

# **The Navy's Next-Generation Tropical Cyclone Model**

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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. 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 judicious 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 and Rita of 2005, and other tropical cyclones. 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 mode (e.g., Hong et al. 2000).

## **OBJECTIVES**

The objective of this project is to develop and validate a next-generation tropical cyclone (TC) model that can analyze, initialize, and predict TC position, structure and intensity, using a high-resolution (< 3 km) air-ocean coupled mesoscale modeling system. The development will leverage emerging data assimilation and modeling techniques as well as observational results from the scientific community to build upon existing modeling capabilities.

## **APPROACH**

Our approach is to integrate emerging data assimilation and modeling techniques, as well as recent observational results, into the existing framework in the Coupled Ocean/Atmosphere Mesoscale

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14. ABSTRACT <p><b>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 judicious 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 and Rita of 2005, and other tropical cyclones. 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 multiscale 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 mode (e.g., Hong et al. 2000).</b></p>		
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Prediction System (COAMPS®<sup>1</sup>) for applications to the analysis and prediction of TC position, structure, and intensity. Specific technologies that will be developed and integrated into COAMPS in this project are physical processes and TC analysis techniques. This project will leverage recent research conducted on the physics of the surface and boundary layers in the recent ONR-sponsored Coupled Boundary Layers/Air Sea Transfer (CBLAST) project. In addition, we will leverage work performed over the past 2 years to integrate COAMPS with other physical parameterization schemes in the Weather Research and Forecast (WRF) repository, including the physics in the WRF-Advanced Research WRF (WRF-ARW) model developed at the National Center for Atmospheric Research (NCAR), and in the WRF-Nonhydrostatic Mesoscale Model (WRF-NMM) developed at the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP).

## **WORK COMPLETED**

The following work was completed in FY08:

The NRL Atmospheric Variational Data Assimilation System (NAVDAS) was modified for tropical cyclone analysis. The tropical cyclone initialization procedure of COAMPS has been improved to better analyze tropical cyclones for structure and intensity forecasts. We have upgraded the tropical cyclone relocation program to relocate not only wind, temperature, moisture, and pressure fields of a tropical cyclone circulation, but also hydrometeors and turbulence kinetic energy associated with the cyclone to the cyclone observed location for consistence. We have revised the method of generating synthetic observations to improve the vertical temperature profile and low level wind of the synthetic observations. We have modified the NRL Atmospheric Variational Data Assimilation System (NAVDAS) to reduce the analysis scale length and the degree of geostrophic coupling in tropical cyclone areas for better handling the multi-scale nature of tropical cyclone circulations. Furthermore, we have upgraded the COAMPS moving grid capability to include an option of selecting a family of nest grids to follow a tropical cyclone during the model forecast.

The complexity of ice nucleation (IN) processes and lack of observations distinguishing ice nuclei (IC) roles lead to large uncertainties in IN formulations, as evidenced by nearly a dozen of IN formulations employed in NWP models. Moreover, the representation of ice microphysics in NWP models applied to the TC core region has been based on mid-latitude observations. We have taken the following steps to evaluate the impact of IN formulations on TC intensity and structure forecasts. First, we identified, based on a wide literature survey, the most commonly used formulations in state-of-art NWP models: namely the Fletcher (1962) and Cooper (1986) schemes. A third alternative is a blend of these two, taking the maximum from the Fletcher and Cooper formulations, which is currently utilized in COAMPS.

A real-time tropical cyclone (TC) prediction system was set up for TC track prediction support for THORPEX-Pacific Asian Campaign (T-PARC) and Tropical Cyclone Structure 2008 (TCS08) (T-PARC/TCS08) experiments. This system was built using the COAMPS, and is referred to here as COAMPS-TC. Specific features of COAMPS-TC include a 3DVAR analysis that incorporates synthetic observations of the TC structure based on the official warning position and observed structure; a 40-level, triply-nested grid structure (45, 15, and 5 km nested grids), in which the inner two meshes are centered on, and automatically move with the tropical cyclone; and a 2D sea-surface

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<sup>1</sup> COAMPS® is a registered trademark of the Naval Research Laboratory.

temperature analysis that is done separately for each of the atmospheric grids. The outermost COAMPS grid (45 km) was made large enough so that it would include all tropical cyclones of interest to TCS-08. The COAMPS-TC forecast model includes new representations of the momentum, heat, and moisture surface exchange processes recently implemented from the recent CBLAST project.

COAMPS-TC was run automatically every 12 hours, with separate runs made for each tropical cyclone in the western Pacific. Each forecast was run to 72 hours. At the completion of each run, selected fields were sent to, and displayed, on the NCAR-EOL T-PARC/TCS08 web site. All the fields produced by the runs were archived so that the results can be examined in future studies.

In support of the T-PARC/TCS08 campaign, adaptive observing guidance for tropical cyclones has been provided from a number of operational, academic and research institutions all over the world. At the Naval Research Laboratory, mesoscale model guidance was produced twice daily using the recently developed adjoint and tangent linear models for the atmospheric portion of the nonhydrostatic COAMPS over the Northwestern Pacific. A unique aspect of this system is that an exact adjoint to the explicit microphysics has been developed. An adaptive response function region is used to target favorable areas for tropical cyclogenesis and development. Real-time COAMPS-adjoint forecasts with lead times of 36 h, 48 h, and 72 h were executed twice daily during T-PARC/TCS08 using a horizontal resolution of 40 km. The adjoint sensitivity results were uploaded to the T-PARC/TCS08 web site at NCAR-EOL and communicated in real time to the T-PARC/TCS08 targeting team. Targeting missions using the C130 and NRL P3 were designed to sample the most sensitive regions.

## RESULTS

The new capability developed for NAVDAS to support the analysis and initialization of tropical cyclones has been tested and evaluated for a number of tropical cyclone cases. With the improvements made to the tropical cyclone initialization procedure, the analyzed tropical cyclone circulation for COAMPS is more realistic relative to the original NAVDAS analysis and the optimal interpolation analysis (Fig. 1). The initial tropical cyclone circulation matches the observed structure well and is in more of a dynamical balance. The new analysis capability support multiple grid meshes and is self-consistent across the mesh interfaces. As a demonstration of the tropical cyclone prediction capability using the new analysis system, forecasts were run for hurricane Katrina, which occurred during August 2008. The multi-level moving mesh capability, shown in Fig. 2, is able to maintain a deep tropical cyclone, exhibits no undesirable noise at the lateral boundary, and is computationally efficient.

The sensitivity of tropical cyclone forecasts to the formulation of the ice microphysical parameterization has been explored. The number of ice crystals resulting from the Cooper and Fletcher ice formulations discussed above as a function of temperature was carefully examined. We then did a series of sensitivity tests using different IN formulations in COAMPS to understand the impact of IN formulations on TC development and its interaction with other components of model physics. Improved structure and intensity forecasts were obtained for the Isabel (2003) and Katrina (2005) tropical cyclones. The Fletcher formulation is as follows:

$$N_{i,Fletcher} = 10^{-2} \exp[0.6(T_0 - T)] \quad (1)$$

where  $T_0=273.16$ ,  $T$  is the ambient air temperature (K), and  $N_i$  is the number of ice crystals initiated ( $m^{-1}$ ). Cooper's relationship is expressed in a similar form:

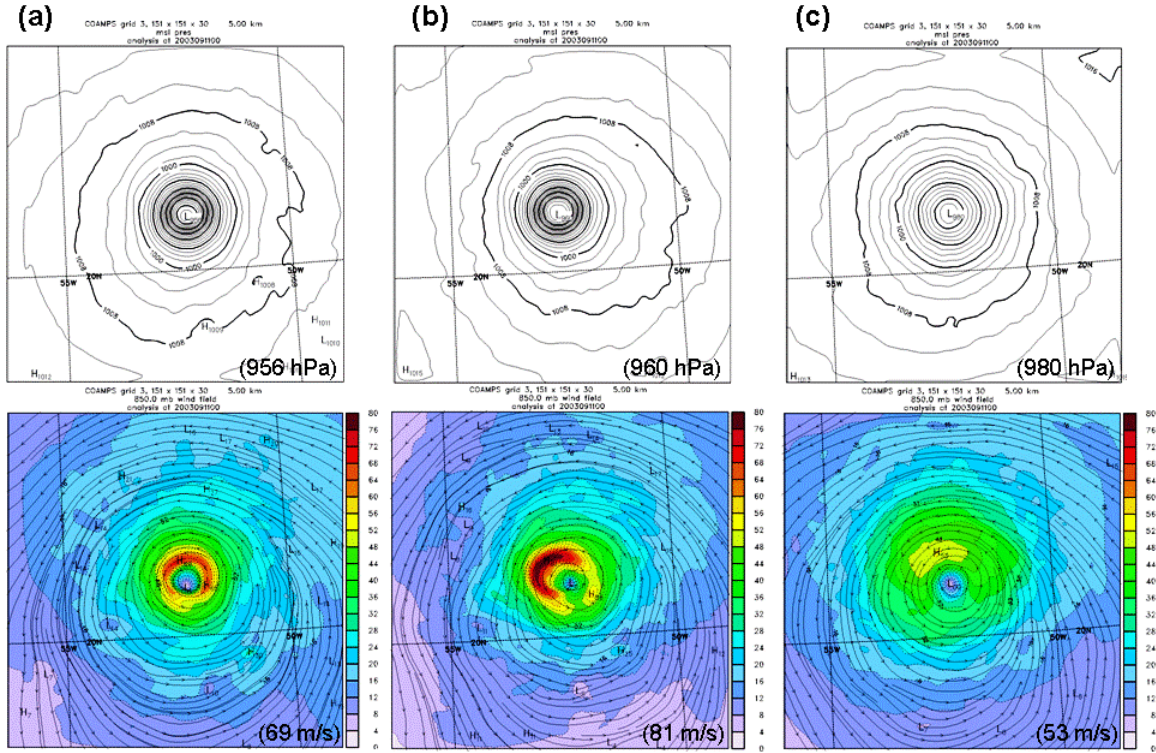
$$N_{i,Cooper} = 5.0 \exp[0.304(T_0 - T)] \quad (2)$$

The uncertainty related to IN calculations is exacerbated when significant differences in the temperature threshold exist not only between the Fletcher and Cooper formulations, but also among the same formulations implemented in various bulk microphysics schemes. These differences could reach as high as 13 K.

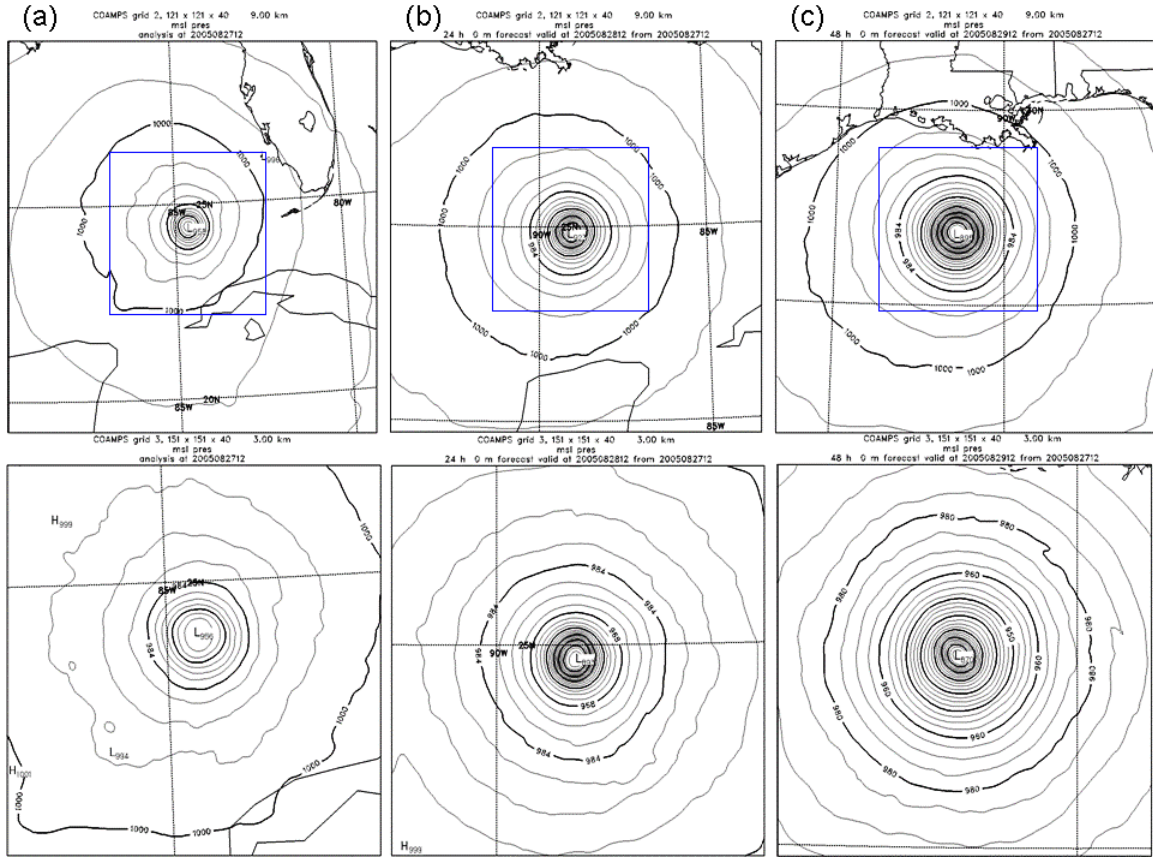
As shown in Fig. 3a, the Cooper formulation produces an order of magnitude greater ice concentration for temperatures above  $-20^{\circ}\text{C}$ , whereas the Fletcher formulation produces more than an order of magnitude greater ice concentration at lower temperatures. COAMPS simulations of Hurricane Isabel (2003) at 5 km resolution using the current set of the formulations (Fig. 3a) produce storms with significantly different intensities. For example, the simulated TC with the current Cooper formulation has a central sea level pressure (SLP) that is approximately 20 hPa deeper (Fig. 4a) and  $18\text{ m s}^{-1}$  stronger surface maximum winds (MAXW) (Fig. 4b) than the current Fletcher formulation. The simulated Isabel intensity converges using the new set of IN formulations (Figs. 4c and d). When replacing the current blending scheme used in the operational version of COAMPS with the new blending scheme (Fig. 3c), the TC intensity forecasts for the Isabel case improved by approximately 10 hPa for SLP and  $10\text{ m s}^{-1}$  for MAXW (comparing the green lines in Figs. 4a,b with those in Figs. 4c,d). The improvement in TC intensity forecasts using the new ice microphysics formulation becomes more substantial for the Katrina case at 3 km grid spacing with a 38 hPa deeper SLP and a  $22\text{ m s}^{-1}$  stronger MAXW (not shown). The Katrina simulation with the new blending formulation also shows much improvement in the azimuthally averaged winds (Figs. 5a, b, and c) and in the 34 kt and 50 kt wind radii (Fig. 5d). While more in-depth research is needed to fully understand the complicated interplay between the thermodynamic and dynamic processes associated with cloud ice, it is demonstrated here that TC intensity and structure forecasts are highly sensitive to IN formulations within bulk microphysics schemes.

The real-time COAMPS-TC forecasts demonstrated skill in the prediction of the tracks of tropical cyclones during the TCS-08 campaign. An example of the skill of the COAMPS-TC forecasts is presented here for the 72 hour forecast of Typhoon Nuri, initialized at 1200 UTC 17 August 2008 (Fig. 6). Starting at the initial time of the forecast, Nuri moved slightly north of due west, to a position just north of the Philippines. COAMPS-TC was able to predict this motion quite well, moving the storm slightly north of the verifying positions, and moving it slightly slower than observed. During the duration of the forecast, the 15 and 5 km grids moved with the TC, providing the highest resolution for the TC and the area around it. Statistics for all COAMPS-TC TCS-08 forecasts will be compiled at the completion of the TCS-08 campaign, and the results from the model runs will be used to address further areas of research to study in tropical cyclone modeling.

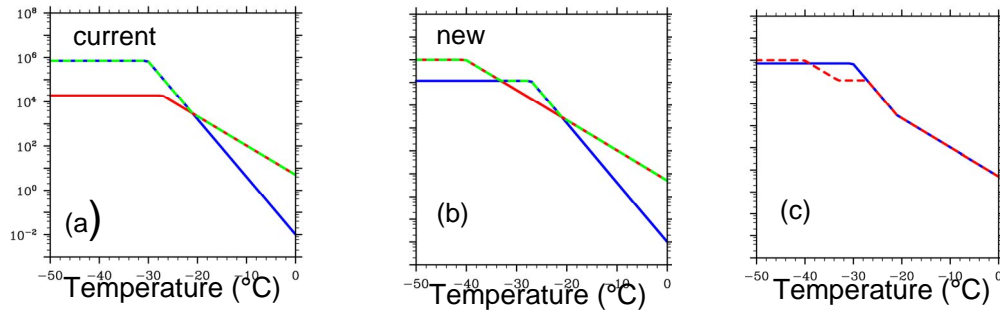
Real-time COAMPS-TC adjoint sensitivity calculations were performed during the T-PARC/TCS08 campaign. An example of a sensitivity forecast is presented here for Typhoon Sinlaku, initialized at 1200 UTC 12 August 2008 (Fig. 7). The sensitivity regions during the latter stages of Sinlaku were generally located on the north and east side of the TC. The spatial location of the sensitivity maxima often were influenced by convection, in this case along the periphery of Sinlaku. Observations from the C130 were taken in the sensitive regions based on the adjoint forecasts as well as guidance derived from other models. The adjoint system was also used for targeting in support of tropical cyclogenesis, which was one of the first times this was ever attempted. Future studies will be needed to assess the significance of the sensitivity calculations and the impact of the dropsonde observations.



**Figure 1. Comparison of analyzed sea-level pressure (upper) and 850 hPa wind (lower) from (a) COAMPS-TC NAVDAS analysis, (b) original NAVDAS analysis, and (c) OI analysis for hurricane Isabel. The observed maximum wind at 10 m is 125 kt and central sea-level pressure is 940 hPa.**

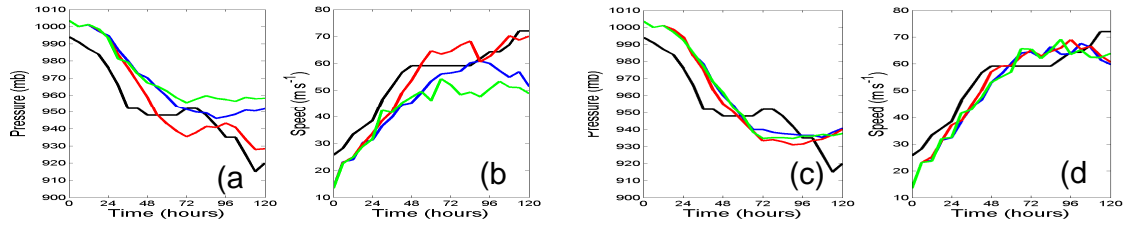


**Figure 2.** Sea-level pressure of Katrina from COAMPS second (upper) and third (lower) mesh forecasts following Katrina movement at (a) initial, (b) 24 h, and (c) 48 h forecasts. The blue boxes indicate the third mesh domain in the second mesh coordinates.

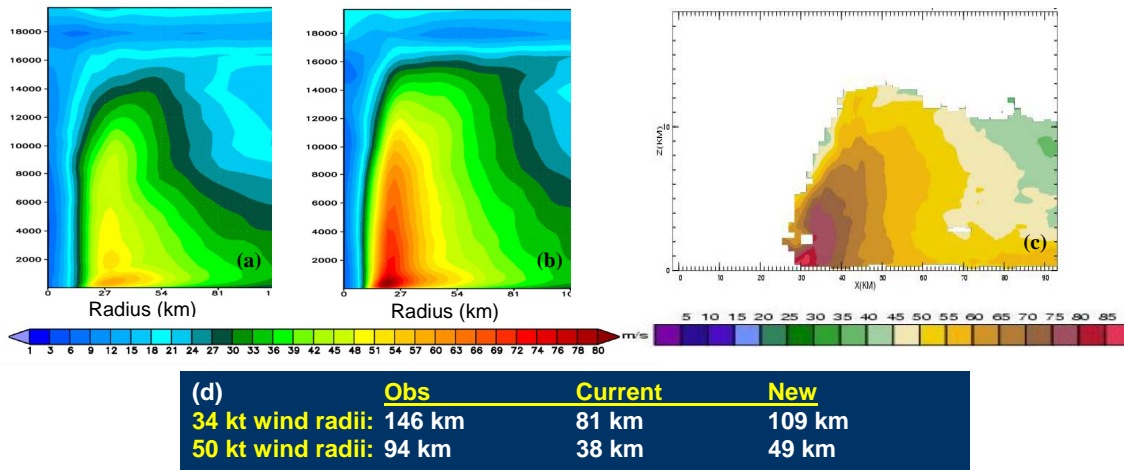


**Figure 3.** Ice number concentration ( $10^3 \text{ m}^{-3}$ ) as a function of temperature from the Fletcher (blue, solid), Cooper (red, solid) and blending (green, dashed) of Fletcher and Cooper, as specified in (a) the current microphysics scheme of COAMPS, (b) the new microphysics scheme; (c) a comparison of the current (blue, solid) and new (red, dashed) blending schemes.

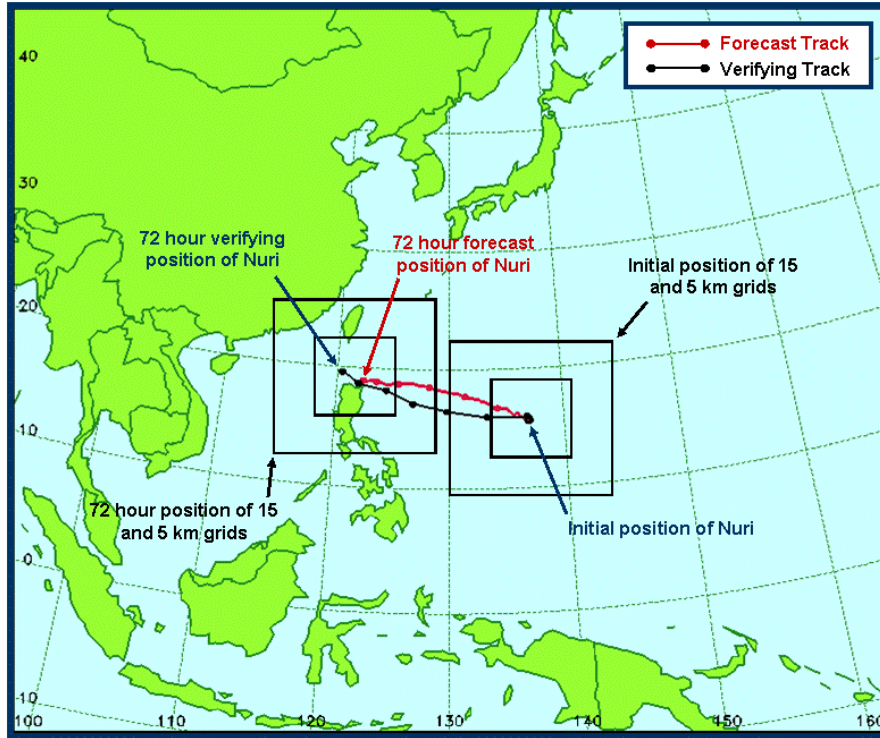




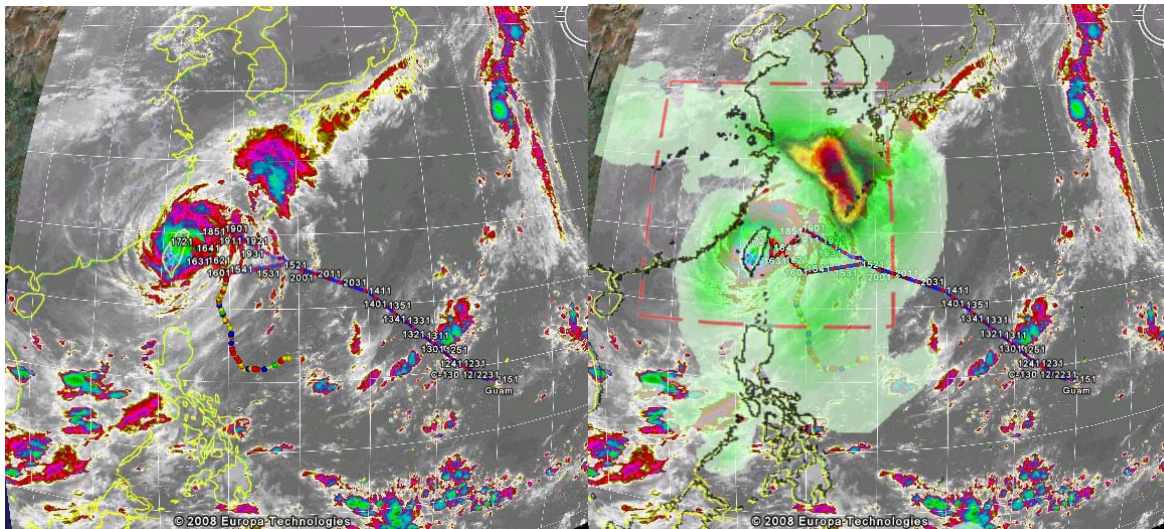
**Figure 4.** COAMPS simulated Hurricane Isabel (2003) intensity using the current formulations (corresponding to Fig. 3a) is shown in 4a for minimal sea level pressure and in 4b for maximum surface winds, black line for observed intensity, blue for simulated intensity using the Fletcher's formulation, red using the Cooper's, and green using the blending. The simulated intensity using the new formulations (Fig.3b) is shown in Figs.4c and d, with the same color code as in Figs.4a and b.



**Figure 5.** Height-radial distributions of azimuthally averaged winds of COAMPS Katrina simulation using the current blending formulation (a) and the new blending formulation (b) compared to RAINEX observations (c). Also listed are the observed and simulated 34 kt and 50 kt wind radii (d).



**Fig. 6.** Area covered by the COAMPS-TC 45 km outermost grid; the initial and 72 hour positions of the 15 and 5 km grids, as labeled; the verifying track of Nuri starting from 1200 UTC 17 August 2008 (black line with dots every 12 hours); and the COAMPS-TC 72 hour predicted track (red line with dots every 12 hours).



**Fig. 7.** Infrared satellite image, C130 flight track, and tropical cyclone track valid at 1200 UTC 13 September 2008 (left). COAMPS adjoint sensitivities, expressed as vertically integrated total energy, are shown on the right in color with green (low sensitivity) to red (high sensitivity) shading for a 24-h sensitivity forecast with a 24-h lead forecast initialized at 1200 UTC 23 September 2008.

## TRANSITIONS

The tropical cyclone application of COAMPS will transition to 6.4 projects within PE 0603207N (SPAWAR, PMW-180) 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.

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