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Impact of AXBT Target Observation to Tropical Cyclone Structure and Intensity Change

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LONG-TERM GOALS

The long-term goal of this project is to improve the observation, analysis, and prediction of the coupled COAMPS-TC hurricane boundary layer in the atmosphere and ocean. This is to be accomplished through assimilation of the experimental in-situ Airborne eXpendable Bathy Thermographs (AXBTs) and the development of a new buoyancy closure in the COAMPS®[1] Turbulent Kinetic Energy (TKE) scheme. The assimilation of the experimental AXBTs deployed during TC reconnaissance flights is hypothesized to give a better representation of the upper-ocean temperature structure which directly impacts the coupled COAMPS-TC intensity prediction. The AXBTs impact to COAMPS-TC prediction is realized through the improved treatment of the TKE buoyancy term to provide a better quantification of the impact of target ocean observation to TC intensity and boundary structure changes.

OBJECTIVE

The objectives for the first year of the project are:

1. Integrate a newly developed adjoint version of Navy Coupled Ocean Data Assimilation (NCODA) into the coupled COAMPS-TC and use it to study the impact of assimilating the AXBTs and other types of ocean observations to COAMPS-TC prediction on selected TC cases
2. Explore an optimal AXBT sampling strategy, including the optimal sampling resolution (horizontally and vertically), sampling location, and sampling frequency for model initialization
3. Test and develop a prototype code to compute the new TKE buoyancy production using the ensemble parcel method

[1] Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) is a registered trademark of the Naval Research Laboratory.

APPROACH

Recent TC cases such as Atlantic hurricanes Ernesto and Isaac from 2012 and Eastern Pacific hurricanes Iselle and Julio from 2014 were sampled by U.S. Naval Academy AXBTs. Furthermore, the upper ocean conditions for Isaac were also sampled by AXBTs and sea gliders deployed by NOAA, Airborne Expendable Conductiivity, Temperature, Depth profiler (AXCTD and Airborne Expendable Current Profiler (AXCP) from University of Miami, and array of drifters by SCRIPPS Institution of Oceanography. The impact of AXBT data assimilation in the COAMPS-TC ocean model - Navy Coastal Ocean Model (NCOM), is determined using the appropriate ocean error cost functions and atmospheric boundary layer biases. These adjoint-based data impact results are compared with data impact results from simple data denial studies where the AXBTs are included and excluded in duplicate runs of the ocean data assimilation component of the coupled model. The dependency of AXBT impact on model resolution will be investigated by varying the AXBT vertical sampling resolution and the model horizontal and vertical resolution.

To improve the calculation of the buoyancy forcing term in COAMPS TKE closure, we will develop a novel new approach using an ensemble-based parcel method. This scheme works by assigning a distribution of parcel thermodynamical properties at each model mass level along with an initial estimate of the parcel vertical velocity. Use will then be made of the COAMPS native form of the first law and the vertical momentum equation (together with the mean profiles) to assess the upward and downward parcel displacements from a given model mass level. Parcels arriving at a fixed displacement both above and below the given mass level will used to compute mean fluxes at the intervening w-levels. A simple vertical gradient of the computed mean turbulent eddy fluxes can then be carried out directly without the need for a mixing length assumption.

WORK COMPLETED

The integration and testing of the NCODA adjoint within the COAMPS-TC framework was completed. We conducted ten forecasting experiments on Hurricane Isaac case. These results were used for the NCODA adjoint ocean target data impact study. We used other types of special in-situ ocean observation as independent source for model validation. New diagnostic software has been developed to process these QC'ed high-resolution in-situ observations that were not assimilated into the model. The problem with the COAMPS current TKE buoyancy term was diagnosed and an interim solution was implemented. A prototype ensemble parcel model has been developed and tested for the growth of dry boundary layer.

RESULTS

Assimilation of the in-situ AXBT observations showed positive impact to reduce the coupled COAMPS-TC ocean forecast errors. Two independent methods were used to evaluate the AXBT data impact. The first approach is the data denial in an observing system experiment (OSE) method and the second approach is to use the analysis adjoint sensitivity method (Langland and Baker 2004; Cummings and Smedstad 2014). The analysis adjoint method is computationally more efficient than the OSE method and ideal for routine observational monitoring. Another advantage of using the analysis adjoint, is the data impact is solely due to analysis differences at each update cycle time and not from the effect of air-sea coupling. Because errors from the air-sea coupling are difficult to separate in the OSE type of experiment, the adjoint method gives the impact from the assimilation

system alone. Here we define the adjoint sensitivity cost function as the difference between COAMPS-TC 24 h and 36 h forecasts (forecast error gradient) valid at the same analysis time.

The hurricane Isaac (2012) case is used to conduct the COAMPS-TC AXBT experiments. The COAMPS-TC domain configuration includes 60 vertical levels of two atmospheric domains (grid spacing of 12 and 4 km, respectively) that have the 4 km nest automatically following the TC center. The horizontal grid resolution of the ocean domain is 4 km with 50 vertical levels and 20 Z-levels in the upper ocean. The coupling interval is every 6 min with a 12 h data assimilation cycle in the atmosphere and ocean. Two sets of experiments with (AXBT) and without (noAXBT) the AXBT assimilation were performed to assess the impact of AXBT assimilation. The model was cold started from 0000UTC, 25 Aug, 2012. The ocean model initial and boundary condition are derived from the global NCOM forecasts. The assimilation periods are from 25-29 Aug, 2012 with each forecast length consists of 5 days.

The pre-Isaac ocean condition in the Gulf of Mexico (GOM) was dominated by a large warm core eddy (WCE) center in the GOM that was shed from the Gulf loop-current earlier in the spring. There was no cold water intrusion of the loop-current during the passage of Isaac. Located on the flank of WCE are a pair of smaller cold core eddies (CCE). Compared to the global HYbrid Coordinate Ocean Model (HYCOM) or Colorado Center for Astrodynamics Research (CCAR) gridded sea surface height anomaly (SSHA), the WCE and CCEs magnitude, size, and position in the COAMPS cold start initial condition had small biases. The position and magnitude errors of these oceanic eddies were corrected in the subsequent assimilation of the AXBT observations.

The analysis adjoint sensitivity shows that all 71 AXBTs assimilated between 25 – 29 Aug had a positive impact on reducing the model forecast sea temperature errors (Fig. 1). The negative values in Fig. 1 indicate beneficial observations (positive impact) to reduce the forecast error. The data impact is defined as the inner product of 3D adjoint sensitivity vector and the innovation vector. The adjoint sensitivity vector computed from the gradient of 24 h and 36 h forecast errors. A large value of observation impact can either be a sensitive region for large error growth or large observation-model difference. The negative values shown in this plot indicate AXBT has a positive impact on reducing the COAMPS-TC 24 h temperature forecast along the AXBT deployment trajectory.

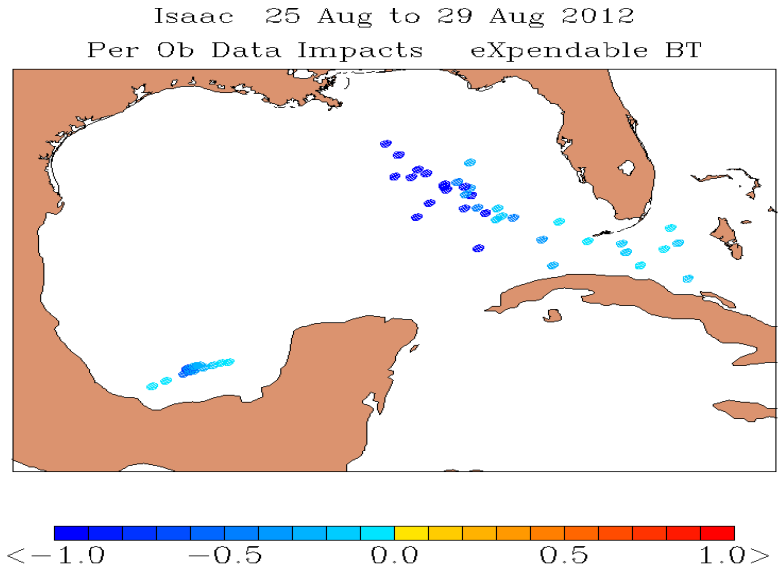

Fig. 1 AXBT per observation impacts between 25 to 29 August, 2012.

Analysis of the horizontal distribution of the temperature imapct between the AXBT and noAXBT experiments shows that the assimilation of AXBT greatly improved the mean sea temperature forecast errors. A large portion of the error reduction was derived from reducing the errors in the innovation vector. The forecast temperature error reduction was extended to the entire AXBT sampling depth with the lagest error reduction in the upper 600 m of the ocean (Fig. 2b). These results are consistent with the per-observation imapct which showed the AXBT has the largest impact on reducing the model forecast sea temperature error nornamlized by the number of observations (Fig. 2a).

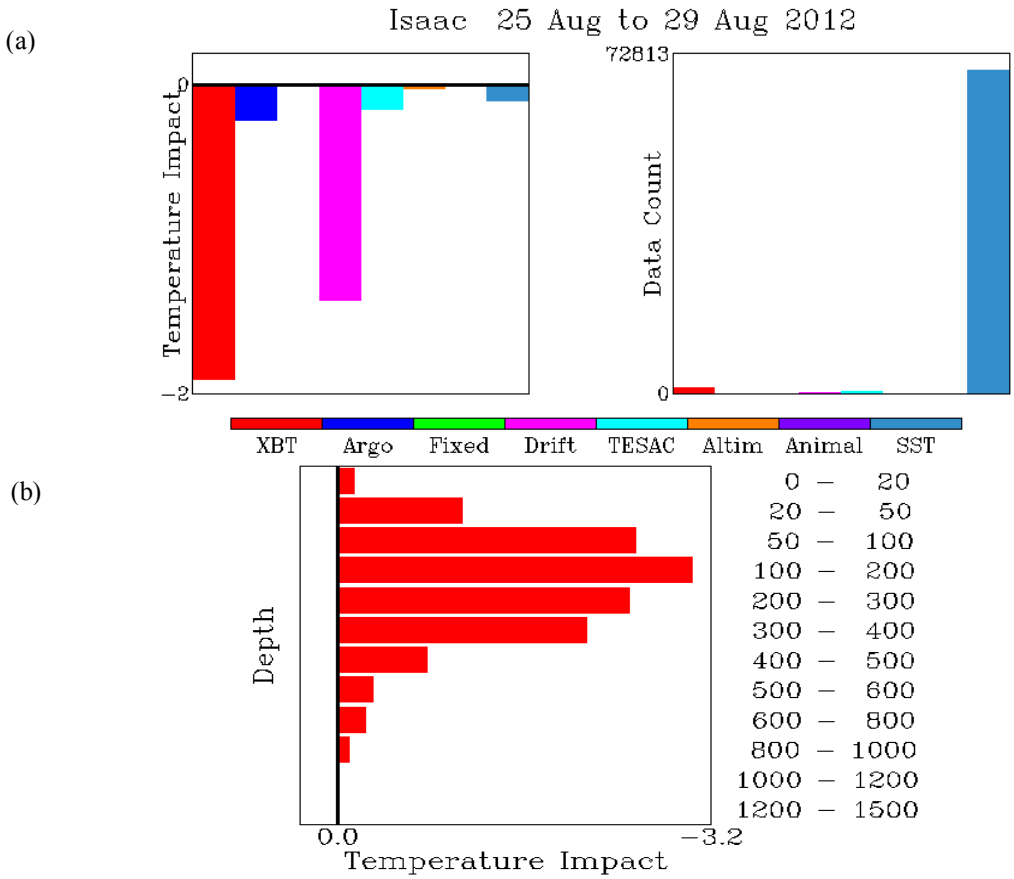

Fig. 2. (a) Sea surface temperature observation impact normalized by the number of samples from AXBT, ARGO profiler, fixed buoys, drifters, gliders, altimeters, and microwave satellites. (b) vertical profile of the AXBT temperature impact.

The upper-ocean response during the strom stage are further assessd using the AXCDT, and the 25 Aug global NCOM analysis. Along the Isaac track, between 28-29 Aug, the freshening of the salinity was as high as 3 psu from Isaac's heavy rain. The wake cooling was in the 0.5 – 1 °C range within the inner eyewall region of Isaac (Fig. 3). Sprouos positive sea surface temperature differences (Fig. 3b) along the track indicated the position and magnitude biases of the WCEs and CCEs in the gobal NCOM analysis. The implication of these results are that the assimlation of the sea surface height is important to improve the initial positions and magnitude of these GOM eddies. In other words, the assimilation of sea surface height by the NCODA data assimilation cycles is required to spin-up the NCOM model in eddy rich oceanic regions such as in the GOM or Western Pacific.

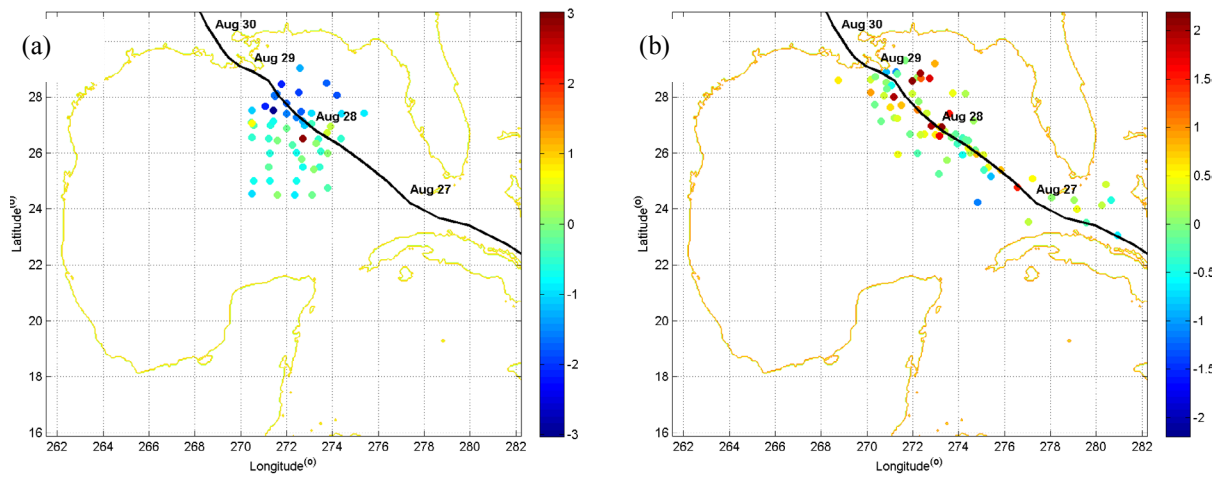

Fig. 3 (a) Sality (psu) and (b) sea surface temperature (°C) differnces between the observations and 0000 UTC 25 Aug, 2012 gobal NCOM analysis.

To improve the buoyancy contribution of the atmospheric hurricane boundary layer TKE, we developed an ensemble-based mixng algorithm that assigns the parcel perturbations based on assumed PDF (Fig. 4a). The vertical displacement of the parcel and associated buoyancy fluxes then is assessed using the COAMPS fist law, the initial assigned perturbation vertical velocity, and the mean temperaure and moisture profiles (Fig. 4b). The vertical momentum equation is then integrated over a short time interval to predict the parcel perturbation properties at the intervening w-levels.If no parcels arrive at an intervening w-level from either above or below that level, the flux at that w-level is assigned a value of zero. This then naturally accounts for the presence of strong static stability profiles through impacts on the parcel acceleration/deceleration obtained through explicit integration of the vertical momentum equation.

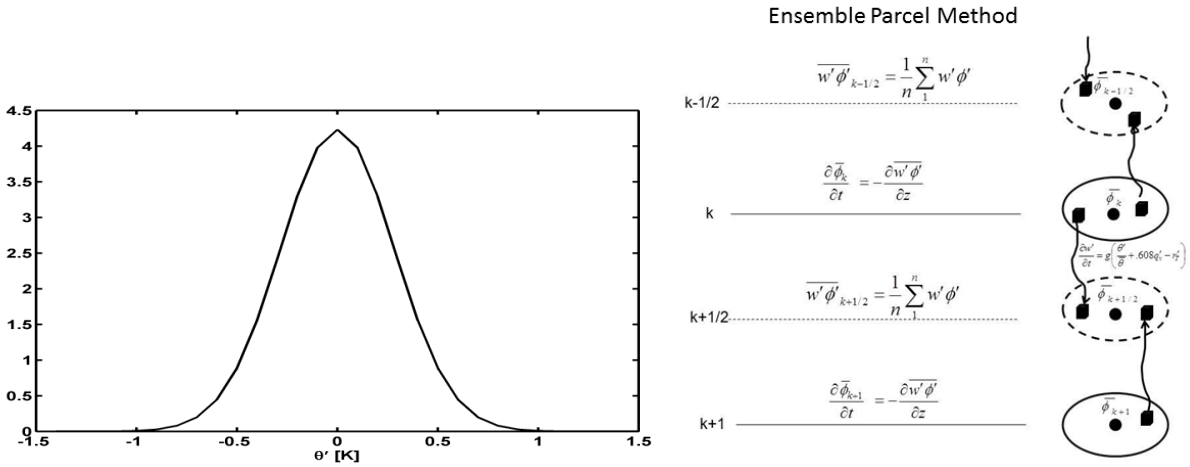

Fig. 4 (a) the assumed PDF distribution of the temperature perturbation of ascending parcel. (b) An illustration of the ensemble parcel method.

We conducted an idealized test of the new ensemble-based parcel mixing on the dry boundary layer growth. The example in Fig. 5 shows that given a warm ocean of 302°K, the growth of the dry boundary layer height reached about 600 m height after 5000 second of integration. Subsequent testing will be done using previously published results of dry boundary layer growth and the inclusion of moist physics processes in the vertical momentum equation in the cases where condensate is either present or likely to form during the parcel ascent. Once tested, the methodology will be implemented within COAMPS-TC and tested against the large suite of mixing algorithms already available within the model framework. It is anticipated that this method will provide greater consistency with model's native First Law of thermodynamics than otherwise obtained using closure techniques based on the vertical profiles of derived conservative variables (such as the ice-liquid potential temperature) that are known to represent different approximations of both the "true" and model formulated First Law.

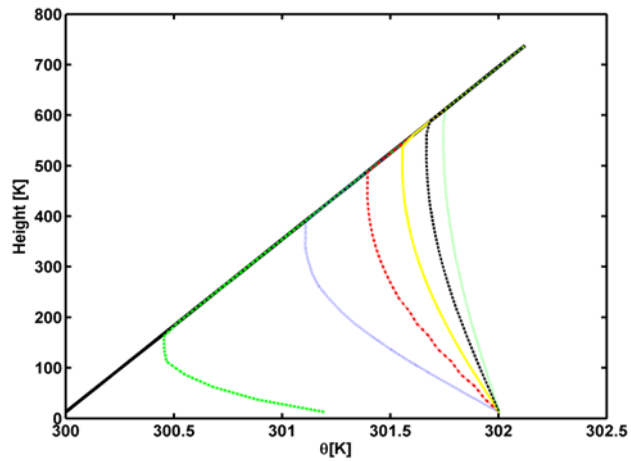

Fig. 5 The growth of dry boundary layer potential temperature (°K) using the ensemble-based parcel mixing. The black line represents the initial potential temperature profile with height (m). The colored lines are the temperature profiles after the mixing processes have taken 200 (green), 1000 (blue), 2000 (red), 3000 (yellow), 4000 (black), and 5000 (light green) seconds of integration. The temperature of the ocean is set to be 302 °K.

IMPACT/APPLICATIONS

This project is aimed to improved COAMPS-TC prediction using a better representation of the coupled boundary layer. The NCODA adjoint can be used to routinely monitor the operational coupled COAMPS ocean assimilation.

TRANSITIONS

The transition path for this project is to FNMOC via 6.4 Small-scale COAMPS.

RELATED PROJECTS

The related projects include 6.2 COAMPS-TC, 6.4 Small-scale COAMPS.

PUBLICATIONS

Selected conference presentations or papers.

S. Chen, J. Cumings, J. M. Schmidt, E. Sanabia, B. Barrett, and P. Black; Impact of AXBT ocean observations on the COAMPS prediction of tropical cyclones. **68th** Interdepartmental Hurricane Conference. College Park, Maryland, 3-4 March 2014.

REFERENCES

Langland, R. H., & Baker, N. L. (2004). Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. *Tellus A*, *56*(3), 189-201.

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