocean data quality control. *Operational Oceanography in the 21st Century*, A. Schiller and G. Brassington, Eds., Springer, 91–121.
- , and O. M. Smedstad, 2013: Variational data assimilation for the global ocean. *Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications*, Vol. II, S. Park and L. Xu, Eds., Springer, 303–343.
- D’Asaro, E. A., 2003: The ocean boundary layer under Hurricane Dennis. *J. Phys. Oceanogr.*, **33**, 561–579.
- Daley, R., and E. Barker, 2001: NAVDAS: Formulation and diagnostics. *Mon. Wea. Rev.*, **129**, 869–883.
- DeMaria, M., and J. Kaplan, 1994: A Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin. *Wea. Forecasting*, **9**, 209–220.
- , and —, 1999: An updated Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic and eastern North Pacific basins. *Wea. Forecasting*, **14**, 326–337.
- , M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity

- Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531–543.
- Doyle, J., and Coauthors, 2012: Real-time tropical cyclone prediction using COAMPS-TC. *Adv. Geosci.*, **28**, 15–28.
- Emanuel, K. A., 1986: An air–sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585–604.
- , 1999: Thermodynamic control of hurricane intensity. *Nature*, **401**, 665–669.
- , C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental controls of tropical cyclone intensity. *J. Atmos. Sci.*, **61**, 843–858.
- Goni, G. J., and Coauthors, 2009: Applications of satellite-derived ocean measurements to tropical cyclone intensity forecasting. *Oceanography*, **22**, 176–183.
- Gopalakrishnan, S., Q. Liu, T. Marchok, D. Sheinin, N. Surgi, R. Tuleya, R. Yablonsky, and X. Zhang, 2010: Hurricane Weather Research and Forecasting (HWRF) Model scientific documentation. NOAA/NCAR/Development Tech Center Tech. Rep., 80 pp. [Available online at http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRF_final_2-2_cm.pdf.]
- Guan, L., and H. Kawamura, 2003: Study on the SST availabilities of satellite infrared and microwave measurements. *J. Oceanogr.*, **59**, 201–209.
- Hodur, R. M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Mon. Wea. Rev.*, **125**, 1414–1430.
- Hong, X., S. W. Chang, S. Raman, L. K. Shay, and R. Hodur, 2000: The interaction of Hurricane Opal (1995) and a warm core ring in the Gulf of Mexico. *Mon. Wea. Rev.*, **128**, 1347–1365.
- Jayne, S. R., J. M. Wahr, and F. O. Bryan, 2003: Observing ocean heat content using satellite gravity and altimetry. *J. Geophys. Res.*, **108**, 3031, doi:10.1029/2002JC001619.
- Jung, B.-J., H. M. Kim, F. Zhang, and C.-C. Wu, 2012: Effect of targeted dropsonde observations and best track data on the track forecasts of Typhoon Sinlaku (2008) using an ensemble Kalman filter. *Tellus*, **64**, doi:10.3402/tellusa.v64i0.14984.
- Kimberlain, T. B., and J. P. Cangialosi, 2012: Tropical cyclone report: Tropical Storm Emily. National Hurricane Center, 17 pp. [Available online at http://www.nhc.noaa.gov/data/tcr/AL052011_Emilypdf.pdf.]
- Ko, D. S., R. H. Preller, and P. J. Martin, 2003: An experimental real-time Intra Americas Sea Ocean Nowcast/Forecast System for coastal prediction. Preprints, *Fifth Conf. on Coastal Atmospheric and Oceanic Prediction and Processes*, Seattle, WA, Amer. Meteor. Soc., 5.2. [Available online at <https://ams.confex.com/ams/pdfpapers/64664.pdf>.]
- , P. J. Martin, C. D. Rowley, and R. H. Preller, 2008: A real-time coastal ocean prediction experiment for MREA04. *J. Mar. Syst.*, **69**, 17–28.
- Leipper, D., and D. Volgenau, 1972: Hurricane heat potential of the Gulf of Mexico. *J. Phys. Oceanogr.*, **2**, 218–224.
- Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov, 2009: Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.*, **36**, L07608, doi:10.1029/2008GL037155.
- Lin, I.-I., C.-C. Wu, K. A. Emanuel, I.-H. Lee, C.-R. Wu, and I.-F. Pun, 2005: The interaction of Supertyphoon Maemi (2003) with a warm ocean eddy. *Mon. Wea. Rev.*, **133**, 2635–2649.
- , and Coauthors, cited 2012: Ocean's impact on typhoon intensity during ITOP and new PI (potential intensity) index. AOML/HRD Seminar. [Available online at ftp://ftp.aoml.noaa.gov/hrd/pub/marks/seminars/I-ILin_HRD_seminar_20120423.wmv.]
- Liou, C.-S., and K. D. Sashegyi, 2011: On the initialization of tropical cyclones with a three-dimensional variational analysis. *Nat. Hazards*, **63**, 1375–1391, doi:10.1007/s11069-011-9838-0.
- Martin, P. J., 2000: Description of the Navy Coastal Ocean Model version 1.0. NRL Rep. NRL/FR/7322-00-9962, 45 pp.
- Millero, F. J., and A. Poisson, 1981: International one-atmosphere equation of state of seawater. *Deep-Sea Res.*, **28A**, 625–629.
- Nagamani, P. V., and Coauthors, 2012: Validation of satellite-derived tropical cyclone heat potential with in situ observations in the north Indian Ocean. *Remote Sens. Lett.*, **3**, 615–620.
- OFCM, cited 2011: National hurricane operations plan. FCM-P12–2011. [Available online at <http://www.ofcm.gov/nhop/11/nhop11.htm>.]
- Price, J. F., 1981: Upper ocean response to a hurricane. *J. Phys. Oceanogr.*, **11**, 153–175.
- , 2009: Metrics of hurricane–ocean interaction: Vertically-integrated or vertically-averaged ocean temperature? *Ocean Sci. Discuss.*, **6**, 909.
- , T. B. Sanford, and G. Z. Forristall, 1994: Observations and simulations of the forced response to moving hurricanes. *J. Phys. Oceanogr.*, **24**, 233–260.
- Rappaport, E. N., and Coauthors, 2009: Advances and challenges at the National Hurricane Center. *Wea. Forecasting*, **24**, 395–419.
- Riehl, H., 1950: A model for hurricane formation. *J. Appl. Phys.*, **21**, 917–925.
- Sanford, T. B., P. G. Black, J. Haustein, J. W. Feeny, G. Z. Forristall, and J. F. Price, 1987: Ocean response to a hurricane. Part I: Observations. *J. Phys. Oceanogr.*, **17**, 2065–2083.
- Shay, L. K., 2009: Upper ocean structure: A revisit of the response to strong forcing events. *Encyclopedia of Ocean Sciences*, J. Steele et al., Eds., Elsevier Press, 4619–4637, doi:10.1016/B978-012374473-9.00628-7.
- , and J. K. Brewster, 2010: Oceanic heat content variability in the eastern Pacific Ocean for hurricane intensity forecasting. *Mon. Wea. Rev.*, **138**, 2110–2131.
- , R. L. Elsberry, and P. G. Black, 1989: Vertical structure of the ocean current response to a hurricane. *J. Phys. Oceanogr.*, **19**, 649–669.
- , P. G. Black, A. J. Mariano, J. D. Hawkins, and R. L. Elsberry, 1992: Upper ocean response to Hurricane Gilbert. *J. Geophys. Res.*, **97** (C12), 20227–20248.
- , G. J. Goni, and P. G. Black, 2000: Effects of a warm oceanic feature on Hurricane Opal. *Mon. Wea. Rev.*, **128**, 1366–1383.
- , B. Jaimes, J. Brewster, C. McCaskill, P. Myers, S. Paul, and T. Richards, 2012: Ocean Data Acquisition System on NOAA WP-3Ds in support of HFIP. *66th Interdepartmental Hurricane Conf.*, Charleston, SC, Office of the Federal Coordinator for Meteorological Services and Supporting Research, 4B.5. [Available online at http://www.ofcm.gov/ihc12/Presentations/04b-Session/05-Shay_ODAS.pdf.]
- Sun, D., R. Gautam, G. Cervone, Z. Boyeyi, and M. Kaptos, 2006: Comment on “Satellite altimetry and the intensification of Hurricane Katrina.” *Eos, Trans. Amer. Geophys. Union*, **87**, 89.
- Tournadre, J., and J. C. Morland, 1997: The effects of rain on TOPEX/Poseidon altimeter data. *IEEE Trans. Geosci. Remote Sens.*, **35**, 1117–1135.

- UNESCO, 1999: Guide to operational procedures for the collection and exchange of JCOMM oceanographic data. 3rd rev. ed. IOC Manuals and Guides, No. 3, 45 pp.
- Walker, N., R. R. Leben, and S. Balasubramanian 2005: Hurricane forced upwelling and chlorophyll *a* enhancement within cold-core cyclones in the Gulf of Mexico. *Geophys. Res. Lett.*, **32**, L18610, doi:10.1029/2005GL023716, 1-5.
- WG/HWSOR, cited 2011: 66th IHC-WG/HWSOR action item summary. [Available online at <http://www.ofcm.gov/ihc12/action-items.pdf>.]
- Wu, C.-C., C.-Y. Lee, and I.-I. Lin, 2007: The effect of the ocean eddy on tropical cyclone intensity. *J. Atmos. Sci.*, **64**, 3562-3578.
- , and Coauthors, 2009: Intercomparison of targeted observation guidance for tropical cyclones in the northwestern Pacific. *Mon. Wea. Rev.*, **137**, 2471-2492.
- Yablonsky, R. M., and I. Ginis, 2008: Improving the ocean initialization of coupled hurricane-ocean models using feature-based data assimilation. *Mon. Wea. Rev.*, **136**, 2592-2607.