LONG-TERM GOALS

The long-term goal of this project is to improve the observations, analysis, and prediction of the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclone (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 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 are:

1. Develop an adjoint based optimal ocean sampling tool to investigate the optimal sampling resolution (horizontally and vertically), sampling location, and sampling frequency that will have the largest benefit of reducing the coupled COAMPS-TC forecast bias
2. Implement and test a novel new TKE buoyancy production in COAMPS-TC using an ensemble-based parcel ascent/descent method

APPROACH

The impact of AXBT data assimilation in the ocean forecast component of COAMPS-TC, i.e. Navy Coastal Ocean Model (NCOM), is determined using the appropriate ocean error cost functions from its assimilation system, the Navy Coupled Ocean Data Assimilation (NCODA), and the atmospheric TC boundary layer forecast biases. These adjoint-based data impact results are compared with data impact results from simple data denial studies where the AXBTs are either included or excluded in identical runs of the ocean data assimilation component of the coupled model. In addition, the impact of AXBT temporal and spatial resolution is investigated using an adjoint-based optimal sampling tool. The dependency of the AXBT impact on model resolution is investigated using different AXBT vertical
sampling resolutions. We investigate the AXBT optimal sampling strategy by developing an optimal sampling tool. This tool is based on the NCODA adjoint method and the pseudo AXBT profiles from COAMPS-TC forecasts are used to compute the data impact.

To improve the calculation of the buoyancy forcing term in COAMPS TKE closure, we developed 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 is then 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 are used to compute mean fluxes at the intervening w-levels by computing their thermodynamic departure from the mean state. 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**

- Completed and tested the new optimal ocean sampling tool
- Completed and tested the prototype 1D ensemble parcel TKE (ETKE) buoyancy flux scheme for stable and unstable test cases over the warm ocean
- Completed the hurricane Isaac AXCTD and dropsonde analysis
- Completed and tested the implementation of the new ETKE in COAMPS-TC

**RESULTS**

**a. Ocean targeting observing application**

The adjoint of a data assimilation system is used to calculate the sensitivity of model forecast error at observation locations used in the analysis. This extension of the adjoint sensitivity methods into observation space can provide estimates of the impacts of real data assimilated on reducing model forecast error (Langland and Baker, 2004a), as well as impacts of synthetic observations (Langland and Baker, 2004b). Synthetic observations are used in targeted observing applications where objective, model-based information provides guidance for deployment of special observations intended to improve model forecasts. In the work described here, using ideas developed by Langland and Baker (2004b), the NCODA adjoint (Cummings and Smedstad, 2014) was modified to compute the sensitivity maps of ocean temperature and salinity at a future time using a proxy of the actual model forecast error. The forecast error sensitivity maps are then used in the NCODA adjoint to determine impacts of targeted AXBT deployments in the vicinity of 36 hour forecasts of tropical cyclones.

The proxy for model forecast error is computed as the squared difference between two forecasts valid at the same time separated by the ocean analysis update cycle interval (12 hours). Two hurricane test cases in eastern Pacific (Hilda, 2015) and Gulf of Mexico (Isaac, 2012) are used to examine the variability of optimal ocean sampling. Figure 1 shows squared temperature differences between a 48 hour forecast issued on 9 Aug 2015 at 00Z and a 36 hour forecast issued on 9 Aug 2015 at 12Z for Hurricane Hilda off the Hawaiian Islands. As expected, forecast error varies with location and depth. Ocean temperature forecast errors at the surface clearly reflect the hurricane circulation in the
atmosphere. Below the surface, ocean forecast errors are associated more with the storm center and tend to diminish with depth. Figure 2 shows how temperature forecast errors evolve with time as the storm intensifies and weakens. Forecast errors are the greatest on 10 Aug 12Z when the storm was expected to intensify.

The expected impact function for targeted observations is the product of the forecast error at the observation location ($\partial J/\partial y$; output from the NCODA adjoint) and the observed model-data difference ($|y-x_b|$), where $J$ is the forecast error sensitivity, $y$ is the observation, and $x_b$ is the model first guess field. Since actual model-data differences are not known when the targeting guidance is prepared, it is necessary to generate pseudo observations. Observed values in this study are 36-hour model forecast temperatures at the synthetic AXBT sampling locations and forecast model levels above 700 m. The analysis field valid at the start of the 36-hour forecast is used as the background field to form the model-data differences. As noted above, the absolute value of these assumed innovations are used in the impact function to estimate data impacts. In this way both the forecast error sensitivity maps and the observations contribute to a positive impact value. The impact of a targeted observation is thus a measure of a change in variance or magnitude of the forecast error cost function (differences between forecasts valid at the same time). A large change in variance is assumed to represent a large data impact and the potential for a reduction in forecast error.

Figure 3 shows sets of 169 pseudo AXBT profiles in sampling patterns centered on the 36 hour forecast position of Hurricane Hilda (2015). The AXBTs are sampled every 20 km in all directions out to a radius of ~150 km from the storm center. The AXBT locations are color coded by the magnitude of the expected profile data impact. Profile data impacts are calculated as the sum of the impacts at each profile level. The data impact pattern varies with time but this targeting example suggests observing near the storm center and along the storm track to the southeast will reduce future ocean model forecast errors. Note that the storm was moving to the northwest during this time period.

Figure 4 shows the impacts of the AXBT profiles as a function of depth. Here, all AXBT profiles in the sampling patterns shown in Fig. 3 were summed within the specified depth interval ranges shown in Fig. 4. The results show AXBT data impacts are greatest in the upper 100 m of the water column near the surface, with somewhat higher values in the two rear quadrants cold wake region, and in vicinity of the mixed layer depth, which was near 50 m in the region during the time period of the storm.

In contrast to the Hilda optimal sample results, the Isaac (2012) test case shows the areas of the largest AXBT data impact are in the two forward quadrants (Fig. 5, top panels). The largest impact on the sea surface and salinity forecasts extends from the sea surface down to 100 m (Fig 5, bottom panels). Because the sample size is only two cases, it is not clear at this time whether the differences between Hilda and Isaac are from the variations of forecast TC environmental or internal TC structure. In addition, since these synthetic AXBTs are from the COAMPS-TC forecast fields, thus they also contain the information of real AXBTs that are assimilated into NCODA at the model initial time. The temporal and spatial resolutions of the real AXBTs that are assimilated may also play a role in determining the location of the largest impact area with respect to the TC center. We plan to increase the number of test cases in the future to further investigate these factors that may contribute to the optimal sampling.

Validation of the impact of the targeted observation sampling patterns on the reduction of actual forecast error is used the NCODA adjoint in data impact mode (Cummings and Smedstad, 2014). This
work is progressing using real AXBTs collected during under flights of Hurricanes Hilda and Guillermo by the TROPIC group (Sanabia et al. 2013).

Figure 1. Temperature forecast errors as a function of depth. The forecast errors are valid on 11 Aug 2015 at 00Z. Forecast errors are computed as \((x_{36} - x_{48}) (x_{36} - x_{48})\), where \(x\) is ocean temperature and the subscripts indicate forecast periods valid at the same time. The 36 hour forecast was issued on 9 Aug at 12Z while the 48 hour forecast was issued on 9 Aug at 00Z.

Figure 2. Temperature forecast errors at 54 m for different forecast times. The date time stamps on the figures are forecast error valid times. Hilda was forecast to intensify from 10 Aug 00Z to 10 Aug 12Z. This expected intensification is reflected in the larger and more expansive forecast errors at depth on 10 Aug 12Z. Forecast errors further away from Hilda are likely due to assimilation of different observations from one update cycle to the next.
Figure 3. Impacts of the AXBT surveys near the forecasted center of Hurricane Hilda at different forecast periods. AXBT locations with warmer colors represent the likelihood those AXBT probes have larger impacts on reducing NCOM forecast error.

Figure 4. Expected impacts of AXBT observations as a function of depth in the sampling patterns generated for Hurricane Hilda. The impacts tend to be larger at the depth of the mixed layer, which was about 50 m.
Figure 5. As in Figure 3 (top panels) and 4 (bottom panels) but for hurricane Isaac (2012).

b. Impact of AXBT vertical resolution on TC intensity forecast

A detail case study of hurricane Isaac (2012) shows there is a positive COAMPS-TC intensity forecast sensitivity to the AXBT data resolution that are assimilated into NCODA. The assimilation of the higher 1-m resolution AXBTs experiment consistently produces a lower intensity bias than the control forecasts that assimilated the lower-resolution AXBT (Fig. 6). These comparisons are performed for four consecutive five-day COAMPS-TC intensity forecasts initiated on 1200 UTC 26 Aug to 0000 UTC 28 Aug with 12 h time interval. In general, assimilation of the high-resolution AXBT results in a cooler initial ocean temperature (not shown). However, significant differences in the forecast SST occurs close to the shelf areas where the mixed layer depth is shallower and therefore more sensitive to the wind stress forcing. Assimilation of higher resolution AXBTs does not show any sensitivity on reducing the track error.
c. Analysis of the salinity

Although the AXBT only measure the ocean temperature, we had the opportunity to also investigate whether salinity measurements may have impact on TC intensity prediction using other types of sensors such as the Airborne eXpendable Conductivity-Temperature-Depth (AXCTD) from pre-, in-, and post-storm flights between 27 and 30 Aug of hurricane Isaac (Jaimes and Shay 2015). In addition, analysis of two Eastern Pacific sequential hurricanes Iselle and Julio (2015) from ARGO floats that happened to be in the vicinity of these two TC tracks are also conducted. We analyzed 153 in situ ocean profiles from these three cases. The freshening of salinity that results from 150-300 mm of rainfall in these hurricanes is about 0.1-0.2 PSU. Eastern Pacific Argo floats near the tracks of Iselle and Julio indicate the barrier layer potential energy (BLPE) values are between 750-2000 J/m² just after TC passage (Fig. 7). AXCTD profiles deployed before, during, and after Isaac in the Gulf of Mexico show how the barrier layer develops throughout a TC passage (Fig.8). In these TCs, the corresponding maximum barrier depths are 10-20 m deep and are independent of the density stratification within the isothermal layer. This suggests BLPE is a better measure of the barrier layers’ capacity to suppress mixing and minimize SST cooling from hurricanes and that the TC can create its
own barrier layer (Steffen et al. 2015). The existence of BLPE suppressed mixing of the cold ocean water from below, thus reduced the negative effect of ocean on TC intensity change.

Analysis of COAMPS-TC simulations and comparisons of model forecast BLPEs with these observations are in progress. Additional numerical experiments to examine the sensitivity of simulated BLPE impact to the TC intensity forecast will be conducted in future studies.

Figure 8. (a) TRMM precipitation totals (mm) from August 01-12, 2014 during Hurricanes Iselle and Julio with Argo float locations (red dots) and (b) corresponding BLPE values pre-storm (triangle), in-storm (circle), and post-storm (square). TC strength is represented by the track color (magenta: major hurricane, red: hurricane, yellow: tropical storm, green: tropical depression). The dashed box covers the area with largest BLPE values calculated from Argo floats 3900665, 4900810, 49001240, 49001443, and 5903467.
Figure 9. (a) TRMM 3-day precipitation totals (mm) from August 14-16, 2012 with pre-storm AXCTD profile locations. (b) TRMM 6-day precipitation totals from August 26-31, 2012 with in-storm (red, circle) and post-storm (red, square) AXCTD profile locations. BLPE values calculated for Hurricane Isaac, (c) pre-storm., (d) in-storm, (e) post-storm, and (f) all profiles.

d. Ensemble-based atmosphere boundary layer mixing

Both the idealized 1D testes in COAMPS on the growth of dry and moist boundary layer over a warm ocean show the new ensemble-based mixing algorithm (ETKE) works well in these conditions (Fig. 10). The buoyancy fluxes and mixing length are determined from the ensemble-based parcel
ascent/descent (EMPM) within the mean environment using 30 parcels. The growth of the Wangara Day 33 growing daytime dry boundary was simulated using 1D ETKE and compared to the observations. The maximum boundary top around 1.2 km was well simulated by ETKE although the boundary layer temperature is less than a half degree cooler than the observation (Fig. 10a). For the growth of moist boundary layer case, the moisture bias is small and is less than 0.25 kg m⁻³. The growth of the moist boundary layer is very similar to the observation (Fig. 10b). The sensitivity of the temperature and moisture bias from the number of ETKE parcels will be examined in a future study.

To test the new ETKE in COAMPS-TC, we implemented the 1D proto-type algorithm into COAMPS TKE scheme. In these cases, the regular TKE scheme is used except that the buoyancy flux term is computed using the ensemble parcel method and the mixing length is diagnosed based on actual parcel displacements. Both the idealized thunderstorm test and real-data test using the hurricane Isaac case are conducted. A preliminary uncoupled COAMPS-TC Isaac one hour forecast using the initial conditions from 00 UTC 28 Aug is compared with the control simulation (CNTL) that has a same setup except without ETKE. The grid 2 (4 km) one-hour simulation of boundary layer height shows ETKE produces a boarder and smoother TC boundary layer structure than CNTL (Fig. 11). The spurious PBL height of more than 7 km in the CNTL simulation over the south east quadrant is now removed in the ETKE experiment. The minimum sea level pressure is about 8 hPa stronger in the ETKE experiment compared to the CNTL. Notable differences are also seen in the precipitation and cloud fields (not shown) both inside and outside the eyewall regions.

In order to compare the ETKE and CNTL model predicted hurricane boundary layer structure with the observations, we analyzed dropsondes deployed by the National Oceanic and Atmospheric Administration (NOAA) before, in, and after storm for the Isaac case. Fig. 12 shows an example of 69 dropsondes temperature, wind speed, and humidity profiles between 28-29 Aug, one day prior to Isaac made landfall. The wind speeds are computed relative to the TC translation speed. Preliminary comparisons of these profiles in four different TC quadrants show larger temperature and relative humidity variances in the southeastern quadrant where the dropsonde temperatures are warmer and drier (Fig. 12f).
Figure 10. (a) Comparison of ETKE Wangara Day 3 daytime dry boundary layer temperature (°K) growth with observation and (b) the mixing of moisture (g kg\(^{-1}\)) using ETKE 30 parcels.

Figure 11. COAMPS-TC nest 2 forecast 1 h PBL height (m) and sea level pressure (hPa) from (a) CNTL and (b) ETKE simulations. The 10-m wind barb is plotted every 10 model grid points.
Figure 12. (a) Locations of NOAA dropsondes deployed during the in-storm stage of Isaac between 28-29 August, 2012. (b) As in (a) except in a storm-relative cylindrical coordinate. (c) Profiles of dropsonde temperature (°C), wind speed (ms⁻¹), and relative humidity (%) from northwest quadrant of Isaac. (d)-(f) as in (c) except for the southwest, northeast, and northwest quadrants respectively.

IMPACT/APPLICATIONS

This project aims to improve the COAMPS-TC prediction through a better representation of the TC coupled boundary layer. The adjoint NCODA can be used to routinely monitor the operational coupled COAMPS ocean assimilation. The new ETKE is a generalized scheme that can be tested for non-TC boundary layer forecasts.

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


REFERENCES


