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Improvement of High-Resolution Tropical Cyclone Forecasts Using COAMPS-TC

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LONG-TERM GOALS

The long-term goal of this project is to develop a robust and hardened high-resolution air-ocean coupled tropical cyclone (TC) data assimilation and prediction system that is able to assimilate the wide variety of available *in-situ* and remotely-sensed observations in order to analyze and predict TC structure and intensity changes in an operational environment. TC intensity prediction by numerical models has shown little improvement over the past several decades and remains a formidable forecast problem. It is generally accepted now that while advancements in data assimilation and modeling have resulted in better analyses and predictions of steering flow, the processes that affect the structure and intensity of tropical cyclones are much more difficult for current numerical models to capture and reproduce. We also seek to improve prediction of TC intensity and structure change through a new understanding and prediction of the TC outflow layer. The outflow layer is hypothesized to play a key role in tropical cyclone intensification and structural changes, and is investigated using the innovative Global Hawk and satellite observations from the Hurricane and Severe Storms Sentinel (HS3) field program in the Atlantic during 2012-2014, observations from the ONR-sponsored Tropical Cyclone Intensity (TCI) experiment in 2015, and state-of-the-science tropical cyclone models.

OBJECTIVE

The objective is to develop, validate, and transition new methods to initialize a coupled tropical cyclone (TC) modeling system using advanced data assimilation and physical parameterization methods in order to achieve superior short and medium term forecasts of TC structure and intensity. Our approach is to leverage emerging data assimilation, modeling, and air-ocean coupling techniques, as well as observational results from the scientific community including the recent T-PARC/TCS08, ITOP, HS3, and TCI field campaigns to build upon the existing modeling capabilities. We will develop multiple approaches to initialize the tropical cyclone including static and dyanmic initialization methods. The boundary layer and cloud microphysics parameterizations, which have a direct impact on the short-term forecasts as well as the analysis background fields, will be developed further and new methods will be tested.

Several key scientific objectives are identified in relation to TC outflow dynamics, processes, and evolution: i) the coupling of the TC outflow with the inner-core convection and its relationship to

intensity changes, ii) the evolution of TC outflow during trough interaction and its importance for accurate intensity prediction, and iii) the impact of observations (HS3 and satellite) in sensitive regions in the TC environment (including outflow regions away from the TC inner core) on predictions of TC intensity and structure.

APPROACH

Our approach is to integrate emerging data assimilation, modeling, and coupling techniques, as well as observational results from recent Office of Naval Research (ONR) and NASA field campaigns, into the existing framework in the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]) for applications to the analysis and prediction of TC position, structure, and intensity (referred to as COAMPS-TC). Our specific goal is to improve the COAMPS-TC analysis and prediction of intensity and structure. Specific technologies that will be developed, tested, and integrated into COAMPS for application to TC prediction in this project using COAMPS-TC are: (1) TC initialization and analysis techniques, (2) TC physical process parameterizations with particular emphasis on the microphysics, (3) air-ocean-wave coupling techniques, and (4) TC outflow basic science issues. The proposed project will also leverage other research that has taken place on COAMPS-TC including the recently completed COAMPS-TC RTP and the coupled modeling development through the Battlespace Environments Institute (BEI), which addressed the coupling of the COAMPS atmospheric model to the Navy Coastal Ocean Model (NCOM) and the SWAN and WWIII wave models using the Earth System Modeling Framework (ESMF). Also, the project will leverage scientific findings from the recent ONR TCS08, ITOP, TCI programs and the NASA/ONR HS3 program.

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WORK COMPLETED

As a direct result of the research performed in this project, the skill of COAMPS-TC was considered superior to the existing Navy tropical cyclone prediction model, GFDN, and the COAMPS-TC code was transitioned to operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC). The COAMPS-TC became fully operational at FNMOC on 6 June 2013. Major upgrades to the system to improve the intensity and track predictions were transitioned to operations in 2014 and more recently in spring 2015 and went operational at FNMOC in June 2015.

In the past year, we developed and evaluated several approaches to initialize the tropical cyclone vortex and environment including an improved static vortex initialization method. An improved dynamical vortex initialization has been developed as well, based on heating profiles in the eye wall. Advancements have been made to the physical parameterizations in the model including the surface drag, boundary layer, and surface flux representations. New methods to represent the model terrain on moving grid meshes and the specification of the lateral boundary conditions for the nest grids and outer mesh have been developed and demonstrated to be superior to the previous model version.

COAMPS-TC has been tested in both coupled and uncoupled modes over the past several tropical cyclone seasons in the Pacific and Atlantic basins. In these applications, the atmospheric portion of the

[1] COAMPS® and COAMPS-OS® are registered trademarks of the Naval Research Laboratory.

COAMPS-TC system makes use of horizontally nested grids with grid spacing of 45, 15, and 5 km. The 15- and 5-km grid-spacing meshes track the TC center, which enables the TC convection to be more realistically represented on the finest mesh in an efficient manner. The forecasts are routinely disseminated in real time to NHC, JTWC, and HFIP researchers. The forecast graphics are available in real time at http://www.nrlmry.navy.mil/coamps-web/web/tc. Additionally, the COAMPS-TC ensemble has been run in real time for the W. Atlantic and E. Pacific.

RESULTS

a. COAMPS-TC Real-Time and Retrospective Model Forecasts

Real-time and retrospective COAMPS-TC forecasts have been conducted using U.S. Department of Defense High Performance Computing (HPC) platforms over the past several years. Verification results for the 2013-2014 seasons in the Western Pacific basin are shown in Fig. 1, for a homogenous sample of retrospective COAMPS-TC forecasts. The new version of COAMPS-TC has considerably smaller track and intensity errors than the control version, which was used in operations in 2014. This promising performance is a result of a large effort devoted to developing and improving COAMPS-TC over the past several years. The new advancements include an improved vortex initialization method, new physics, improved terrain specification, and various other minor improvements.

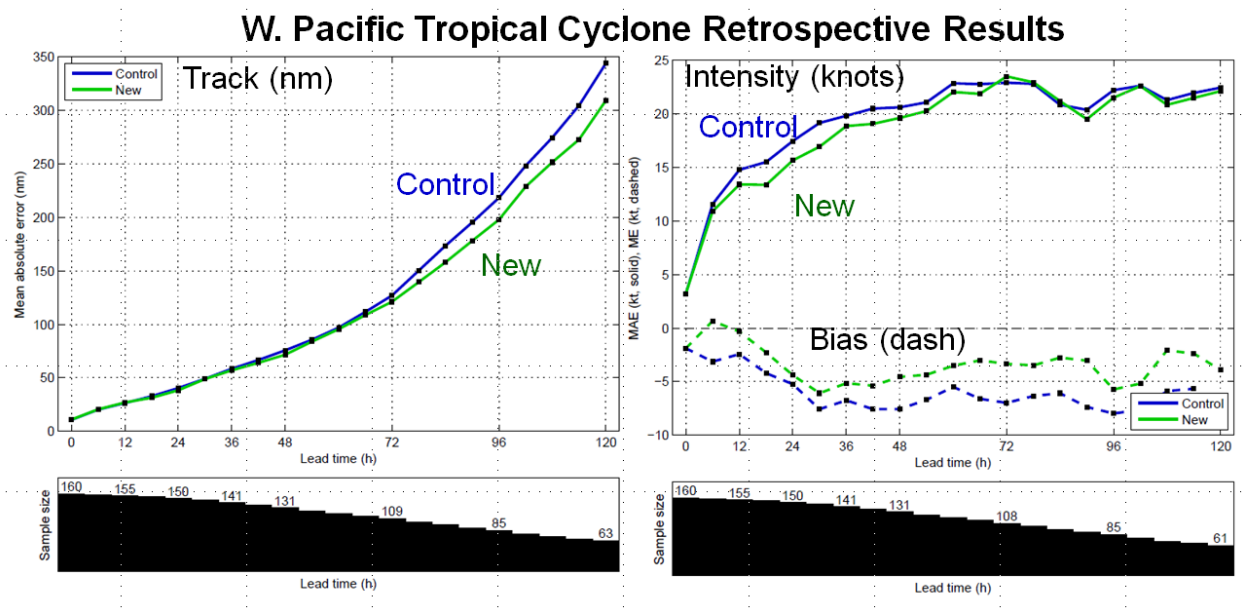

Figure 1: Track and intensity verification results for the 2013 Western Pacific basin season, for a homogeneous comparison of the control version (used in 2013) and a new version of COAMPS-TC. The intensity results show mean absolute error (solid) and mean error (dashed), while the track results show mean absolute error.

b. Coupled COAMPS-TC Forecast Experiments

The representation of air-sea interaction processes is crucial for the accurate prediction of tropical cyclone intensity. We have investigated some key challenges related to TC intensity prediction and air-sea interaction processes using the Navy's operational COAMPS-TC prediction system coupled with

the 3D circulation Navy Coastal Ocean Model (NCOM). We have identified a low intensity bias in COAMPS-TC that stems from model biases in the momentum flux utilized by NCOM. The recent case of hurricane Blanca (2015), a storm that occurred off the Baha California which produced a significant ocean cold wake of 4-6 °C, is used to examine the sensitivity of ocean response to wind stress in the air-ocean and air-ocean-wave coupled COAMPS-TC. The results show both the coupled TC track and intensity differ substantially relative to the uncoupled COAMPS-TC. When the wind stress magnitude is reduced to just 1/3 of the uncoupled value, there is a significant damping of the ocean internal wave structure and cold wake magnitude. In an ongoing study, recent advancements in COAMPS-TC have been used to quantify the prediction of momentum flux across the air-sea interface by coupling with a wave model Simulating Wave NearShore (SWAN).

c. Dynamic Initialization Development and Experiments

A new dynamic initialization method for COAMPS-TC was developed and evaluated The improvements are based on adding prescribed satellite-derived latent heating rates. The new method allows for separate relaxation to the nondivergent and divergent momentum components with different nudging coefficients. Strong nudging is applied to the nondivergent wind (which is captured well by the analysis), and the divergent winds are derived through satellite-derived convective and stratiform latent heating rates and weak analysis nudging. Using this new method, COAMPS-TC can be "warm-started" with model physics and hydrometeors, and improved mass-wind balance, which should be superior to that provided by the static initialization. The methodology is still in the early stages of development, however, the results are already promising.

d. COAMPS-TC Ensemble Forecasts

While research is ongoing to improve deterministic atmospheric forecasts through advancements to the forecast model and more accurate estimates of the initial state, simultaneously there has been interest in obtaining probabilistic information derived from ensemble forecasts. A new COAMPS-TC ensemble system that is capable of providing probabilistic forecasts of TC track, intensity, and structure has been developed by scientists at NRL in Monterey, CA. A real-time COAMPS-TC ensemble system has been run in a demonstration mode in 2014-2015 for the W. Atlantic basin. Ten-member forecasts are performed four times daily to five days using three nested grids with horizontal resolutions of 27, 9, and 3 km. An example of probabilistic products for Hurricane Edouard (2014) are shown in Figure 2 for both track (left panel) and intensity (bottom panel). This is a real time forecast initialized at 1200 UTC 23 August, which is four days prior to landfall. The probabilistic track product shows the TC position from the individual ensemble members every 24 h and ellipses that encompass the 1/3 and 2/3 of the ensemble member forecast positions. Note that the observed landfall location of the eye was within the ensemble distribution, with considerable spread at the TC moved into the extratropics. The probabilistic intensity product (right panel) shows a considerable spread among the members, particularly in the near term during intensification. These products can be valuable to assess the uncertainty in both track and intensity forecasts and NRL is currently developing these capabilities and products further.

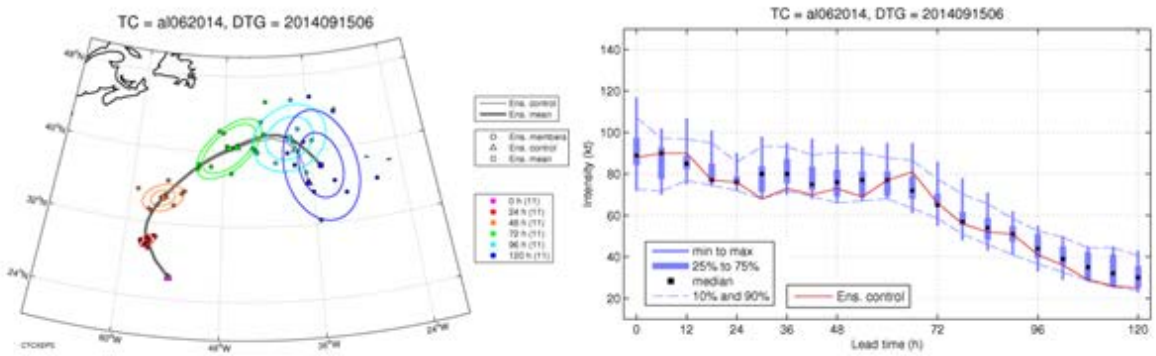

Figure 2. Probabilistic products from the COAMPS-TC ensemble for Hurricane Edouard corresponding to the track (left panel) and intensity (right panel). This real-time forecast was initialized at 0600 UTC 15 September 2014. The probabilistic track product shows the TC position from the individual ensemble members every 24 h and ellipses that encompass 1/3 and 2/3 of the ensemble members. The intensity (knots) is shown as a function of forecast lead time (hours) using boxplots with the median, minimum, maximum, and 10% and 90% percentile of the distribution marked. The control ensemble member intensity time series is shown in red.

e. Analysis of Global Hawk Observations from the HS3 Field Campaign

In the third year of the NASA HS3 program, we continued the work we started in previous years investigating the morphology of upper-tropospheric outflow jets, using the observations taken by AV-6 in the 2012-2014 field campaign. In particular, we were interested in analyzing the detailed vertical structure of outflow jets, as resolved by the Global Hawk AV-6 dropsondes.

Comparisons are made between strengthening and weakening systems that were observed amongst the entire 2012-2014 HS3 dataset, with an emphasis on warm core and outflow structure since the ability to directly sample these upper-level features is a relatively unique aspect of HS3. In addition to the four flights into Nadine (2012) and one flight into Humberto (2013), AV-6 sampled Hurricanes Cristobal and Edouard in 2014 during both intensification and weakening phases, as well as Tropical Storm Dolly during its weakening phase. While significant case-to-case variability exists, some general results are also observed.

Overall, a larger and stronger upper-level divergence signature is associated with intensifying than non-intensifying systems regardless of current intensity, especially from 180-150 hPa, with less difference between the samples at or below 200 hPa. Stronger tropical cyclones are not necessarily associated with greater divergence aloft. However, intense upper-level divergence does not guarantee a strengthening system, as two non-developing tropical waves flown during HS3 demonstrate. While virtually all of the hurricanes flown exhibit some reflection of an upper-level anticyclone all the way to 100 hPa which is typically vertically-aligned with the center of the cyclone, few if any of the tropical storms do, and the ones that do fail to have the center of the cyclone vertically-aligned with the center of the upper-level anticyclone. Additionally, the upper-level anticyclone is found to collapse inwards to smaller and smaller radius above the cyclone upwards from 200 hPa through 100 hPa. This

phenomenon is evident to varying degrees for all the hurricanes sampled, and was most evident for hurricane Nadine but not evident for tropical storms. It is suspected that an upward bulge of the tropopause may be in part responsible for this phenomenon, although results are as of yet inconclusive. Complementary to this finding, azimuthal cross-sections of radial and tangential winds reveal a downward outward slope of the upper-level anticyclone away from the TC which is quite steep for hurricanes (e.g. Hurricane Edouard, Fig. 3a) while being relatively flat for tropical storms (e.g. Tropical Storm Nadine, Fig. 3b). Lastly, the structure and magnitude of the outflow varies rapidly in the vertical in the majority of cases. Typically the level of maximum radial wind or minimum tangential wind is sharply-defined in the vertical, with extreme vertical gradients especially evident in the radial-component of outflow and more so above than below the maximum. It is also worth noting that the level of minimum tangential wind is typically slightly (25-50 hPa) above the level of maximum radial winds. Somewhat unexpectedly, one or more inflow layers were also observed just above and below the primary outflow layer. Much of this vertical variation in outflow structure captured in the HS3 dropsondes data is only poorly resolved in satellite-derived atmospheric motion vectors (AMVs).

Interesting variability in warm-core structure was also observed in the HS3 data. Several cases exhibited pronounced double warm cores, although the higher warm core was almost always dominant. The one exception to this finding was the final flight into Tropical Storm Edouard which exhibited a warm core as low as 600-700 hPa as the system was rapidly weakening and strongly interacting with extra-tropical features. Alternatively, the 14 Sep 2014 flight into Hurricane Edouard in Fig. 4 suggests an elongated warm core, strongest at 250 hPa but prominent through 700 hPa and below. A broad warm anomaly closer to 100 hPa away from the hurricane's center associated with a lowering of the tropopause is also evident.

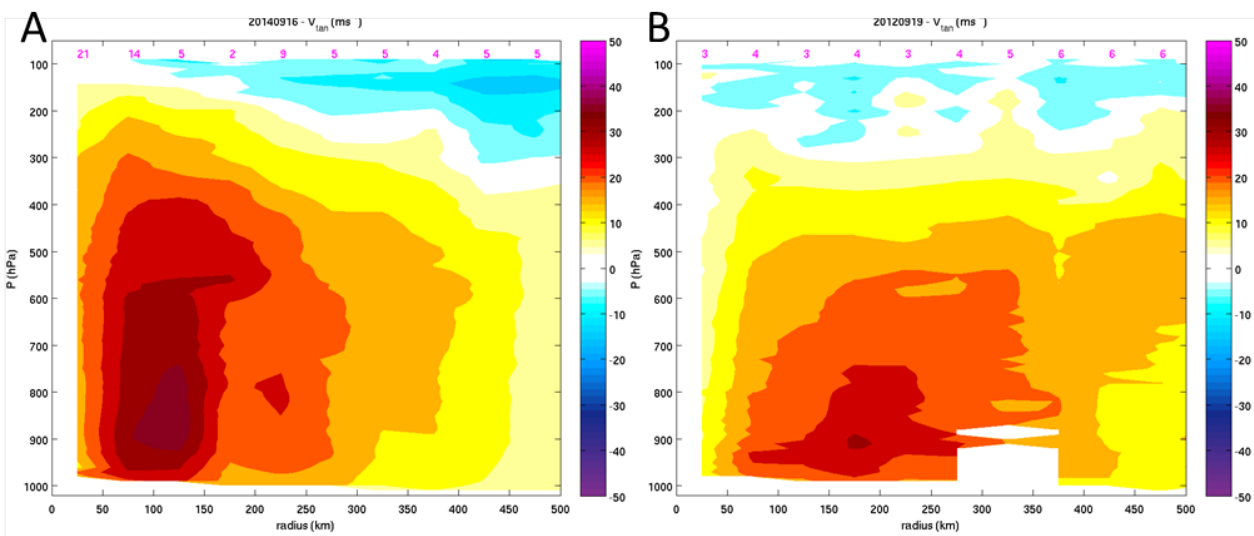

Figure 3: azimuthal-average tangential winds (m s^{-1}) for (A) the 16 September 2014 flight into Hurricane Edouard and (B) the 19 September 2012 flight into Tropical Storm Nadine (right), computed in 50-km radius bins. The magenta numbers indicate the number of dropsondes within each bin.

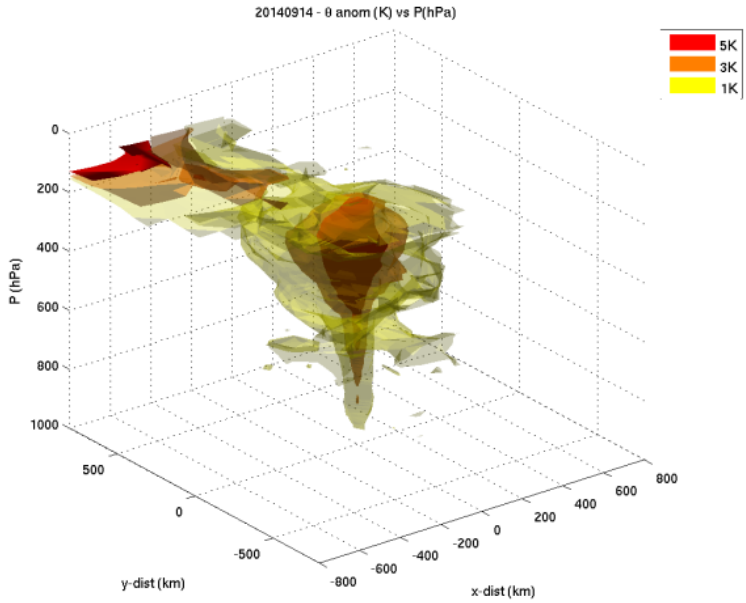

Figure 4: A three-dimensional visualization of potential temperature anomalies (K) for intensifying Hurricane Edouard on 14 September 2014 with respect to the mean temperature profile sampled by all dropsondes during the flight. Warm anomalies depicting the tropical cyclone warm core and a lowering of the stratosphere are contoured at 1, 3 and 5K.

f. Tropical Cyclone Outflow Dynamics

The effect of having tropical cyclone outflow interact with a variety of jet and trough structures on the cyclone's structure and intensity is examined via a large number of idealized COAMPS-TC simulations. These simulations, run at 5km resolution with full moist physics on a beta-plane with periodic boundary conditions in x, allow us to reduce a complicated problem down to the fewest possible degrees of freedom while still allowing for realism. It is found that enhancing upper-level divergence without simultaneously reducing inertial stability (or vice versa) is insufficient to lead to a meaningful intensification of the cyclone. It is also typically necessary to reduce both the tangential wind and the vorticity terms in the inertial stability equation in order to achieve having the cyclone's outflow to effectively phase with a neighboring synoptic-scale feature, whether it is a trough or a jet. Direct perturbation of the upper-level wind field via nudging the near the outflow region reveals that it is possible to enhance one term in the inertial stability equations while reducing another, resulting in a cancelation effect and having no meaningful effect on the cyclone. An upper-level trough has the advantage versus the zonal jet of having a more sharply defined inertial stability minimum, which by correctly placing the cyclone and the trough at the initial time, one can investigate the optimal spacing and timing that allows the hurricane's secondary-circulation to couple with the jet. An example of a pronounced inertial stability minimum to the northwest of a tropical cyclone in the region of jet interaction appears in Fig. 5. Also evident in Fig. 5 is the fact that the region of reduced inertial stability in a curved trough may actually be quite small, occupying less than a single quadrant of the cyclone outflow region while still acting to intensify the cyclone. The curvature of the trough also allows the additional mass evacuated in the outflow to propagate downstream and not return to its point of origin.

It is found that the tropical cyclone is very sensitive to its exact initial placement relative to the trough or jet with which it is interacting. If the cyclone is too far from the jet, there will be minimal interaction and the cyclone will neither strengthen nor weaken, an example of which appears in Fig. 6. If the cyclone is too close to the jet, it will become subject to vertical wind shear and weaken. Lastly, if the cyclone is not optimally placed with respect to the trough axis, the trough will not effectively evacuate mass at the upper levels away from the cyclone. Instead, the outflow will eventually curve back towards the cyclone, consistent with studies which have examined the real-world environments of non-intensify tropical cyclones.

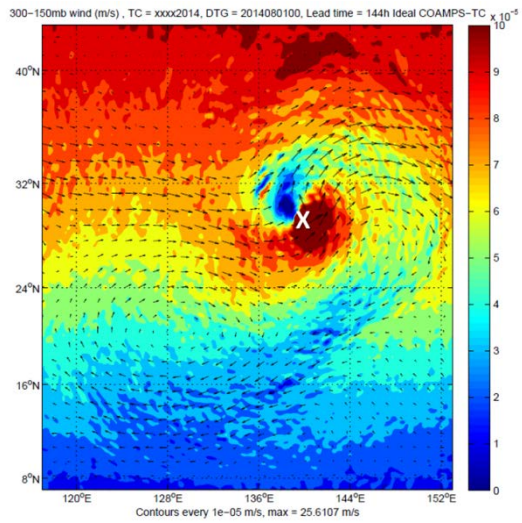

Figure 5: 300-150 hPa mean wind vectors and storm-relative inertial stability (shaded). The center of the tropical cyclone is indicated by the white 'X'.

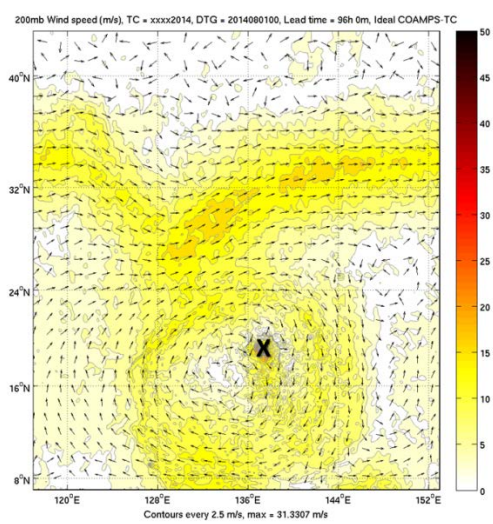

Figure 6: 200 hPa wind vectors and wind speed (m s^{-1}, shaded). The center of the tropical cyclone is indicated by the black 'X'.

IMPACT/APPLICATIONS

Tropical cyclones remain the most disruptive and devastating environmental threat impacting Fleet operations. We anticipate that an increase in accuracy of tropical cyclone forecasts will result in significant cost benefit to the Navy. Additionally, with more accurate tropical cyclone forecasts, the cost-loss ratio for Fleet sortie events should be improved. Improvements to COAMPS-TC accomplished under this project have led to an accelerated transition of the latest version of COAMPS-TC to Navy operations, which has a tremendous benefit. Improved tropical cyclone prediction, with regard to the position, intensity and structure, will reduce shipping diverts, Fleet sorties-and canceled/modified carrier operations.

Additionally, the real-time forecast and operational Navy forecasts are shared with the civilian sector through the Joint Typhoon Warning Agency and the NOAA National Hurricane Center. The cost of evacuating coastal areas before a hurricane is estimated to cost $1 million for every mile of coastline evacuated. These dramatically improved track, intensity, and structure forecasts can reduce the size of evacuation areas and mitigate costs for both DoD and the civilian population.

TRANSITIONS

As a direct result of the research performed in this project, the COAMPS-TC was considered superior to the existing Navy tropical cyclone prediction model, GFDN, and the COAMPS-TC code was transitioned to operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC) and became fully operational at FNMOC in 2013. Major upgrades to the system were made in 2014 and 2015 and the latest version of COAMPS-TC became operational in June 2015. The tropical cyclone application of COAMPS transitioned to the 6.4 project within PE 0603207N (PMW-120), which has a focus on the transition COAMPS to FNMOC.

RELATED PROJECTS

COAMPS and COAMPS-TC will be used in related 6.1 projects within PE 0601153N that include studies of tropical cyclone dynamics, air-ocean coupling, and boundary layer studies, and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components (QC, analysis, initialization, and forecast model) of COAMPS and COAMPS-TC. Also, this project is closely coordinated with a NASA supported project focused on the HS3 program.

PUBLICATIONS

Refereed Publications: Submitted or appeared.

Black, P.G., L. Harrison, M. Beaubien, R. Bluth, H. Jonsson, A. B. Penny, R. W. Smith and J. D. Doyle, 2014: High Definition Sounding System (HDSS) for atmospheric profiling, *J. Atmos. Oceanic Technol.*, Submitted- in review.

Doyle, J.D., R.M. Hodur, S. Chen, Y. Jin, J. Moskaitis, S. Wang, E.A. Hendricks, H. Jin, and R.A. Smith, 2014: Tropical Cyclone prediction using COAMPS-TC, *Oceanography*, **27**, 62-73.

Doyle, J.D., C. Amerault, C.A. Reynolds, P. Alex Reinecke, 2014: Initial condition sensitivity and predictability of a severe extratropical cyclone using a moist adjoint. *Mon. Wea. Rev.*, 142, 320-342.

Hendricks, E. A., W. H. Schubert, Y.-H. Chen, H.-C. Kuo, and M. S. Peng, 2014: Hurricane eyewall evolution in a forced shallow water model. J. Atmos. Sci, 71, 1623-1643.

Hendricks, E. A., Y. Jin, J. R. Moskaitis, J. D. Doyle, M. S. Peng, C.-C. Wu and H.-C. Kuo, 2015: Numerical simulations of Typhoon Morakot (2009) using a multiply-nested tropical cyclone prediction model, *Wea. Forecasting* (submitted).

Jin, H., M. Peng, Y. Jin, J.D. Doyle, 2014: An Evaluation of the impact of horizontal resolution on tropical cyclone predictions using COAMPS-TC, *Wea. Forecasting,* **29**, 252-270.

Jin, Y., S. Wang, J. Nachamkin, J.D. Doyle, G. Thompson, L. Grasso, T. Holt, J. Moskaitis, H. Jin, R.M. Hodur, Q. Zhao, M. Liu, and M. DeMaria, 2014: The impact of ice phase cloud parameterizations on tropical cyclone prediction. *Mon. Wea. Rev., **142,*** 606-625.

Peng, J. , M. S. Peng, T. Li, and E. A. Hendricks, 2014: Effect of baroclinicity on vortex axisymmetrization, Part II: Baroclinic basic vortex. *Adv. Atmos. Sci*., 31, 1267-1278.

Peng, M. S., J. Peng, T. Li, and E. A. Hendricks, 2014: Effect of baroclinicity on vortex axisymmetrization, Part I: Barotropic basic vortex. *Adv. Atmos. Sci*., 31, 1256-1266.

Yang, Y.-T., E. A. Hendricks, H.-C. Kuo, and M. S. Peng, 2014: Long-lived concentric eyewalls in Typhoon Soulik (2013). *Mon. Wea. Rev*., 142, 3365-3371.

Yang, Y.-T., H.-C. Kuo, E. A. Hendricks, Y.-C. Liu, and M. S. Peng, 2015: Relationship between Concentric Eyewalls Typhoons and ENSO in the western North Pacific basin, *J. Climate*, submitted.