DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Improvement of High-Resolution Tropical Cyclone Structure and Intensity Forecasts using COAMPS-TC

James D. Doyle
Naval Research Laboratory
Monterey, CA 93943-5502
phone: (831) 656-4716 fax: (831) 656-4769 e-mail: james.doyle@nrlmry.navy.mil

Award Number: N0001412WX20683
http://www.nrlmry.navy.mil/coamps-web/web/tc

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. Significant gains have been made in TC track prediction over the past three decades. This considerable achievement is due, in large part, to the steady improvement of numerical models, especially the global scale prediction systems, and the judicial utilization of multi-model ensemble results. In contrast, the TC intensity forecast by numerical models has shown very little improvement during the same time period, and remains a formidable forecast problem. Advanced statistical prediction models nowadays are able to predict the trend for intensification, but as statistical tools, they inherently cannot predict the rapid intensity changes, as evident in Katrina of 2005, and Roke in the W. Pacific in 2011. It is generally accepted now that while advancements in data assimilation and modeling have resulted in better analyses and predictions of steering flows, the processes that affect the structure and intensity of tropical cyclones are much more difficult for current numerical models to capture and reproduce. Physical processes in tropical cyclones that can affect their structure and intensity include enthalpy and mechanical interchanges with the underlying ocean and land surfaces, shallow and deep atmospheric convection in the convectively unstable tropical atmosphere with vertical and horizontal wind shears, and internal multi-scale non-linear dynamic interactions. Current prediction systems have been shown to be able to reproduce rapid intensification in case studies involving complex upper tropospheric and oceanic conditions in a carefully conducted simulation model.

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 advanced physical parameterization methods in order to achieve superior short term forecasts (0-2 days) 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 and ITOP field campaigns to build upon the existing modeling capabilities. We will develop multiple approaches to initialize the tropical cyclone including (from least to most

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **SEP 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Improvement of High-Resolution Tropical Cyclone Structure and Intensity Forecasts using COAMPS-TC**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,7 Grace Hopper Avenue,Monterey,CA,93943-5502**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

sophisticated and challenging method): i) bogus initialization, ii) three-dimensional variational analysis (3D-Var) using synthetic observations, iii) dynamical initialization (TCDI), iv) an ensemble Kalman filter approach, and v) four-dimensional variational (4D-Var) analysis. 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.

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) 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 0-48 h 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, and (3) air-ocean-wave coupling techniques. 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 emerging scientific findings from the recent TCS08 and ITOP in the Northwestern Pacific.

WORK COMPLETED

We are currently developing and evaluating several approaches to initialize the tropical cyclone vortex and environment including (from least to most sophisticated and challenging method): i) bogus initialization, ii) three-dimensional variational (3D-Var) analysis using synthetic observations, iii) dynamical initialization (TCDI), iv) an ensemble Kalman filter (EnKF) approach, and v) four-dimensional variational (4D-Var) analysis. Versions of several these methods, namely the 3D Var with synthetics and TCDI, have already been developed for COAMPS-TC and to varying degrees evaluated. However, their performance has been lacking in a number of aspects including short term intensity and track error issues. Greater promise for more accurate initialization of the TC vortex exists for the more sophisticated EnKF and 4D-Var methods. The EnKF and 4D-Var methods will be advanced further as part of this project, and all of the methods will be statistically evaluated for a large set of TC cases using a variety of datasets include remote sensing.

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 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 make use of the Navy or the NOAA global model for lateral boundary conditions. The forecasts are routinely

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

disseminated in real time to NHC, JTWC, and HFIP researchers. The forecast graphics are also available in real time at http://www.nrlmry.navy.mil/coamps-web/web/tc.

A two-stage dynamic initialization scheme for COAMPS-TC has been developed and evaluated. The scheme consists of a tropical cyclone dynamic initialization (TCDI) method in conjunction with a forward dynamic initialization (DI). In the TCDI stage, a dynamically spun-up vortex matching the observed intensity is inserted into the COAMPS-TC initial conditions after 3D-Var. In the subsequent DI stage, COAMPS-TC is integrated for a period of 12 h, with Newtonian relaxation to the modified 3D-Var analysis horizontal momentum with the addition of the TCDI vortex. This two stage dynamic initialization scheme improves both the vortex nonlinear balance and consistency in the transverse circulation, while reducing spurious gravity wave activity generated by interpolation and analysis errors in the 3D-Var scheme. In addition the benefits listed above, this two-stage dynamic initialization scheme represents only a minor additional cost to the 3D-Var scheme, and it is significantly cheaper in a computational sense than either the 4D-Var or EnKF methods.

RESULTS

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

Real-time COAMPS-TC forecasts have been conducted using U.S. Department of Defense High Performance Computing (HPC) platforms over the past several years. An example of the intensity forecast performance of COAMPS-TC for a large number of cases (more than 450 cases at the 24 h forecast time) in the W. Atlantic region for the 2010 and 2011 seasons is shown in Figure 1 (for a homogeneous statistical sample). The COAMPS-TC model had the lowest intensity error of any dynamical model for the 36-120 h forecast times, which is an important period for forecasters and decision makers. Other numerical models included in this analysis are operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). This promising performance is a result of a large effort devoted to developing and improving COAMPS-TC over the past several years. Key aspects of the COAMPS-TC system that have contributed most to the forecast intensity skill improvement (as deduced from sensitivity tests) include: i) new synthetic observations and data assimilation system modifications; ii) modified turbulence parameterization (in particular the mixing length) in and above the boundary layer; iii) surface drag, heat, and moisture exchange consistent with recent field campaigns; and iv) fidelity of the microphysical parameterization.

An example of a real-time COAMPS-TC forecast for the recent Hurricane Irene is shown in Figure 2. The composite National Weather Service radar reflectivity is shown in the top panel near the time of landfall in North Carolina at 1148 UTC 27 August 2011 and the COAMPS-TC predicted radar reflectivity at 36 h valid at 1200 UTC is shown in the bottom panel. The COAMPS-TC forecast shown in Figure 2 is for the model second grid mesh (15 km horizontal resolution). The model prediction was accurate in the track (skill similar to other dynamical models), eventual landfall location (Figure 2), storm intensity (Figure 4), as well as the structure and size (from a qualitative perspective), an especially important characteristic of this particular storm in such close proximity to the U.S. East Coast. One noteworthy aspect of Irene was its large size, with tropical storm force winds (34 knot) extending radially outward from the eye for nearly 300 km. The large size of Irene is also apparent in the observed radar reflectivity in Figure 2. The COAMPS-TC prediction captures the large areal extent of the precipitation field, as well as its asymmetry about the TC center (most of the precipitation is north and east of the center. This large shield of heavy precipitation caused severe river flooding as it slowly moved north through the mid-Atlantic and Northeast U.S. The simulated radar reflectivity for the COAMPS-TC grid mesh 3 (5 km horizontal resolution), shown in Figure 3, illustrates the capability of the model to capture the finer-scale features, such as the eyewall and rainbands, in generally good agreement with the observed reflectivity. Sensitivity tests (not shown) indicate that the synthetic observations and TC-related data assimilation system modifications, along with the in-cloud turbulent mixing representation, are important for the proper simulation Irene's structure. It should also be noted that COAMPS-TC makes use of a 1.5 order closure turbulence parameterization that predicts turbulent kinetic energy (TKE) and includes advection of TKE as well. We hypothesize that the advection of TKE may be important for the proper representation of the turbulence evolution within the hurricane boundary layer beneath and near the eyewall.

Overall, the Navy's COAMPS-TC real-time intensity predictions of Hurricane Irene were more skillful than the other leading operational governmental forecast models, as shown in Figure 4. All of the available models except for COAMPS-TC had a tendency to over-intensify Irene, often by a full storm category or more. These real-time COAMPS-TC forecasts were used by forecasters at the National Hurricane Center as part of an experimental HFIP multi-model ensemble. The COAMPS-TC consistently provided accurate real-time intensity forecasts during the period 23-28 August 2011, when critical decisions were made by forecasters and emergency managers including evacuations.

b. COAMPS-TC Ensemble Forecasts Experiments

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. This system makes use of the community-based Data Assimilation Research Testbed (DART) capability developed at the National Center for Atmospheric Research, which includes various options for Ensemble Kalman Filter (EnKF) data assimilation. The COAMPS-TC DART system constitutes a next generation data assimilation system for tropical cyclones that uses flow dependent statistics from the ensemble to assimilate observational information on the mesoscale.

A real-time COAMPS-TC ensemble system was run in a demonstration mode in 2011 for the W. Atlantic, E. Pacific, and W. Pacific regions. The system comprised an 80-member COAMPS-TC cycling data assimilation ensemble on three nested grids with horizontal spacing of 45, 15, and 5 km. Ten-member forecasts were performed twice daily to five days using the same three nested grid configuration as the data assimilation ensemble. The first 10 members of the data assimilation ensemble were used to define the forecast ensemble. Lateral boundary conditions for the forecast ensemble were drawn from the GFS-EnKF ensemble forecast. Examples of probabilistic products for Hurricane Irene are shown in Figure 5 for both track (top 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 1/3 and 2/3 of the ensemble member forecast positions. Note that the observed landfall location of the eye (see Figure 2) was within the ensemble distribution, although the ensemble mean landfall was approximately 12 h later than observed. The probabilistic intensity product (lower panel) shows a considerable spread among the members, particularly beyond 84 h, just prior to landfall. These products can be extremely valuable to assess the uncertainty in both track and intensity forecasts, and NRL is currently developing these capabilities and products further.

c. Coupled COAMPS-TC Forecast Experiments

The COAMPS-TC system was run in a fully coupled mode, interactive with NCOM, during the Office of Naval Research sponsored Interaction of Typhoon and Ocean Project (ITOP) during the summer and fall of 2010. An example of a fully coupled COAMPS-TC forecast for Typhoon Fanapi performed in real time is shown in Figure 6. The NCOM ocean model was applied using a 10-km horizontal grid increment in this example, and the finest mesh for the atmospheric model used a 5-km grid increment. The atmosphere and ocean fluxes were exchanged every ocean model time step. The COAMPS-TC predicted track (red) from a 90-h real time forecast valid at 0600 UTC 19 September 2010 is quite close to the observed or best track (black). The sea surface temperature, shown in color shading, indicates significant cooling was predicted by COAMPS-TC during the passage of Fanapi due to enhanced mixing by the strong near-surface winds of the typhoon. The predicted cooling of the sea surface temperatures of 2-4°C is in agreement with estimates from in situ and remote sensing observations in this region. The negative impact of the ocean cooling underneath the tropical cyclone can reduce the TC intensity and broaden the tropical cyclone secondary circulation, which underscores the importance of properly representing these air-sea interaction process.

d. Dynamic Initialization Development and Experiments

An evaluation of the track and intensity performance of the two-stage dynamic initialization scheme was conducted. Historical TCs were simulated using COAMPS-TC with the 3D-Var and synthetics initialization method (CNTL) and the two-stage dynamic initialization method (TCDI/DI). Improvements in both the initial vortex dynamic and thermodynamic balance and intensity and track errors were found by using TCDI/DI. An example of an improvement in the initial balance is shown in Fig. 7. As shown by Fig. 7, in the CNTL initialization method, a spin-down occurs early in the forecast causing the large errors in the subsequent intensity. In the TCDI/DI method, the TC is in a state of improved initial balance, leading to more minor adjustments early and a much improved intensity forecast in the first 6 hours. Both initializations were tested on multiple TCs in the western North Pacific and North Atlantic basins in 2010-2011. The intensity and track errors on a large sample of cases are given in Fig. 8. As shown by Fig. 8, the TCDI/DI method reduced the average track errors slightly (approximately 10-30 nm, left panel) and reduced the average intensity errors significantly (approximately 25%, with statistical significance at many lead times, right panel). These results demonstrate that the TCDI/DI method can be used to improve TC intensity forecasts. This method combines the benefits from the TCDI method (red curve) the early part of the forecast, and the DI method (purple) curve later in the forecast to produce improvements at all lead times, in comparison to the CNTL method.

TRANSITIONS

The tropical cyclone application of COAMPS will transition to 6.4 projects within PE 0603207N (PMW-120) that focus on the transition COAMPS to FNMOC.

RELATED PROJECTS

COAMPS will be used in related 6.1 projects within PE 0601153N that include studies of 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.

PUBLICATIONS

Refereed Publications: Submitted or appeared.

Baranowski, D., P.J. Flatau, S. Chen, P.G. Black, 2012:Air-sea interaction in two co-located typhoons. Submitted to JPO.

Doyle, J.D., C.A. Reynolds, C. Amerault, 2011: Diagnosing tropical cyclone sensitivity. Computing in Science and Engineering, 13, 31-39.

Doyle, J.D., Y. Jin, R. Hodur, S. Chen, H. Jin, J. Moskaitis, A. Reinecke, P. Black, J. Cummings, E. Hendricks, T. Holt, C. Liou, M. Peng, C. Reynolds, K. Sashegyi, J. Schmidt, S. Wang, 2012: Real-time tropical cyclone prediction using COAMPS-TC. Advances in Geosciences (ADGEO) Asia Oceana Geophysics Society (AOGS) (to appear).

Doyle, J.D., C.A. Reynolds, C. Amerault, J. Moskaitis, 2012: Adjoint sensitivity and predictability of tropical cyclogenesis. *J. Atmos. Sci.* (to appear)

Hendricks, E.A., J.R. Moskaitis, Y. Jin, R.M. Hodur, J.D. Doyle, M.S. Peng, 2011: Prediction and Diagnosis of Typhoon Morakot (2009) Using the Naval Research Laboratory's Mesoscale Tropical Cyclone Model. Terr. Atmos. Ocean. Sci., 22, 579-594.

Hendricks, E. A., M. S. Peng, X. Ge, and T. Li, 2011: Performance of a dynamic initialization scheme in the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC), Wea. Forecasting, 26, 650-663.

Knaff, J. A., C. R. Sampson, P. J. Fitzpatrick, Y. Jin, and C. Hill, 2011: Simple Diagnosis of Tropical Cyclone Structure via Pressure Gradients. *Wea Forecasting,* 26, 1020-1031.

Liou, C.-S., and K. Sashegyi, 2012: On the initialization of tropical cyclones with a three dimensional variational analysis. Natural Hazards, 63, P1375-1391.

Smith, T.A., S. Chen, T. Campbell, E. Rogers, S. Gabersek, D. Wang, S. Carroll, R. Allard, 2012: Ocean-Wave Coupled Modeling in COAMPS-TC: A Study of Hurricane Ivan (2004). *submitted to Ocean Dynamics.*

Selected Conference Presentations

Billings, B.J., and J.D. Doyle, 2012: Coastal winds associated with tropical cyclones interacting with complex terrain. *Observations and Modeling of Land-Falling Tropical Cyclones. 10th Symposium on the Coastal Environment.* AMS Annual Conference. 23-27 January 2012, New Orleans, LA.

Chen, S. J. Cummings, P.G. Black, E. Sanabia, 2012:Forecasting rapid intensity changes with land-falling tropical cyclones, 10th symposium on the coastal environment, 22-26 Jan 2012, New Orleans, Chen, S., 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 Conference. Miami, FL, 28 Feb – 3 March, 2011.

Chen, S., T.A. Smith, S. Gaberšek, T. Campbell, S. Wang, J. Doyle, and R. Allard, 2011: Sensitivities of air-ocean-wave coupling on the prediction of hurricane Frances and Ivan. 65th Interdepartmental Hurricane Conference. Miami, FL, 28 Feb – 3 March, 2011.

DeMaria, M., M. Brennan, A. Schumacher, K. Musgrove, T. Marchok, and J. R. Moskaitis: Application of ensemble tropical cyclone products to National Hurricane Center forecasts and warnings. Warn-on-Forecast High Impact Weather Workshop, Norman, OK, 2012

Doyle, J.D, R.M. Hodur, S. Chen, J. Cummings, E. Hendricks, T. Holt, H. Jin, Y. Jin, C.S. Liou, J.R. Moskaitis, M.S. Peng, P.A. Reinecke, K. Sashegyi, J. Schmidt, and S. Wang, 2012: Prediction of tropical cyclone intensity and track using COAMPS-TC. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Doyle, J.D, R.M. Hodur, S. Chen, J. Cummings, E. Hendricks, T. Holt, H. Jin, Y. Jin, C.S. Liou, J.R. Moskaitis, M.S. Peng, P.A. Reinecke, K. Sashegyi, J. Schmidt, and S. Wang, 2012. Prediction of tropical cyclone intensity and track during landfall using COAMPS-TC. *Observations and Modeling of Land-Falling Tropical Cyclones. 10th Symposium on the Coastal Environment.* AMS Annual Conference. 23-27 January 2012, New Orleans, LA. (invited)

Doyle, J.D., 2011: An Overview of NRL's COAMPS System and Physics. EMC Physics Workshop. 26-27 July 2011, NCEP/EMC.

Doyle, J.D., C. Reynolds, C. Amerault, S. Chen, M. Flatau, J. Goerss, R. Hodur, T. Holt, H. Jin, Y. Jin, J. McLay, J. Moskaitis, A. Reinecke, J. Ridout, E. Serra, S. Wang, 2011: Multi-scale Prediction of Tropical Cyclone Track and Intensity. HPC Users Group Meeting, 23-27 June, 2011, Portland, OR.

Doyle, J.D., C.M Amerault, J.R. Moskaitis, C.A. Reynolds, 2012: Tropical cyclogenesis sensitivity and predictability. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Doyle, J.D., R. Hodur, S. Chen, J. Cummings, E. Hendricks, T. Holt, H. Jin, Y. Jin, C.-S. Liou, J. Moskaitis, M. Peng, K. Sashegyi, J. Schmidt, and S. Wang, 2011: An Overview of COAMPS-TC Development and Real-Time Tests. 65th Interdepartmental Hurricane Conference. Miami, FL, 28 Feb – 3 March, 2011.

Doyle, J.D., S. Chen, J. Cummings, R. M. Hodur, E. Hendricks, T. Holt, H. Jin, Y. Jin, C. S. Liou, J. R. Moskaitis, M. Peng, K. D. Sashegyi, and J. Schmidt, 2011: Application of COAMPS-TC for HFIP. AMS 20th Conference on Numerical Weather Prediction. 24-28 January, Seattle, WA.

Doyle, J.D., S. Chen, J. Cummings, R. M. Hodur, E. Hendricks, T. Holt, H. Jin, Y. Jin, C. S. Liou, J. R. Moskaitis, M. Peng, K. D. Sashegyi, J. Schmidt, S. Wang, 2011: Prediction of Tropical Cyclone Intensity and Track during Landfall using COAMPS-TC. AMS 20th Coastal Conference, Landfalling Hurricane Session. 24-28 January, Seattle, WA.

Doyle, J.D., Y. Jin, S. Wang, R. Hodur, 2011: An Overview of the COAMPS-TC Tropical Cyclone Boundary Layer Parameterization. HFIP Physics Workshop. 9-11 August 2011, NCEP/EMC.

Hendricks, E. A., 2011: Axisymmetric convective/dynamic instability and tropical cyclone intensity and structural variability. 14th Conference on Mesoscale Processes, Los Angeles, CA, 1-4 August 2011.

Hendricks, E. A., and W. H. Schubert, 2011: Potential vorticity mixing in a continuously stratified fluid. 15th Cyclone Workshop, Monterey, CA, 28 March – 1 April, 2011.

Hendricks, E. A., J. R. Moskaitis, Y. Jin, R. M. Hodur, J. D. Doyle, and M. S. Peng, 2011: Prediction and diagnosis of Typhoon Morakot (2009) using the Naval Research Laboratory's mesoscale tropical cyclone prediction model. International Workshop on Typhoon and Flood, Monterey, CA, 23-24 June, 2011.

Hendricks, E. A., M. S. Peng, T. Li, and X. Ge, 2011: Initialization of tropical cyclones in numerical prediction systems, AMS 24th Conference on Weather and Forecasting/20th Conference on Numerical Weather Prediction, Seattle, WA, 23–27 January, 2011.

Hendricks, E., Y. Jin, J.R. Moskaitis, J.D. Doyle, M.S. Peng, and R.M. Hodur, 2012: Numerical simulations and analysis of typhoon Morakot (2009) using the Navy's mesoscale model. *Observations and Modeling of Land-Falling Tropical Cyclones. 10th Symposium on the Coastal Environment.* AMS Annual Conference. 23-27 January 2012, New Orleans, LA.

Hendricks, E., Y. Jin, J.R. Moskaitis, J.D. Doyle, M.S. Peng, and R.M. Hodur, 2012: Numerical simulations and analysis of typhoon Morakot (2009) using the Navy's mesoscale model. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Hodur, R.M, J.D. Doyle, C.S. Liou, and K.D. Sashegyi, 2012: Tropical cyclone prediction: Initial condition sensitivity. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Jin, H., S. Wang, 2012: Impact of Air-Sea Interaction on the Tropical Cyclone Intensity. *18th Conference on the Air-Sea Interaction,* 8–13 July 2012, Boston, Massachusetts.

Jin, H., S. Wang, S. Chen, and J. Doyle, 2012: Coupled COAMPS-TC real-time forecasts for the ITOP experiment. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Jin, H., S. Wang, Y. Jin, 2012: Coastal Oceanic Variability during Typhoon Fanapi (2010) Passage. *10th Symposium on the Coastal Environment,* 22–26 January 2012, New Orleans, Louisiana.

Jin, Y., G. Thompson, S. Wang, J. Nachamkin, J. Doyle, R. Hodur. T.R. Holt, J.R. Moskaitis, and Q. Zhao, 2012: Evaluating cloud microphysical parameterizations in COAMPS-TC for tropical cyclone intensity and structure prediction. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Jin, Y., J. Doyle, R. Hodur. J.R. Moskaitis, 2012: Evaluation of tropical cyclone landfall track forecasts by the Navy's regional model. *Observations and Modeling of Land-Falling Tropical Cyclones. 10th Symposium on the Coastal Environment.* AMS Annual Conference. 23-27 January 2012, New Orleans, LA.

Jin, Y., J. Moskaitis, H. Jin, J. Doyle, R. Hodur, M. DeMaria, B. McNoldy, K. Musgrave, 2011: COAMPS-TC Model diagnostic 2011 and Multi-Model Comparison. HFIP Annual Review, Nov. 7-9, 2011, Miami, FL.

Kuo, H.-C., E. A. Hendricks, and M. S. Peng: Internal dynamic control on tropical cyclone intensity and structural variability. 8th Asia Oceania Geosciences Society Meeting, Taipei, Taiwan, 8-12 August 2011.

Moskaitis, J. R., Are Atlantic basin tropical cyclone intensity forecasts improving? *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Moskaitis, J. R., J. D. Doyle, and R. M. Hodur, 2011: Diagnostic verification of COAMPS-TC performance for the HFIP retrospective forecasts. AMS 20th Conference on Numerical Weather Prediction. 24-28 January, Seattle, WA.

Moskaitis, J. R., Y. Jin, and J. Doyle: A case study of the intensification of Hurricane Maria (2011) in a real-time COAMPS-TC prediction. 66th Interdepartmental Hurricane Conference, Charleston, SC, 5-8 March 2012.

Moskaitis, J., Y. Jin, and J.D. Doyle, 2012: Verification of COAMPS-TC predictions of the synoptic-scale flow in the tropics and subtropics. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Park, M.-S., A.B. Penny, R.L. Elsberry, B.J Billings, and J.D. Doyle: 2012: Latent heating and cooling rates in developing and non-developing tropical disturbances during tcs-08: radar-equivalent retrievals from mesoscale numerical model simulations and ELDORA observations. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Reinecke, P.A., 2012: The impact of radiance assimilation with an ensemble Kalman filter on tropical cyclone forecasts in COAMPS-TC. *16th Conference on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, AMS Annual Conference. 23-27 January 2012, New Orleans, LA.

Reinecke, P.A., Moskaitis, J. R., Jin, H., J. D. Doyle, 2012: Real-time Ensemble Prediction and Data Assimilation of Tropical Cyclones with COAMPS-TC. *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, Florida.

Smith, T.A. S. Chen, T, Campbell, E. Rogers, S. Gaberšek, D. Wang, S. carroll, R. Allard, 2012: Air-ocean-wave coupling of hurricane Ivan (September 2004) in COAMPS-TC, 30th Conference on Hurricanes and Tropical Meteorology 15-20 April 2012, Ponte Vedra Beach, FL

Smith, T.A., S. Chen, T. Campbell, E. Rogers, D. Wang, R. Allard, 2012: Abstract Submission: Air-sea-wave coupled modeling of western north pacific typhoon FANAPI (September 2010), Ocean Sciences 2012, February 20-24, 2012, Salt Lake City, UT.

Zhao, Q. and Y. Jin, 2012: Radar-observed development of three-dimensional structures of tropical cyclones at landfall. *Observations and Modeling of Land-Falling Tropical Cyclones. 10th Symposium on the Coastal Environment.* AMS Annual Conference. 23-27 January 2012, New Orleans, LA.

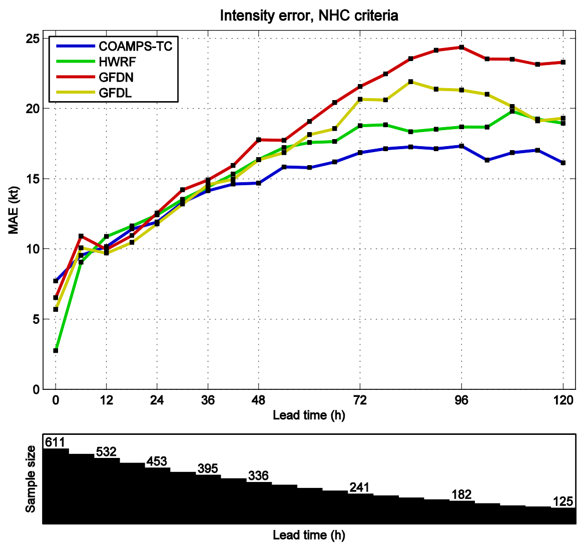

Figure 1. Wind speed mean absolute error (MAE) (knots; 1 knot=0.514 m s^{-1}) as a function of forecast time for the 2010 and 2011 seasons in the Atlantic basin for a homogeneous statistical sample. The numerical models included in this analysis are the Navy's COAMPS-TC, operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). The number of cases is shown at the bottom.

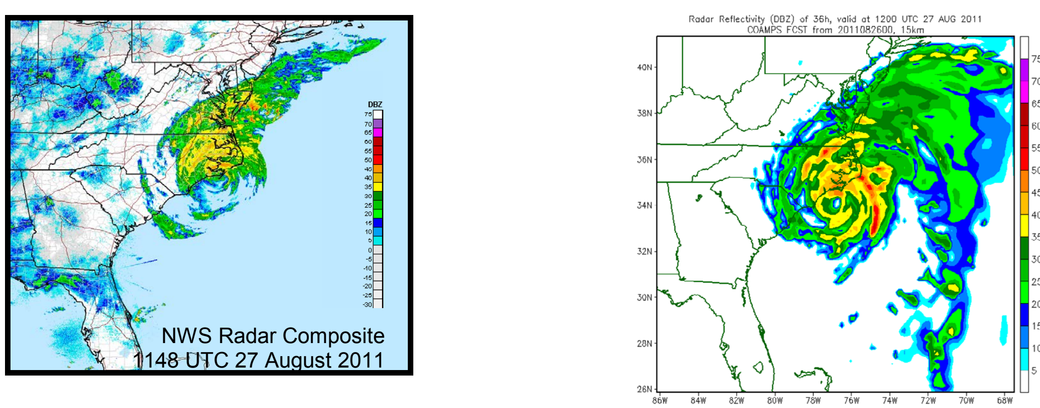

Figure 2. The NWS composite radar reflectivity (from NOAA) valid at 1148 UTC 27 August 2011 (left) (source NOAA) and the COAMPS-TC 36-h forecast radar reflectivity performed in real time and valid at 1200 UTC 27 August (right) for Hurricane Irene. The COAMPS-TC reflectivity is shown for the second grid mesh, which has a horizontal resolution of 15 km.

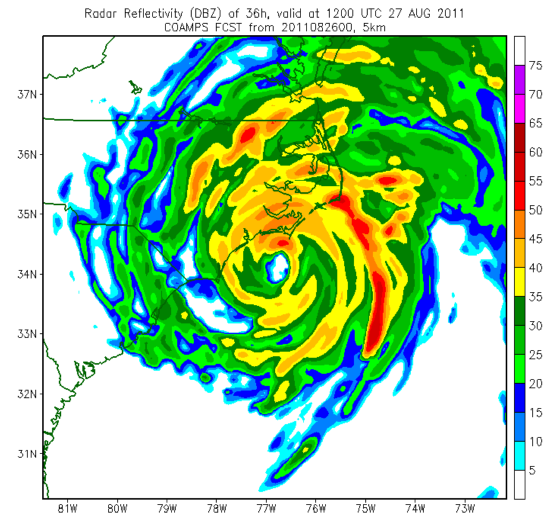

Figure 3. The COAMPS-TC 36-h forecast radar reflectivity valid at 1200 UTC 27 August for the third grid mesh, which has a horizontal resolution of 5 km.

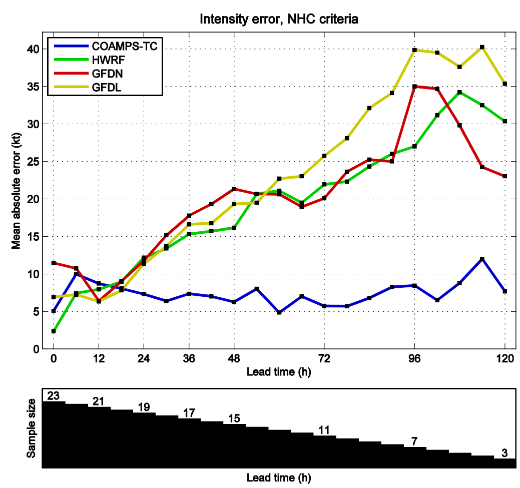

Figure 4. Wind speed mean absolute error (MAE) (knots) as a function of forecast time for Hurricane Irene for a homogeneous statistical sample. The numerical models included in this analysis are the Navy's COAMPS-TC, operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). The number of cases is shown at the bottom. Only forecasts after Irene has moved away from Hispaniola are shown here.

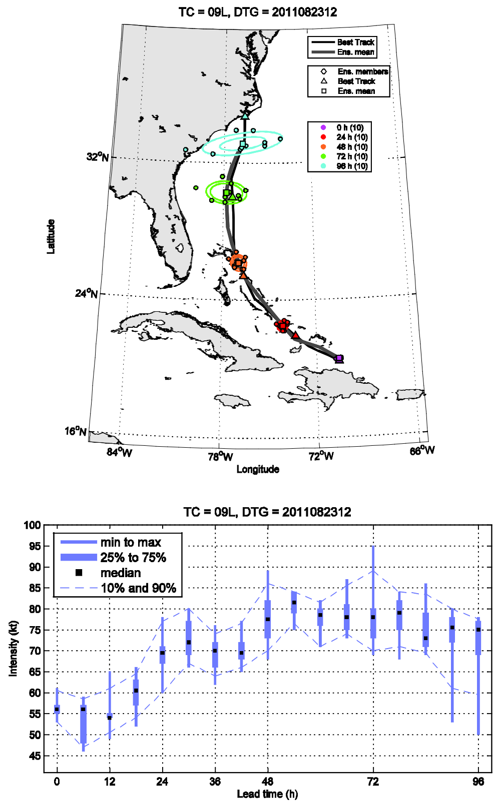

Figure 5. Probabilistic products from the COAMPS-TC ensemble for Hurricane Irene corresponding to the track (top panel) and hurricane intensity (bottom panel). This real time forecast was initialized at 1200 UTC 23 August, which is approximately four days prior to landfall. The probabilistic track product shows the TC position from the individual ensemble members every 24 h and ellipses that encompass 1/3 and 2/3 of the ensemble members. The intensity (knots) distribution is shown as a function of forecast lead time (hours) with the minimum value, maximum value and various quantiles of the ensemble distribution shown as denoted by the legend.

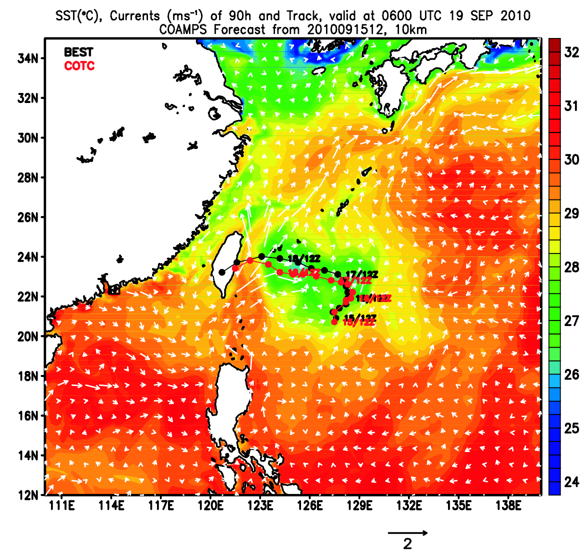

Figure 6. The COAMPS-TC predicted track (red) for Typhoon Fanapi from a 90 h real-time forecast valid at 0600 UTC 19 September 2010 and the observed best track (black). The sea surface temperature (°C) is shown in color shading and indicates significant cooling during the passage of Fanapi. The surface currents are shown by the white vectors.

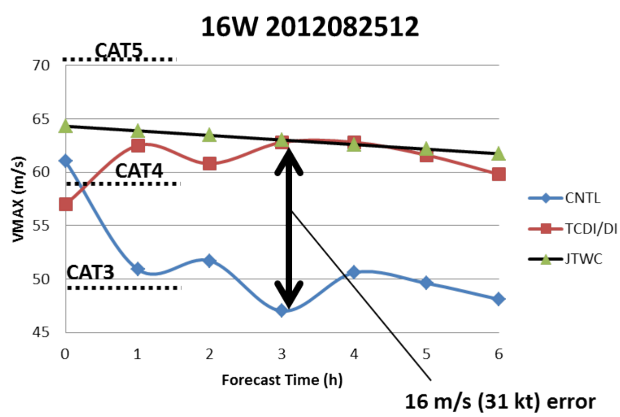

Figure 7. The intensity max maximum sustained wind (VMAX, m/s) of both the CNTL and TCDI/DI runs in the first 6 hours of the COAMPS-TC forecast of 16W (Bolaven) in the western North Pacific basin, in comparison to the best track estimate of the intensity from the Joint Typhoon Warning Center (JTWC). Saffir-Simpson hurricane categories are also given.

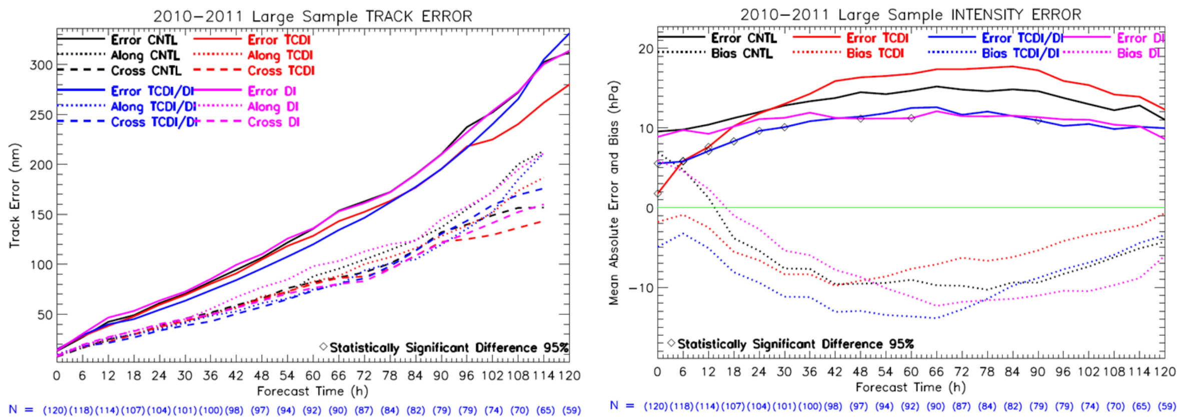

Figure 8. (left panel) The average track errors, and (right panel) the average intensity errors for a large sample of cases (120 at the initial time to 59 at the 120 h lead time). The CNTL is depicted by the black curve, and TCDI/DI is depicted by the blue curve. Additional curves for running DI (purple) and TCDI (red) alone are also given. In the left panel, the total track error is solid, the along-track error is dotted, and the cross-track error is dashed. In the right panel, the average errors are solid, and the biases are dotted. Black diamonds indicate that a statistically significant difference exists between any of the colored error curves and the black CNTL.