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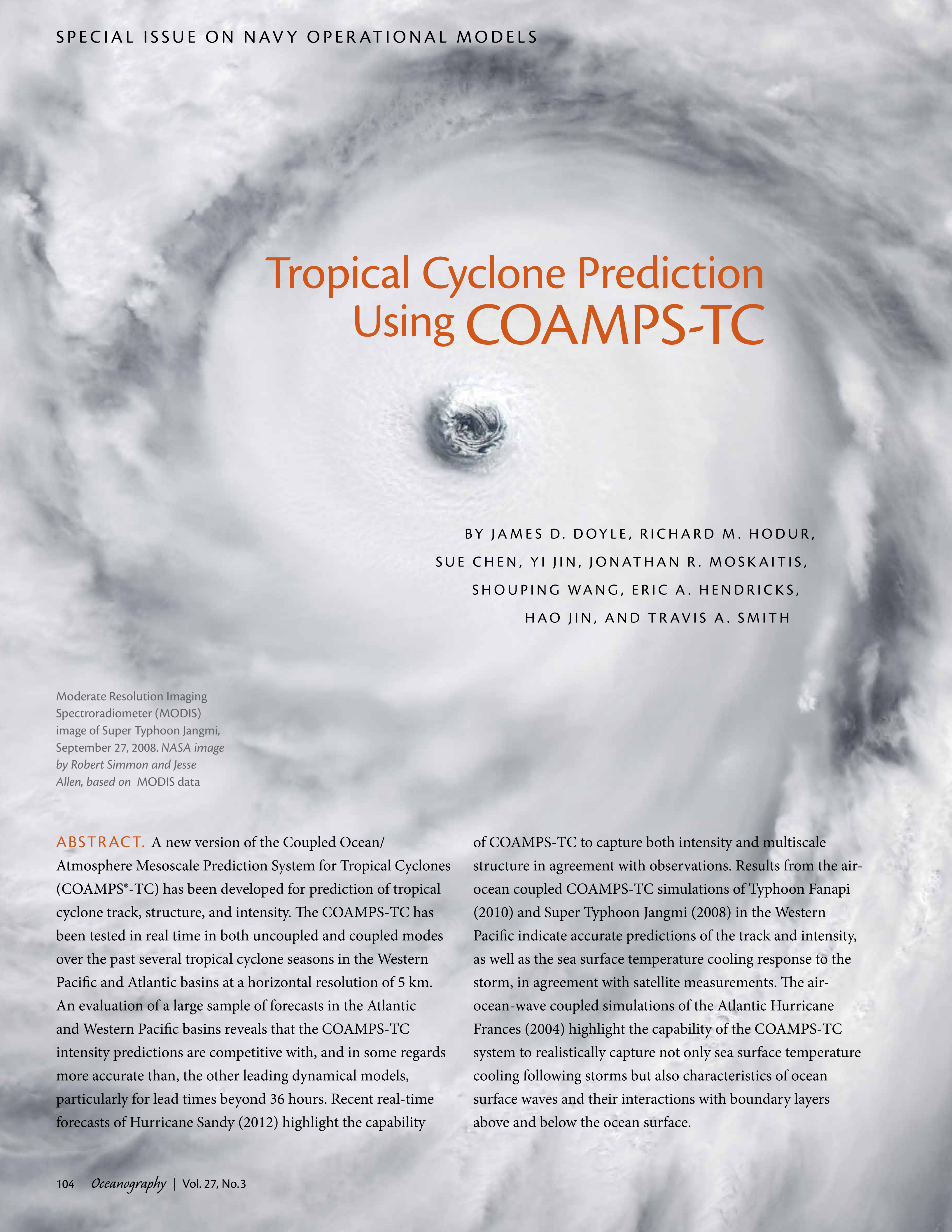
Tropical Cyclone Prediction Using COAMPS-TC

BY JAMES D. DOYLE, RICHARD M. HODUR, SUE CHEN, YI JIN, JONATHAN R. MOSKAITIS, SHOUPING WANG, ERIC A. HENDRICKS, HAO JIN, AND TRAVIS A. SMITH



Moderate Resolution Imaging Spectroradiometer (MODIS) image of Super Typhoon Jangmi, September 27, 2008. *NASA image by Robert Simmon and Jesse Allen, based on* MODIS data

ABSTRACT. A new version of the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS®-TC) has been developed for prediction of tropical cyclone track, structure, and intensity. The COAMPS-TC has been tested in real time in both uncoupled and coupled modes over the past several tropical cyclone seasons in the Western Pacific and Atlantic basins at a horizontal resolution of 5 km. An evaluation of a large sample of forecasts in the Atlantic and Western Pacific basins reveals that the COAMPS-TC intensity predictions are competitive with, and in some regards more accurate than, the other leading dynamical models, particularly for lead times beyond 36 hours. Recent real-time forecasts of Hurricane Sandy (2012) highlight the capability of COAMPS-TC to capture both intensity and multiscale structure in agreement with observations. Results from the air-ocean coupled COAMPS-TC simulations of Typhoon Fanapi (2010) and Super Typhoon Jangmi (2008) in the Western Pacific indicate accurate predictions of the track and intensity, as well as the sea surface temperature cooling response to the storm, in agreement with satellite measurements. The air-ocean-wave coupled simulations of the Atlantic Hurricane Frances (2004) highlight the capability of the COAMPS-TC system to realistically capture not only sea surface temperature cooling following storms but also characteristics of ocean surface waves and their interactions with boundary layers above and below the ocean surface.

INTRODUCTION

The demand for more accurate forecasts of tropical cyclone track and intensity with longer lead times is greater than ever due to the enormous economic and societal impact. A dramatic example occurred during October 2012 as Hurricane Sandy threatened many communities along the US Eastern Seaboard. Basic questions such as where Sandy would track and how strong it would become had profound implications for the millions of people in its path and billions of dollars of vulnerable assets. With an estimated total damage amount of $50 billion USD or more, Hurricane Sandy is the second costliest hurricane since 1900, and the deadliest hurricane to hit the northeastern United States in four decades.

The potential impact of tropical cyclones on military operations can also be enormous. Typhoon Cobra, also known as Halsey's Typhoon after Admiral William Halsey, struck the US Navy's Pacific Fleet in December 1944 during World War II. Three destroyers were lost, and a total of 790 sailors perished. More recently, during Sandy, the decision to sortie Navy assets from Norfolk, VA, and other ports along the Eastern Seaboard days in advance of the storm was critically dependent on forecasts of Sandy's track, intensity (maximum sustained wind speed at the surface), and storm structure (i.e., the size of the storm or radius of key wind speed thresholds). In the western North Pacific basin, an area of strategic importance for the US Navy, the Navy Pacific Fleet in the Philippine Sea has been affected by numerous storms, such as Typhoon Nanmadol (2011) that exhibited erratic movement and was poorly forecasted.

There has been remarkable improvement in tropical cyclone (TC) track prediction through the use of global prediction models (e.g., Goerss, 2007; Hamill et al., 2011). A three-day hurricane track forecast today is as skillful as a one-day forecast was 30 years ago. Evacuating coastal areas before a hurricane is estimated to cost $1 million for every mile of coastline evacuated (e.g., Whitehead 2003). These dramatically improved track forecasts have reduced the size of evacuation areas and mitigated costs. However, intensity prediction remains a significant challenge, and progress has been considerably slower (DeMaria et al., 2005, 2014; Rogers et al., 2006). The slow improvement in TC intensity and structure forecasts has been attributed to a variety of reasons, ranging from a lack of critical observations in the TC inner core and the surrounding environment to inaccurate representations of physical processes in numerical weather prediction (NWP) models. Marks and Shay (1998) note that track prediction depends more on large-scale processes, while intensity depends on both inner-core dynamics and its relationship to the environment. This motivates the requirement for accurate representation of the key physical and dynamical processes within the storm itself and in the larger-scale environment. The need to explicitly resolve the inner part of the storm, including the eye, the eyewall, and spiral rainbands, has motivated modeling of the inner core at high horizontal resolution (e.g., Zhu et al., 2004, 2006; Braun et al., 2006; Chen et al., 2007; Davis et al., 2008). One distinct advantage of applying models at high resolution (grid increments of 5 km or less) is that convection can be explicitly represented in the model, which precludes the need for a convection parameterization and results in more accurately resolved convective characteristics (e.g., structure, morphology, propagation), at least for continental locations (Fowle and Roebber, 2003; Done et al., 2004).

The Coupled Boundary Layer Air–Sea Transfer (CBLAST) field program (Black et al., 2007), conducted from 2002 to 2004, provided important air–sea interaction observations in hurricanes and motivated new approaches to parameterization of these processes in tropical cyclone models. Coupled air-ocean and air-ocean-wave tropical cyclone modeling systems more realistically represent these key air-sea interaction processes (e.g., Bao et al., 2000; Bender et al., 2007; Chen et al., 2007, 2010). The coupling to an ocean-circulation model can improve the storm intensity forecast through a more realistic representation of storm-induced cooling in the upper ocean and sea surface. Inclusion of ocean waves and their feedback to the atmosphere and ocean boundary layers of a hurricane can yield more realistic momentum fluxes across the air-sea interface (e.g., Bao et al., 2000; Doyle, 2002) and improve the model-predicted maximum wind speed–central pressure relationship (e.g., Chen et al., 2007), which is an important aspect of the hurricane intensity and structure relationship. Inclusion of wave-current interaction through the use of an observation-based momentum drag formulation in the wave model, the wind source generation, and the total volumetric dissipation is shown by Smith et al. (2013) to reduce coupled model forecast errors in significant wave height and wave period for Hurricane Ivan (2004).

Advances in high-resolution TC modeling and data assimilation are thought to be necessary in order to significantly improve the intensity and structure prediction. To this end, the Naval Research Laboratory (NRL) in Monterey, CA, developed the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC), a new version of COAMPS designed specifically for high-resolution tropical cyclone prediction (Doyle et al., 2011). The model builds on the existing COAMPS infrastructure and provides the framework to add new capabilities and advancements in data assimilation, vortex initialization, physical parameterization, and air-sea coupling appropriate for high-resolution tropical cyclone prediction.

This paper provides an overview of the main capabilities of COAMPS-TC through examination of several different representative tropical cyclone cases and statistical analysis of real-time and retrospective forecasts that were conducted as part of a pre-operational evaluation of the system. We next provide a brief description of the COAMPS-TC system, after which we address aspects of the air-sea coupling, including boundary layer and surface flux parameterizations and fully coupled air-ocean and air-ocean-wave options. The final section provides an overview of the statistical performance of the system, and we conclude with a summary of the results.

> "AN EVALUATION OF A LARGE SAMPLE OF FORECASTS IN THE ATLANTIC AND WESTERN PACIFIC BASINS REVEALS THAT THE COAMPS-TC INTENSITY PREDICTIONS ARE COMPETITIVE WITH, AND IN SOME REGARDS MORE ACCURATE THAN, THE OTHER LEADING DYNAMICAL MODELS, PARTICULARLY FOR LEAD TIMES BEYOND 36 HOURS."

COAMPS-TC DESCRIPTION

The COAMPS-TC system is composed of data quality control, analysis, initialization, and forecast model subcomponents (Doyle et al., 2011). The system was transitioned to operations at the Fleet Numerical Oceanography and Meteorology Center (FNMOC) in 2012, and the first operational forecasts occurred in June 2013. The Navy Atmospheric Variational Data Assimilation System (NAVDAS) is used to blend observations of winds, temperature, moisture, and pressure from a plethora of sources such as radiosondes, pilot balloons, satellites, surface measurements, ships, buoys, and aircraft (Daley and Barker, 2000). As part of the TC analysis procedure, the pre-existing circulation in the COAMPS-TC first guess fields is relocated to allow for accurate representation of TC position for the analysis background following Liou and Sashegyi (2012).

Synthetic observations or profiles are used to incorporate TC structure and intensity into the initial conditions based on National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC; Liou and Sashegyi, 2012) specifications. This is accomplished by using these synthetic observations in NAVDAS to represent the hurricane's characteristics, and then blending the synthetic observations with other available real-time observations that describe the larger-scale environment outside the TC circulation. The TC synthetics are necessary due insufficient real-time in situ observations of tropical cyclones. Recently, a new method of generating TC synthetics was introduced into COAMPS-TC that is based on TC position, maximum winds, radius of maximum winds, mean radius of the 34 knot winds, and recent storm motion. The TC synthetics are generated at one point in the center of each TC, and at eight points around each of nine concentric circles centered over the TC, for a total of 73 individual points. At each of these points, profiles of the u- and v-components are prescribed at 1000, 925, 850, 700, 600, 500, and 400 hPa, along with geopotential height at 1,000 hPa. The winds' horizontal structure is generated from a modified Rankine wind vortex that best fits the observed value of the maximum winds, the radius of the maximum winds, and the radius of the 34-knot winds. A Rankine vortex is a simplified model of the radial structure of the tangential wind field. The prescribed vertical profile of the winds follows the method described by Liou and Sashegyi (2012). The mean storm motion is added to the Rankine-vortex winds. The 1,000 hPa geopotential heights are created by solving the equation for the Rankine vortex for the geopotential field. The innermost ring of synthetics can be set to either the reported radius of maximum wind (RMW) or to the location of the RMW in the COAMPS-TC first-guess fields. The latter is typically used to minimize the size of the analysis increments. The remainder of the rings is evenly spaced with increasing distance from the RMW to the outermost ring at 600 km from the center.

Sea surface temperature is analyzed directly on the model computational grid using the Navy Coastal Ocean Data Assimilation (NCODA) system, which makes use of all available satellite, ship, float, and buoy observations (Cummings, 2005). In coupled applications, both the NCODA and NAVDAS systems are applied using a data assimilation cycle in which the first guess from the analysis is derived from the previous short-term forecast.

The COAMPS-TC atmospheric model uses the nonhydrostatic and compressible form of the dynamics and has prognostic variables for the three components of the wind (two horizontal wind components and the vertical wind), the perturbation pressure, potential temperature, water vapor, cloud droplets, raindrops, ice crystals, snowflakes, graupel (soft hail), and turbulent kinetic energy (Hodur, 1997). Physical parameterizations include representations of cloud microphysical processes, convection, radiation, boundary layer processes, and surface layer fluxes. The COAMPS-TC model contains a representation of dissipative heating near the ocean surface, which has been found to be important for tropical cyclone intensity forecasts (Jin et al., 2007). The COAMPS-TC system uses a flexible nesting design, which has proven useful when more than one storm is present in a basin at a given time, as well as special options for moving nested grid families that independently follow individual tropical cyclone centers of interest. In the applications shown in this paper (unless otherwise noted), the atmospheric portion of COAMPS-TC uses three nested grids of 45 km, 15 km, and 5 km horizontal resolution and 40 vertical levels that extend from 10 m to approximately 30 km. The inner two grid meshes follow the storm.

The COAMPS-TC system has the capability to operate in a fully coupled air-sea interaction mode (Chen et al., 2010, 2011; Doyle, et al., 2011). The atmospheric module within COAMPS-TC is coupled to the Navy Coastal Ocean Model (NCOM; Martin, 2000; Martin et al., 2006) to represent air-ocean interaction processes. The COAMPS-TC system has an option to predict ocean surface waves and the interactions between the atmosphere, ocean circulation, and waves using either the Simulating WAves Nearshore (SWAN) or WAVEWATCH III models. Wave and current interaction is parameterized through inclusion of Stokes drift currents and Langmuir turbulence (Kantha and Clayson, 2004; see Allard et al., 2014, in this issue). The wind-wave interaction is represented through the prediction of a sea-state-dependent Charnock parameter (Moon et al., 2004) that is a function of wave age and wind speed. A sea spray parameterization (Fairall et al., 1994, 2009; Bao et al., 2011) can be used to represent the injection of droplets into the atmospheric boundary layer due to ocean surface wave breaking and shearing of the crest of breaking waves. The spray droplets impact the momentum and enthalpy fluxes through increased mass loading, air flow stratification, and evaporation and/or condensation.

BOUNDARY LAYER AND AIR-SEA INTERACTION SENSITIVITY

Momentum exchange at the sea surface is dependent on the sea-state-dependent drag coefficient, C_d. Prior to the past decade, the characteristics of C_d had not been observed in a tropical cyclone and were primarily based on extrapolations from field campaign measurements conducted in much weaker wind conditions. In a seminal study, Powell et al. (2003) analyzed data from GPS dropwindsondes deployed from aircraft into hurricanes; they found that the mean wind speed varied logarithmically with height in the lowest 200 m and was a maximum at 500 m. They estimated the surface stress, roughness length, and neutral stability C_d, and found a markedly reduced C_d at wind speeds above 30 m s^{-1}. Their analysis showed a leveling off of the surface momentum flux as the winds increase above the hurricane threshold and even a slight decrease of the C_d with further increases in wind speed. Donelan et al. (2004) extended the Powell et al. (2003) study through a series of wind-wave tank experiments and found that C_d saturation occurs when wind speed exceeds 33 m s^{-1}. Beyond this wind speed threshold, the surface roughness no longer increases. Donelan et al. (2004) found a C_d saturation level of 0.0025, similar to the saturation value of 0.0026 found by Powell et al. (2003).

Both surface drag and sea spray processes play major roles in regulating energy exchange at the air-sea

James D. Doyle (*james.doyle@nrlmry.navy.mil*) *is a meteorologist and head of the Mesoscale Modeling Section in the Marine Meteorology Division, Naval Research Laboratory (NRL), Monterey, CA, USA.* **Richard M. Hodur** *is a scientist at Science Applications International Corporation, Monterey, CA, USA.* **Sue Chen**, **Yi Jin**, **Jonathan R. Moskaitis**, **Shouping Wang**, **Eric A. Hendricks**, *and* **Hao Jin** *are all meteorologists in the Marine Meteorology Division, NRL, Monterey, CA, USA.* **Travis A. Smith** *is an oceanographer in the Oceanography Division, NRL, Stennis, MS, USA.*

interface. An advanced version of a sea spray parameterization developed by Fairall et al. (1994, 2009) and a drag parameterization where C_d is limited for wind speed above 30 m s^{-1} (hereafter referred to as the "limited C_d" experiment) following Powell et al. (2003) and Donelan et al. (2004) are both evaluated in COAMPS-TC. Figure 1 illustrates the sensitivity of TC intensity forecasts to the C_d and the sea spray parameterizations using COAMPS-TC simulations of Hurricane Isabel (2003). All of the simulations capture the initial rapid intensification apparent in the best track data within the first 40 hours. The simulation with the standard Charnock parameterization (blue line in Figure 1a,b), however, attains a minimum surface pressure that is 29 hPa higher and an intensity 20 m s^{-1} weaker than the best track analysis. In contrast, storm intensity is increased in the limited C_d experiment (Figure 1, magenta line), likely a result of reduced surface friction. Including sea spray processes substantially increases the surface latent heat fluxes, and the additional energy input at the air-sea interface further enhances convection (not shown). The simulation with both the limited C_d and the sea spray parameterization (red line) attains a minimum pressure of 931 hPa and a 68 m s^{-1} maximum wind speed at 120 h, a significant improvement over the standard Charnock parameterization. An increase in the energy input, attributable to the sea spray along with the higher wind speeds due to the limited C_d at high wind speeds, is clearly apparent in Figure 1c,d, which compares the enthalpy flux from the standard Charnock C_d with that from the experiment that used the limited C_d and sea spray parameterization. The magnitude of the enthalpy flux is nearly doubled due to the stronger wind speeds and evaporation of sea spray drops. The maximum enthalpy flux reaches 2,000 W m^{-2} on the right side of the storm track where the wind speed is stronger due, in part, to the contribution by the translation speed of the storm. It should be noted that the differences in the enthalpy fluxes in Figure 1c,d correspond to a time when the two simulations are quite different (there is a ~ 20 m s^{-1} difference in the maximum wind speed at 110 h). Thus, the differences in the enthalpy fluxes are mostly due to integrated differences in the development pathways of each simulation. The impact of the limited C_d and sea spray is also manifested by the strong asymmetry shown by the enthalpy flux

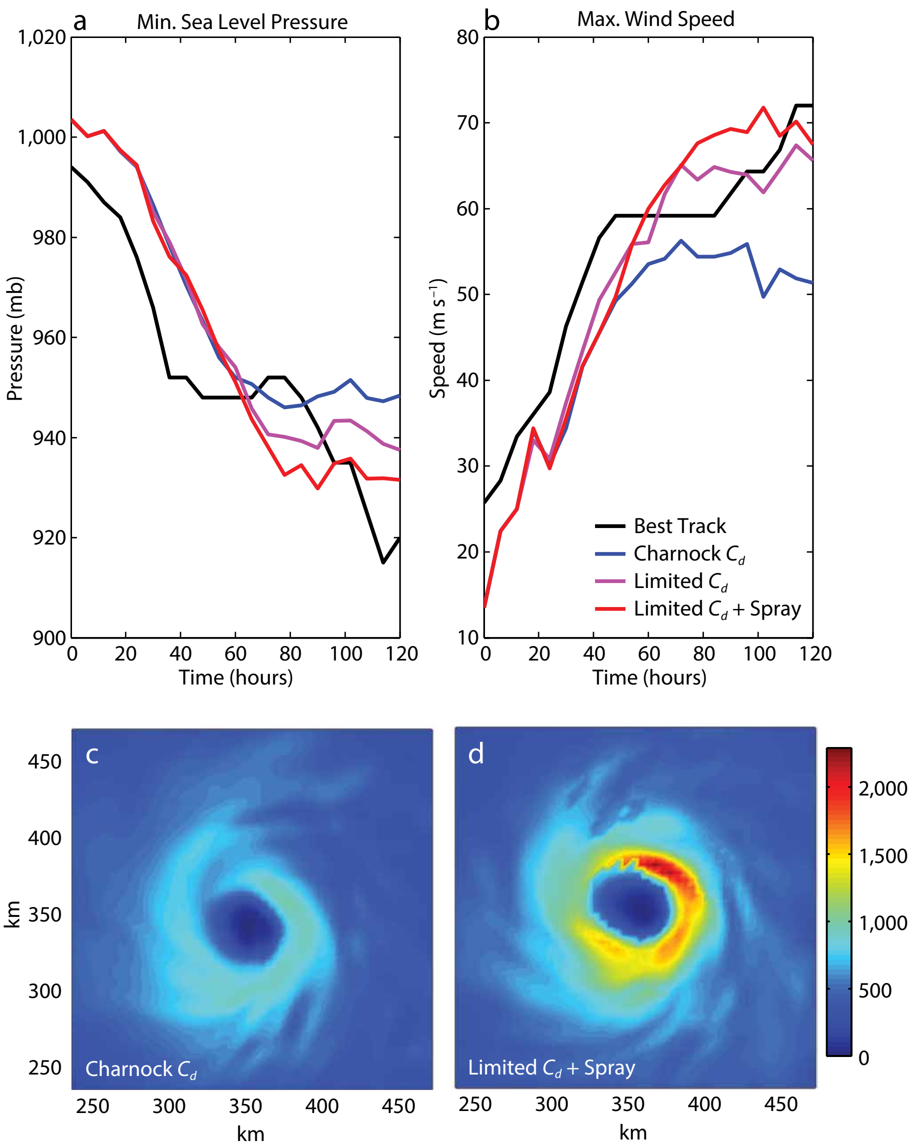


Figure 1. Impact of drag coefficient and sea-spray parameterizations on Hurricane Isabel (2003) simulations. Time series of: (a) minimum sea level pressure, and (b) 10 m maximum wind speed. The 120 h Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS®-TC) simulation is initialized at 0000 UTC September 7, 2003. In these sensitivity tests, Charnock C_d represents the standard Charnock relationship and "limited C_d" corresponds to a C_d (drag coefficient) that is constant at high wind speeds (above 30 m s^{-1}). Enthalpy flux (W m^{-2}) valid at 110 h for utilizing: (c) a standard Charnock C_d, and (d) limited C_d and a sea spray parameterization. The enthalpy flux is displayed from the 5 km grid mesh.

pattern in Figure 1d, which further suggests that these processes impact not only the TC's intensity but also its structure. In general, the current state-of-the-science sea spray parameterizations are still limited by numerous uncertainties, in part due to the lack of reliable and accurate measurements of sea spray (e.g., Andreas et al., 2008; Bao et al., 2011). It remains an outstanding challenge to develop a physically based and observationally verifiable sea spray parameterization that is fully interactive with ocean waves and the atmospheric boundary layer.

The sensitivity of the predicted track, intensity, and structure of tropical cyclones to the representation of the atmospheric planetary boundary layer (PBL) is illustrated through a comparison of two different versions of the turbulence parameterization in COAMPS-TC. One version of the PBL parameterization makes use of a buoyancy-based nonlocal mixing length to represent turbulent mixing (e.g., Bougeault and André, 1986; Grinier and Bretherton, 2002). This approach has significantly improved COAMPS-TC intensity forecasts due to its suitability for turbulent mixing in deep convection. The radius of the 34 kt winds, however, is too large, a result of the excessive mixing in the boundary layer. In order to improve the prediction of the TC wind field within the boundary layer, the Bougeault and André mixing length is replaced with a Mellor-Yamada mixing length representation (Mellor and Yamada, 1982) in the lowest 3 km, where wind shear dominates in the turbulence production, while maintaining the Bougeault and André mixing length above the boundary layer. This new method leads to a reduction in the intensity bias (Figure 2a) in a large sample of Atlantic basin TC forecasts verified against best-track values. In addition, as Figure 2b shows, the radii of the 34 kt wind speed mean absolute error and mean error decrease for all lead times. In particular, at 96 h, the mean absolute error is reduced by 20% and the mean error almost by half.

As a demonstration of the COAMPS-TC air-ocean coupled capability, Figure 3 shows results from an air-ocean coupled simulation of Super Typhoon Jangmi, a 2008 category-5 storm in the western North Pacific basin that occurred during the THe Observing system Research and Predictability EXperiment (THORPEX) Pacific Asian Regional Campaign (T-PARC) and the Office of Naval Research's (ONR's) Tropical Cyclone Structure-08 (TCS-08) experiments. During its lifetime from September 24 to October 2, Jangmi formed in a region of deep ocean mixed layer northeast of the island of Yap, then moved northwestward, crossing over several warm eddies followed by a series of cold eddies, and then made landfall over northern Taiwan on September 28. Jangmi's intensity change is highlighted here to show the impact of the evolving ocean during the forecast through comparisons of high-resolution coupled and uncoupled simulations. The NCOM ocean model is employed, with a single domain at 15 km resolution and 36 vertical levels from the ocean surface to ~ 4 km depth. First guess and boundary conditions are from the US Navy Operational Global Atmospheric Prediction System (NOGAPS) for the atmosphere and global NCOM for the ocean for a series of five-day forecasts; here, we highlight the forecast initialized at 0000 UTC September 25, 2008. The same initial sea surface temperature (SST) is used for the coupled and uncoupled forecasts, but SST is unchanged during the uncoupled run, and the ocean model predicts SST during the coupled run.

Both the coupled and uncoupled simulations accurately predicted Jangmi's track for the four days prior to landfall (Figure 3a). However, the intensity is considerably different between the two

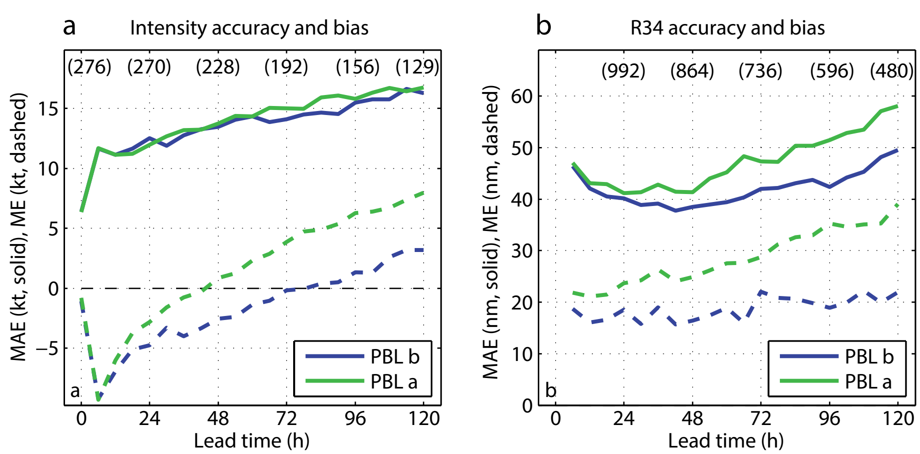


Figure 2. Comparison of two planetary boundary layer (PBL) parameterizations for: (a) forecast intensity, and (b) forecast radius of the 34 kt wind. The mean absolute errors (MAE, solid) and mean errors (ME, dashed) are shown for a large sample of western Atlantic Ocean storms. PBL-a uses a Bougeault and André (1986) mixing length only, while PBL-b features a combination of Bougeault and André (1986) and Mellor and Yamada (1982) mixing lengths. The number of samples for each forecast lead time is shown along the top of the plot, with a greater number of samples in (b) because the evaluation is performed for each quadrant.

simulations. The coupled simulation reduces the intensification rate during the second day of the simulation, and has an improved intensity forecast relative to the uncoupled simulation (Figure 3b). After reaching peak intensity, the storm in the coupled simulation decays faster after day four and compares better with the best track than the uncoupled simulation. This more rapid decay prior to landfall in the coupled simulation is associated with a considerably reduced surface enthalpy flux associated with up to 4°C cooling of the SSTs that occurred as Jangmi passed over the series of cold eddies (Figure 3a).

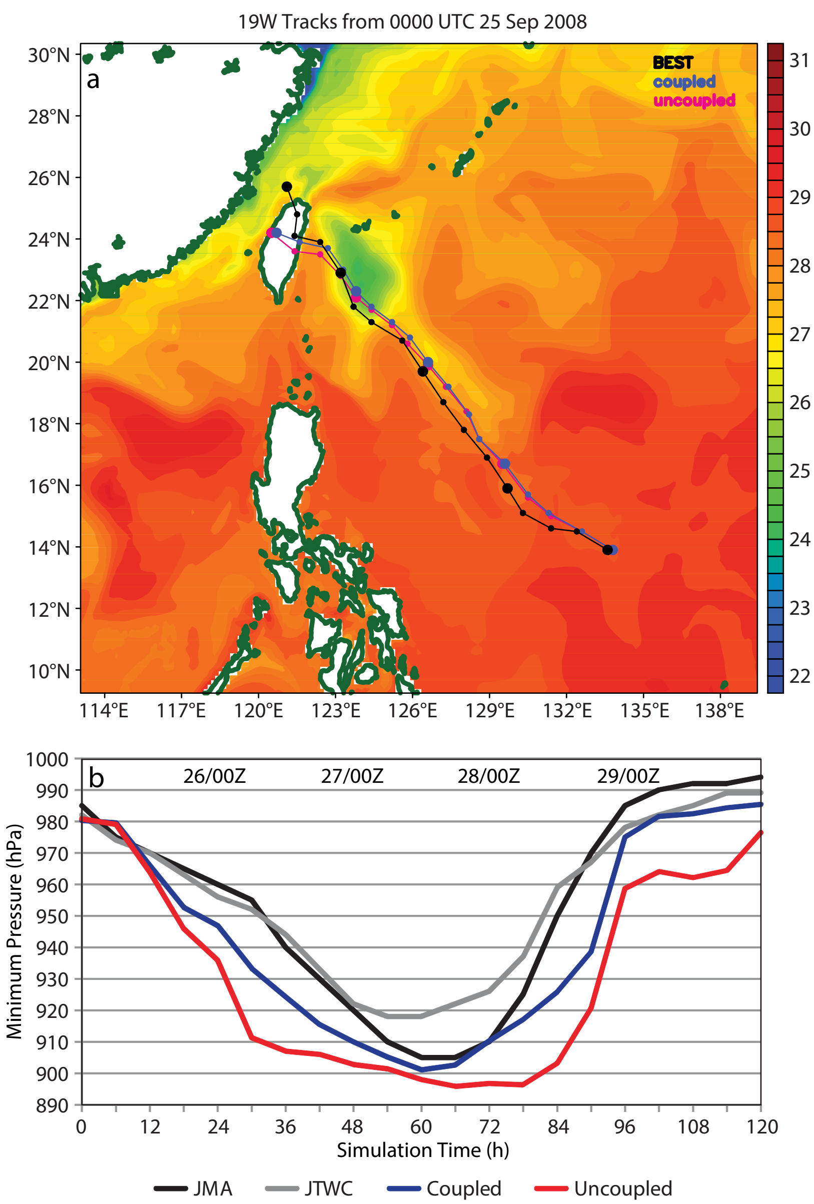


Figure 3. Simulations of Super-Typhoon Jangmi corresponding to the coupled and uncoupled COAMPS-TC experiments initialized at 0000 UTC September 25, 2008, for a five-day forecast displaying (a) track and sea surface temperature (°C) valid at 96 h (0000 UTC September 29), and (b) minimum central pressure (hPa) for the five day forecast. The best track from the Joint Typhoon Warning Center (JTWC) is displayed in (a), and the JTWC (gray) and Japan Meteorological Agency (black) estimates of the minimum central pressure are shown in (b).

During September–November 2010, the air-ocean coupled version of COAMPS-TC was used to provide real-time forecasts in support of the ONR Impact of Typhoons on the Ocean in the Pacific (ITOP) field program (D'Asaro et al., 2011), which was focused on gaining a new understanding of tropical cyclone forced cold wakes, surface fluxes, and the dynamical interaction between tropical cyclones and the ocean. The COAMPS-TC forecasts were successfully used during ITOP to guide the observing strategy in both the atmosphere and ocean. A storm of particular focus during ITOP was Typhoon Fanapi, which formed southeast of Taiwan in mid-September, intensified to a category-3 storm, and then made landfall in Taiwan on September 19. The predicted storm track is in excellent agreement with the best track, as Figure 4 shows for a forecast initialized at 0000 UTC September 15, 2010. There is general agreement in SST distribution as well, derived from satellite observations (Figure 4a) and the forecast (Figure 4b). Both predicted and satellite-observed cold wakes form on the right side of the track, with a similar amount of cooling (~ 3°C) relative to SST prior to the storm. The most intense cooling occurs on the eastern flank of the wake, in both the observations and the forecast, due to the initial slow movement of the storm in the September 15–17, 2010, time period. It is noteworthy that cold water is advected to the north at both the western and the eastern ends of the wake, surrounding the warm water near 126°E and 24.5°N. Note that cooling in the wake evolves during the forecast and is not present in the ocean initial conditions.

The capabilities of the air-ocean-wave coupled COAMPS-TC system are highlighted for Atlantic Hurricane

Frances (2004), which was observed during the ONR CBLAST field campaign near the northern shore of the Bahamas Archipelago. The three-way coupled COAMPS model configuration includes the three grid meshes (45/15/5 km), a single 3 km horizontal resolution ocean mesh, and a single 10 km horizontal resolution wave model. In this application, the atmospheric model has 60 vertical sigma levels and the ocean model has 49 vertical levels with 35 sigma layers. The wave model, SWAN, has 36 discrete directional and 33 frequency bands. For the forecast highlighted here, the coupled COAMPS-TC is initialized on 1200 UTC August 31, 2004. The initial and boundary conditions for the atmospheric and ocean models are provided by NOGAPS and global NCOM, respectively.

Figure 5 shows the air-ocean-wave coupled COAMPS-TC forecast SST, significant wave height, 10 m wind, total surface currents, and Stokes currents at the 48 h time. Comparisons with the best track show that the 48 h forecast track error is 100 nm and the intensity error is about 5 m s^{-1} (not shown). The COAMPS-TC minimum SST in the wake is 25.5°C, which is 3.7°C colder than the model initial SST. The forecast SST is in good agreement with the 229 ocean temperature profiles sampled by nine in situ CBLAST floats during a three-day forecast (D'Asaro et al., 2007; not shown). The quite reasonable COAMPS-TC mean upper 50 m and 50–100 m ocean temperature biases are −0.07°C and 1.83°C, respectively. The maximum significant wave height is located in the front right quadrant of the storm ahead of the trailing cold wake on the right side of the model track. The forecast mean significant wave height error on September 1 is about 3.5 m

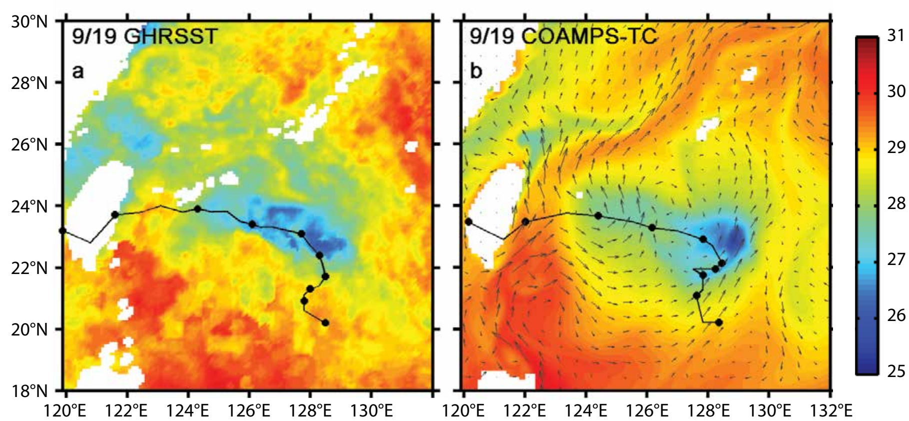


Figure 4. The cold wake generated by Typhoon Fanapi (2010) as shown by the: (a) GHRSST (Group of High Resolution Sea Surface Temperature) and (b) coupled COAMPS-TC 96 h forecast during the 2010 Impact of Typhoons on the Ocean in the Pacific (ITOP) field campaign (initialized at 0000 UTC September 15, 2010). Color shading denotes the daily mean SST on September 19, 2010; the solid black line corresponds to the storm track with its positions marked by black dots every 12 h starting at the initial time and arrows displaying the mean surface current vectors. The observed track is shown in (a) and the COAMPS-TC forecast track in (b).

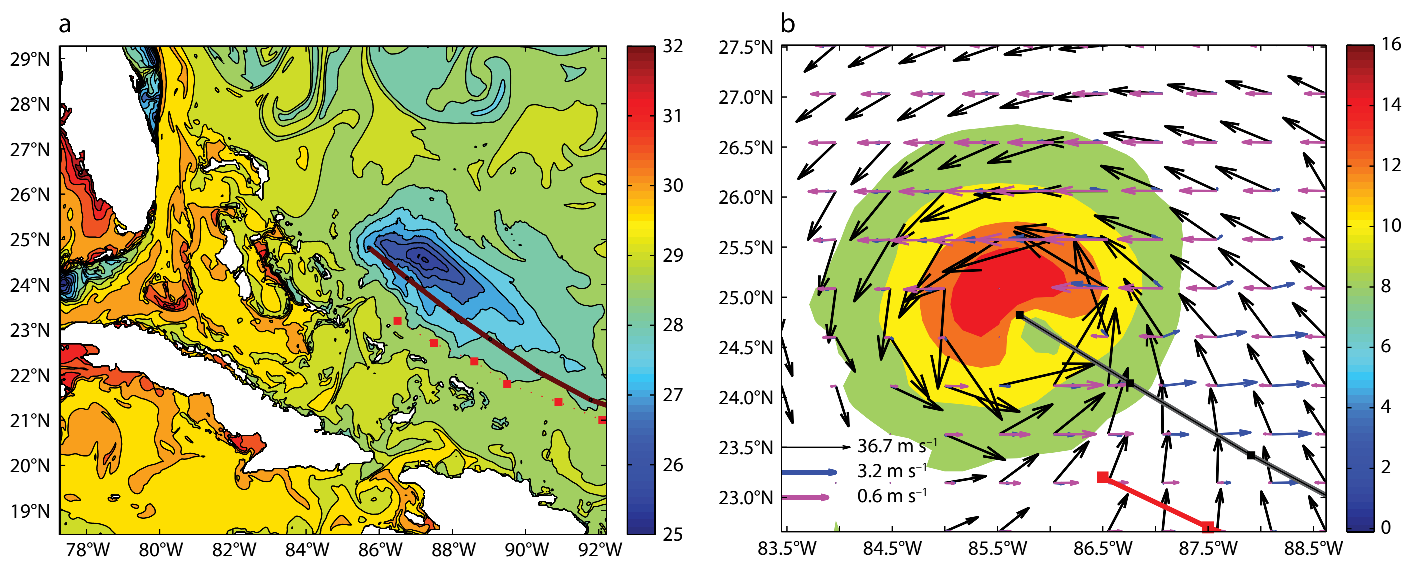


Figure 5. Air-ocean-wave coupled COAMPS-TC 48 h forecast of (a) sea surface temperature (°C) and (b) significant wave height (m; shading), wind (black arrows), surface current (blue arrows), and surface Stokes current (magenta arrows) vectors for Hurricane Frances (2004). COAMPS-TC is initialized on 1200 UTC August 31, 2004. The unit vectors for the wind, surface current, and surface Stokes current vectors are shown in (b). A subset of the domain is shown in (b) as well for clarity purposes. The model and best track are by the black and red lines and squares, respectively (every 6 h).

as verified using the Scanning Radar Altimeter on the NOAA-P3 aircraft. Alignment of the 10 m wind and Stokes surface current vectors are seen in the cold wake (not shown), suggestive of an increase in Langmuir turbulence (Van Roekel et al., 2012).

PREDICTION OF TRACK, INTENSITY, AND STRUCTURE

We validated COAMPS-TC predictions of track and intensity over large samples of cases in both the Atlantic and the western North Pacific tropical cyclone basins. For these tests, COAMPS-TC was run in uncoupled mode for efficiency reasons. The background field for the NAVDAS analysis corresponding to the first forecast for a storm (cycling data assimilation used beyond) and lateral boundary conditions for these tests used the Global Forecast System (GFS). The COAMPS-TC forecasts for a particular TC were produced every 6 h while it was defined to exist according to the operational assessment of NHC (for Atlantic TCs) or JTWC (for western North Pacific TCs) (typically numbered or named storms). In the Atlantic, we produced retrospective forecasts for 41 tropical cyclones that occurred in 2010–2012, yielding nearly 800 forecasts. In the western North Pacific, we produced real-time forecasts for 65 tropical cyclones from 2010–2012, yielding just over 1,100 forecasts. While it is computationally costly to build such large sample of COAMPS-TC forecasts, it is vital to validate the model for as many samples as possible in order to ensure robust performance for the variety of different TC forecast scenarios seen in nature.

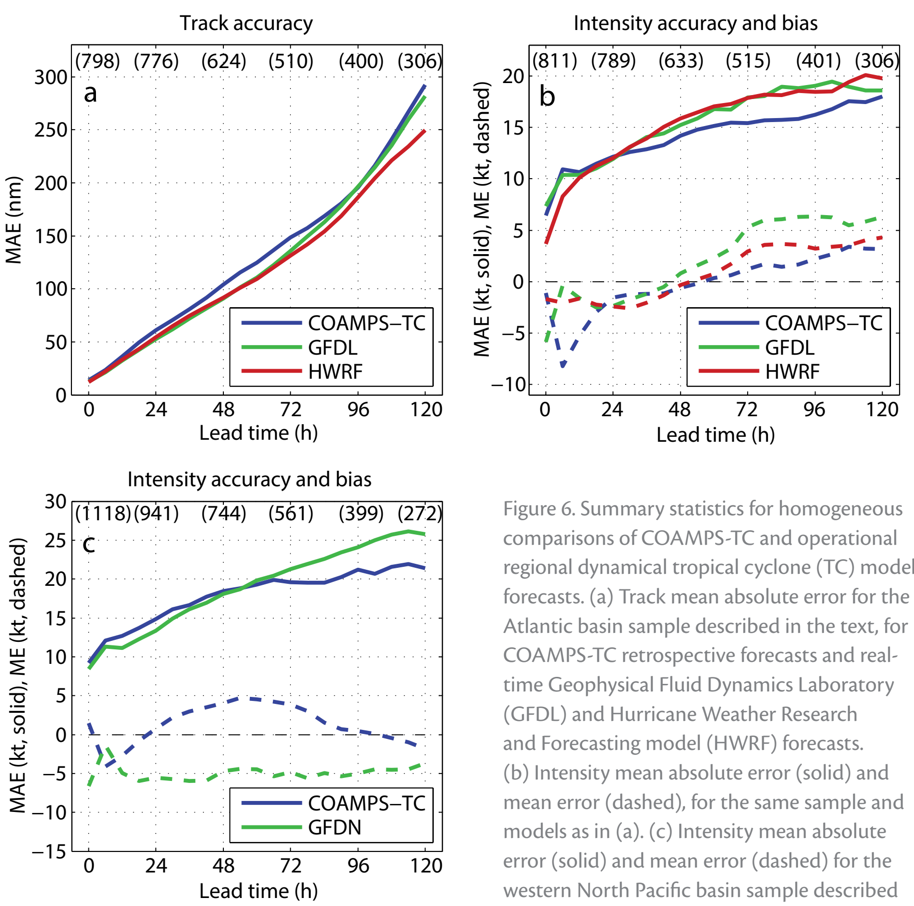


Figure 6. Summary statistics for homogeneous comparisons of COAMPS-TC and operational regional dynamical tropical cyclone (TC) model forecasts. (a) Track mean absolute error for the Atlantic basin sample described in the text, for COAMPS-TC retrospective forecasts and real-time Geophysical Fluid Dynamics Laboratory (GFDL) and Hurricane Weather Research and Forecasting model (HWRF) forecasts. (b) Intensity mean absolute error (solid) and mean error (dashed), for the same sample and models as in (a). (c) Intensity mean absolute error (solid) and mean error (dashed) for the western North Pacific basin sample described in the text, for COAMPS-TC and GFDN (GFDL-Navy model) real-time forecasts. In all panels, the sample size is shown as a function of lead time via the numbers at the top of the plot.

Figure 6 summarizes the statistics comparing the performance of COAMPS-TC forecasts and real-time forecasts from other operational regional dynamical tropical cyclone models. The operational model forecasts were sourced from the Automated Tropical Cyclone Forecast system (Sampson and Schrader, 2000) archive, along with the "best-track" analyses of TC position and intensity used as verification. Following conventional TC forecast validation procedures, a forecast case is only included in the validation sample if the best-track indicates the storm is a TC at the forecast initial time and valid time, and also that all models in the comparison made a forecast (i.e., the sample is homogeneous). For the Atlantic sample, COAMPS-TC forecasts are compared against those from the Geophysical Fluid Dynamics Laboratory model (GFDL) and the Hurricane Weather Research and Forecasting model (HWRF), both run by the National Centers for Environmental Prediction. Figure 6a displays track accuracy results and Figure 6b shows intensity accuracy (solid lines) and bias (dashed lines) results. The COAMPS-TC mean absolute error for track is slightly higher than the corresponding values for the operational models. However, the COAMPS-TC intensity forecasts are more skillful than HWRF and GFDL for all lead times beyond 24 h. The mean intensity error for COAMPS-TC is generally closer to zero than for the operational models, indicating that COAMPS-TC also performs better in terms of intensity bias as well as intensity accuracy. Figure 6c shows intensity error and bias results for the western

North Pacific sample of COAMPS-TC forecasts, in comparison with the GFDN model, the Navy's version of the Geophysical Fluid Dynamics Laboratory model. At lead times from 0 to 48 h, the GFDN mean absolute error is slightly lower than that of COAMPS-TC, but for later lead times, COAMPS-TC has a considerably lower mean absolute error than GFDN. Encouraging results for such large samples of cases provided the necessary evidence to facilitate the transition of COAMPS-TC into operations at FNMOC.

In spite of the generally successful performance of COAMPS-TC, the statistical evaluation points to several issues in which the forecast model requires additional improvement. One of the most obvious issues impacting the intensity predictions is the rapid development of a weak maximum wind speed bias in the first 12 h of the forecasts, apparent in Figure 6b,c and Figure 2a. This bias results from an adjustment process due to an unbalanced initial state within the TC vortex. The imbalance arises from the NAVDAS analysis, which is not able to accurately represent the wind and mass field correlations within the vortex. Examination of new methods for initializing the vortex and minimizing the adjustments during the early stages of the forecasts is underway.

Perhaps the most well-known tropical cyclone from the validation samples described above is Hurricane Sandy (2012). Sandy had a very atypical track and was an unusually large tropical cyclone due to the interaction of the TC with multiple mid-latitude weather systems. COAMPS-TC real-time forecasts of Sandy handled these complex interactions quite well, producing accurate simulations of the storm's track, intensity, and structure. Figure 7 highlights a particularly accurate forecast, initialized at 12 UTC October 25, 2012. Figure 7a shows the 120 h COAMPS-TC track forecast for this case alongside the observed track (from the National Hurricane Center "best-track"). The forecast shows landfall close to the observed location along the New Jersey coast between four and five days lead time, capturing the remarkably unusual "hard left turn" caused by the mutual interaction of Sandy with a deep mid-latitude trough over the East Coast. The model also had a reasonable intensity forecast (Figure 7b), but perhaps more relevant to the prediction of coastal impacts of such a storm (waves, surge), the model made an accurate prediction of Sandy's surface wind field. Figure 7c shows the 84 h lead time COAMPS-TC forecast of the 10 m wind field, which can be compared to the OSCAT (Oceansat-2 scatterometer) ocean surface wind observations (Figure 7d) collected near the forecast valid time. The COAMPS-TC forecast captures the large size of the wind field

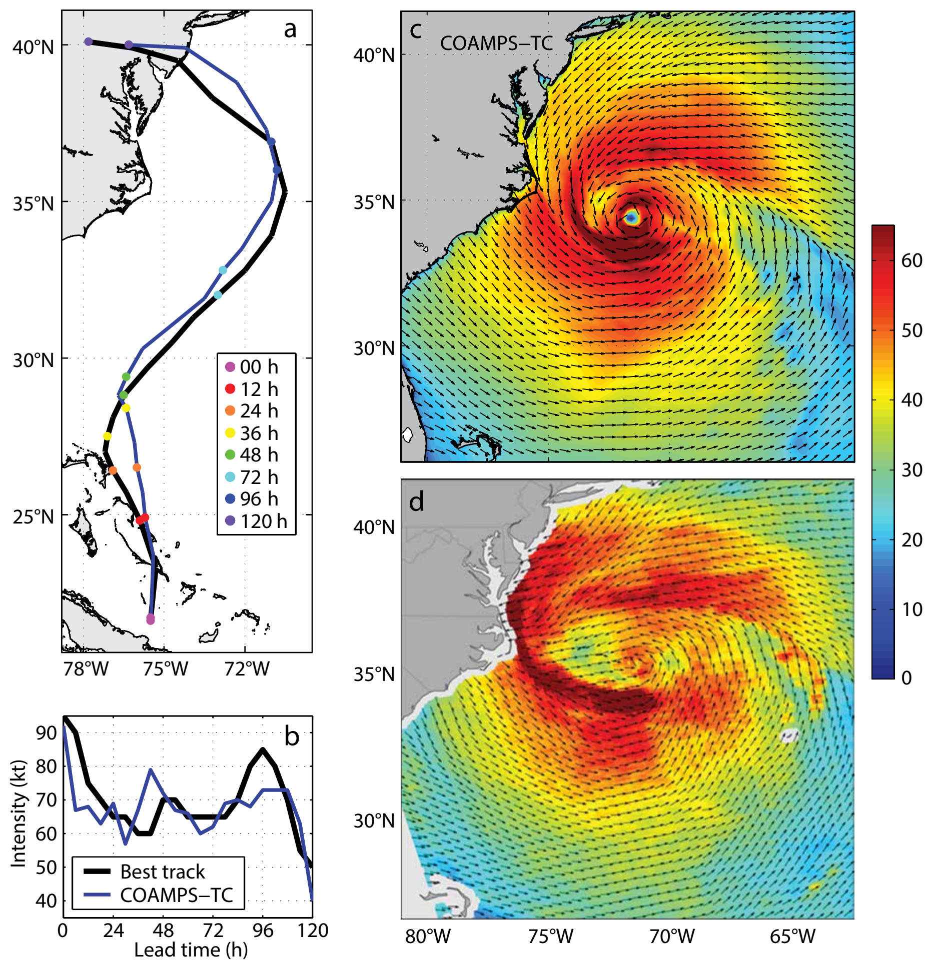


Figure 7. (a) COAMPS-TC real-time forecast track (blue) for Hurricane Sandy, initialized at 1200 UTC October 25, 2012, and corresponding best-track (black). The multicolored circles show the TC forecast position at different lead times and the corresponding best-track position valid at those times. (b) COAMPS-TC intensity forecast (blue) and best-track intensity (black). (c) COAMPS-TC forecast 10 m wind field at 84 h lead time, valid at 0000 UTC October 29, 2012. (d) OSCAT (Indian Space Research Organization's OceanSat-2 satellite) ocean surface wind observations collected near 0000 UTC October 29, 2012. *Image courtesy of NASA* In panels (c) and (d), the wind speed in miles per hour (mph) is shown in color and the vectors show wind direction.

and shows a core of strong winds near the center surrounded by an east-west elongated area of relatively light winds, qualitatively similar to the observations. However, the OSCAT data do indicate stronger winds than the model along the coast north of 35°N.

SUMMARY AND CONCLUSIONS

Prediction of tropical cyclone track and, particularly, intensity and structure, remains among the greatest challenges facing meteorologists today. The results of this research highlight the promise of a new high-resolution capability for tropical cyclone prediction using the Navy's COAMPS-TC. During the past several tropical cyclone seasons in the Western Pacific and Atlantic basins, COAMPS-TC has been tested in real time and for a series of retrospective cases in both coupled and uncoupled modes at high horizontal resolution.

An evaluation of a large sample of forecasts for 2010–2012 in the Atlantic and Western Pacific basins reveals that the COAMPS-TC intensity predictions are competitive with, and in some regards more accurate than, the other leading dynamical models, particularly for lead times beyond 36 h. Recent real-time forecasts of Hurricane Sandy (2012) illustrate the capability of COAMPS-TC to capture both the intensity and the fine-scale structure in agreement with observations. Typhoon Fanapi (2010) and Super Typhoon Jangmi (2008) in the Western Pacific are accurately predicted using the air-ocean coupled COAMPS-TC, with regard to not only the track and intensification but also the sea surface cooling induced through the mixing and upwelling in agreement with satellite measurements. The air-ocean-wave coupled simulations of the Atlantic Hurricane Frances (2004) highlight the capability of the COAMPS-TC system to realistically capture not only the SST cooling in the wake of the storm, but also the characteristics of the ocean surface waves, such as the significant wave height maximum in the front right quadrant of the storm.

While COAMPS-TC has accurately predicted the evolution of Sandy, Fanapi, Frances, and Jangmi, as well as other tropical cyclones (not shown) in real time and in retrospective cases, there are other examples that were not predicted as well. These storms, and the data collected during their life cycles, provide great opportunities to study and obtain a greater appreciation of the complex physical interactions that occur in these systems, and to use this information to improve our COAMPS-TC modeling system.

This research will lead to new capabilities in the form of mesoscale TC ensemble forecasts, providing the Navy with probabilistic forecasts of tropical cyclone intensity and structure for the first time. It is also expected that this research will help motivate new field campaigns that focus on the key measurements needed to further advance our understanding of the convective structure and dynamics of these systems and also provide forecast validation. The flexibility of the COAMPS-TC design will also allow us to test more advanced physics and numerical methods in an effort to gain a better physical understanding of the model's intensity forecast skill.

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