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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 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 to analyze and predict TC structure and intensity changes in an operational environment.

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 (< 5 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, modeling, and coupling techniques, as well as recent observational results, 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). 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 analysis techniques, (2) TC initialization, (3) Physical processes and parameterizations, and (4) Air-Ocean and Air-Wave coupling. This project will accelerate the testing and transition of the new air-sea/sea-spray flux parameterizations developed during the ONR CBLAST[2] program, and will leverage emerging scientific findings from the recent Tropical Cyclone Structure (TCS-08) in the Northwestern Pacific. The project will also leverage other work on coupled modeling found within the Battlespace Environments Institute (BEI) that addresses the coupling of the COAMPS atmospheric

[1] COAMPS® and COAMPS-OS® are registered trademarks of the Naval Research Laboratory.
[2] CBLAST was the 2001-2003 Coupled Boundary Layers/Air-Sea Transfer experiment sponsored by Office of Naval Research.

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14. ABSTRACT
The long-term goal of this project is to develop a robust 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 to analyze and predict TC structure and intensity changes in an operational environment.

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model to the Navy Coastal Ocean Model (NCOM) using the Earth System Modeling Framework (ESMF).

The key participants of this project include the principal investigator Dr. James Doyle and Drs. Chi-Sann Liou, Yi Jin, and Shouping Wang, all of NRL. The participants work closely with other members of the COAMPS-TC team including Dr. Richard Hodur (SAIC), Dr. Hao Jin (NRL), and Dr. Keith Sashegyi (NRL).

WORK COMPLETED

We have examined cases of problematic tropical cyclone (TC) analyses that appeared in the real-time COAMPS-TC forecasts during the Tropical Cyclone Structure 2008 (TCS-08) experiment. Through careful analysis of the results, we found that the minimization iteration routine in the NRL Atmospheric Variational Data Assimilation System (NAVDAS) had not converged in these poor-performing cases. The source of the problem has been identified to be the analysis length scale near the center of the tropical cyclones. We then modified the NAVDAS length-scale algorithm, which addressed the convergence problem. We have also modified and improved the TC relocation capability within NAVDAS by applying a variational adjustment to the relocated height and temperature fields for improving the hydrostatic balance. The improvement to the balance conditions in the first-guess fields for NAVDAS yields an analysis with a realistic balance.

COAMPS-TC physics has been updated to improve tropical cyclone (TC) intensity and structure forecasts. In addition to the transition to 6.4 of the modified software for ice nucleation formulation, we implemented a recent version of a sea-spray algorithm. The turbulent kinetic energy (TKE) dissipation has also been modified from an explicit calculation to a semi-implicit form. Correspondingly, the calculation of the dissipative heating at the air-sea interface is now consistent with the dissipative heating calculation in the layers above the surface. These changes, along with a new mixing-length implementation in the boundary-layer parameterization and the updated initialization scheme, have shown to substantially improve the COAMPS-TC forecast skill for a re-forecast of the 2008 TC season over both the Atlantic and West Pacific basins.

COAMPS-TC was set up for TC track prediction support for the THORPEX-Pacific Asian Campaign (T-PARC) and the Tropical Cyclone Structure 2008 (TCS-08) (T-PARC/TCS-08) experiments. Specific features of COAMPS-TC include a 3D variational analysis (NAVDAS) 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 horizontal resolution), in which the inner two meshes are centered on, and automatically move with the tropical cyclone; and a 2D sea-surface temperature analysis that is performed 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 CBLAST project.

In support of the T-PARC/TCS-08 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/TCS-08 using a horizontal resolution of 40 km. The adjoint sensitivity results were uploaded to the T-PARC/TCS-08 web site at NCAR-EOL[3] and communicated in real time to the T-PARC/TCS-08 targeted observing team. Targeting missions using the C130 and NRL P3 aircraft were designed to sample the most sensitive regions affecting potential TC development.

RESULTS

In the original NAVDAS algorithm, the lower limit of the analysis length-scale results in a rapid change environment is the length scale near the tropical cyclone center. The change in the length scale was so rapid that the quasi-linear assumption implicit within NAVDAS was violated. After the length-scale algorithm was modified to provide a smoothly varying range near the TC center, with a new lower limit of 192 km, the minimization iteration in the NAVDAS converged properly and the analysis subsequently improved significantly, as shown in Fig. 1.

Although the TC relocation algorithm will not generate noise or sharp gradients in the horizontal, through careful analysis of the results it was found that the relocation may cause poor hydrostatic balance in the vertical. As a result, small-scale noise may be generated early in the COAMPS-TC forecast period. The small-scale noise was removed from the initial forecast when the variational adjustment for hydrostatic balance was applied to the relocated geopotential height and temperature first-guess fields for the NAVDAS analysis, as shown in Fig. 2.

It has long been recognized that sea spray may considerably impact sensible and latent heat flux at the ocean surface, and thus change the effective transfer coefficient for enthalpy. However, the extent to which sea spray can affect the surface enthalpy flux (hence its effective transfer coefficient) has not been determined due to a lack of understanding of the process and relevant observations. It remains unclear how the droplet-produced latent heat flux should be partitioned to offset the sensible heat flux; this issue critically defines the extent to which the enthalpy flux can be increased due to the spray droplet latent heat release. Even though significant challenges remain, progress has been made in sea-spray parameterizations. The latest improved sea-spray parameterization (Fairall 2008, personal communication) has been implemented in COAMPS-TC. A comparison of high-resolution (3-km) COAMPS simulations of Hurricane Katrina (2005) with and without the sea-spray parameterization indicates that contributions from sea spray become significant when the storm reaches hurricane intensity (Fig. 3) since more moisture is supplied to the boundary layer (BL) from the ocean. The latent-heat flux in the eyewall increases by approximately 900 Ws^{-2} with the inclusion of the sea-spray parameterization (Figs. 4c, d). The evaporative cooling generated by the spray results in regions of significant negative sensible heat flux in the eyewall (Figs. 4a, b). This cooling tends to reduce the intensification to some extent and make the BL more stable. It should be noted that in the previous version of the COAMPS-TC, the effect of sea spray was accounted for through the increasing value of moisture transfer coefficient C_E with surface winds (Black et al. 2008).

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[3] NCAR-EOL is the National Center for Atmospheric Research Earth Observing Laboratory in Boulder, CO.

The performance of the new version of COAMPS-TC, which includes changes in the enthalpy exchange coefficient, the ice nucleation formulation, the TKE dissipation, the dissipative heating at the surface, and the mixing length, were evaluated against the best track data and field experiment data for both intensity and structure forecasts. The surface maximum wind forecast from the Katrina simulation using the new version (Fig. 5a) compares much better with the Doppler radar observations (Fig. 5c) than that from the previous version of COAMPS-TC (Fig. 5b). The previous COAMPS-TC version failed to intensify the storm during the first 4 days of simulation. The azimuthally averaged inner-core structure is much better captured by the new version (Fig. 6a) than the old version (Fig. 6b), when compared with the Doppler radar observations (Fig. 6c).

An example of a real-time COAMPS-TC forecast during T-PARC/TCS-08 initialized on 26 September 2008 performed in support of T-PARC/TCS-08 objectives is shown in Fig. 7. The forecast and best track positions shown in Fig. 7a indicate a skillful forecast of the track of super-Typhoon Jangmi. The model forecasted radar reflectivity (Fig. 7b) indicates a well-developed convective eye-wall structure in the 5 km resolution grid along with spiral rain bands. The forecast structure of the spiral rain bands is in general agreement with the Tropical Rainfall Measuring mission (TRMM) 85 Ghz imagery shown in Fig. 8 valid at 1856 UTC 27 September (approximately 5 hours prior to the forecast shown in Fig. 7b). For example, the prominent rain band along the eastern flank of the tropical cyclone is well represented.

The real-time COAMPS-TC forecasts demonstrated skill in the prediction of the tracks of tropical cyclones during the TCS-08 campaign. An analysis of the TC track performance during T-PARC/TCS-08 indicates that the COAMPS-TC track error was an improvement over the operational version of COAMPS for the Western Pacific (COAMPS-WPAC) and comparable or better than NOGAPS (particularly for the 36-48 h times) and a baseline forecast derived from a combination of climatology and persistence (CLIPER), as shown in Fig. 9. The track verification statistics were performed using a homogeneous sample. The number of cases for the verification ranges from 95 at the initial time to 49 at the final time. It should be noted that the operational COAMPS-WPAC has a horizontal resolution of 27 km, and has not been used for operational prediction of tropical cyclones.

The adjoint results indicate that forecasts of Western Pacific tropical cyclones during both formation and mature stages are very sensitive to the initial state given the rapid growth of small perturbations, discussed below. The adjoint-based sensitivity fields indicate structured patterns in the wind, thermal, and microphysical fields that project onto the model simulated deep convection, which ultimately influences the intensification rate. For example, sensitivity fields for Typhoon Sinlaku, valid at 1200 UTC 10 September 2008, are shown in Fig. 10. At this time, Sinlaku is near its peak intensity of 125kts, as given by the Joint Typhoon Warning Center (JTWC) best-track estimate. The sensitivity of the final time kinetic energy in the box shown in the figure to the initial vorticity at 800 hPa indicates a highly structured pattern with anticylonically curved sensitivity maxima (Fig. 10a). The structure of these bands is closely related to the tropical cyclone circulation, as apparent from the 800-hPa geopotential height and wind fields from the nonlinear forward model valid at 1200 UTC 10 September, shown in Fig. 10a. These anticyclonically curved maxima share characteristics with the optimal perturbations found by Nolan and Farrell (1999) in their simple-model study of vortex instability. Nolan and Farrell illustrate how finite-time optimal perturbations exhibit an initial tilt against the vortex shear, similar to that found in this case and others. Similar banded structures are apparent in the vorticity sensitivity fields for T-PARC/TCS-08 tropical cyclones that had strong circulations, and hence significant horizontal shear around the cyclone periphery. The region of the perturbation total energy maximum near the cyclone is well sampled by the C130 aircraft soundings deployed during this flight (Fig. 10b). Adjoint sensitivity images were routinely transformed into the Google Earth display software to enable the flight tracks and dropsondes to be displayed in real time along with the COAMPS adjoint model results at the T-PARC/TCS-08 forecast center.

A second example of adjoint sensitivity fields for super-Typhoon Jangmi valid at 0000 UTC 25 September 2008 is shown in Fig. 11. The COAMPS forecast started from an analysis valid for 1200 UTC 23 September 2008, before Jangmi reached tropical storm status. The JTWC upgraded the likelihood of development on 1300 UTC 23 September 2008 from "poor" to fair" and issued its first warning on 1800 UTC 23 September 2008. JTWC estimated sustained winds of 35kts at 0000 UTC 24 September 2008, 50kts at 1800 UTC 24 September 2008 and 80kts on 1800 UTC 25 September. Thus, the forecast started before Jangmi became a tropical storm, and the adjoint calculation covers the time when Jangmi intensified from a tropical storm to a typhoon. At this time, the vorticity sensitivity at 800-hPa (Fig. 11a) gives the appearance of a wave packet characterized by a series of positive and negative sensitivity regions. The strongest regions of sensitivity correspond to regions of active convection in the model and are distributed along the axis of a monsoon trough. Given this sensitivity pattern, an observational strategy to sample in and near regions of organized convection is consistent with the model sensitivity fields. The nonlinear evolution of the adjoint-derived optimal perturbations are very similar in magnitude and structure to the tangent linear evolved perturbations in the region of the vorticity features, which lends support for the relevance of these sensitivity structures for predictability and perturbation growth in this case. The perturbation total energy (Fig. 11b) indicates three prominent maxima, one located near the region of the Jangmi circulation and two maxima positioned much farther to the south near a region of convection in the model. Because of the relatively large spatial region of sensitivity, the aircraft flight on this particular day was only able to sample a part of the northern portion of the sensitivity near the Jangmi circulation. The differences in the adjoint sensitivity shown in Fig. 11a and total energy in Fig. 11b are a reflection of the dominance of the moisture and temperature sensitivity.

The corresponding sea and land surface adjoint sensitivity field is shown in Fig. 12, valid at 0000 UTC 25 September 2008. Sea and land surface temperature sensitivity products were produced routinely in real time, and allow for a quantitative assessment in how changes to the sea surface temperature (SST) would impact storm development. In this particular example, a relatively large region of sensitivity to the underlying sea surface is located near and to the south of the Jangmi track. The SST sensitivity is a maximum in regions where deep convection is especially vigorous in the model, as suggested by the relationship between the sensitive regions and heavy precipitation areas shown in Fig. 12. Additionally, the SST sensitivity is a maximum to the west and ahead of the TC track along the trough axis.

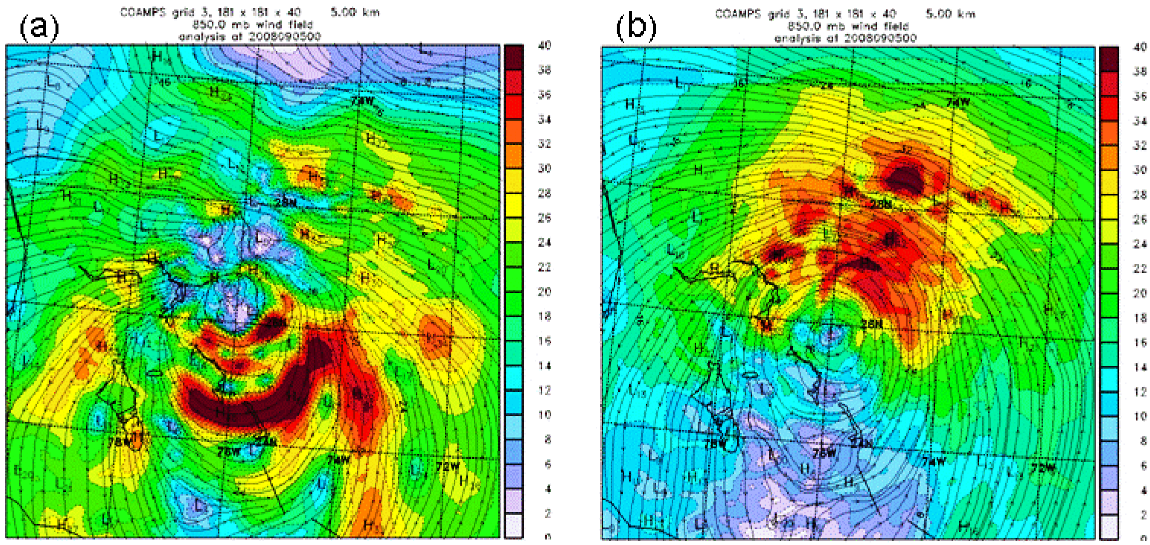

Figure 1. Comparison of analyzed 850-hPa winds for typhoon Sinlaku at 0000 UTC 5 September 2008 (a) before and (b) after modification of the NAVDAS analysis scale length algorithm. The minimization iteration did not converge before the modification (a).

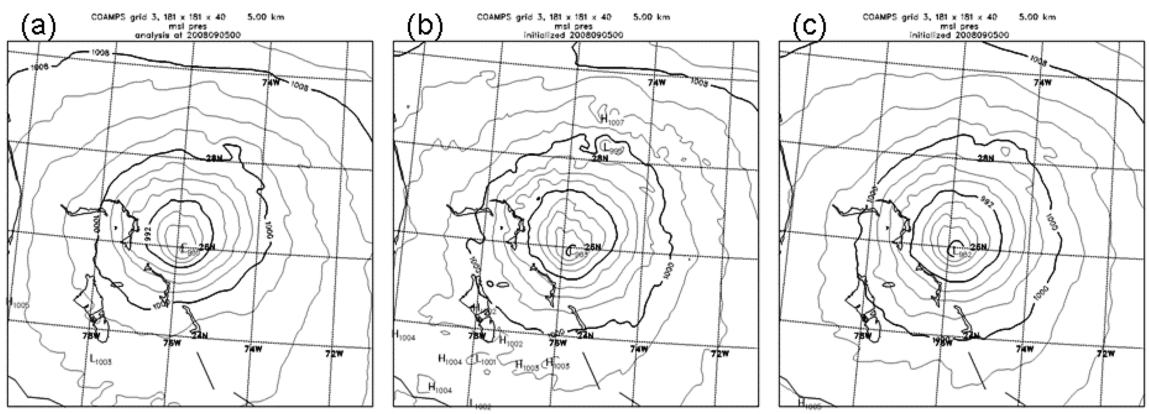

Figure 2. Comparison of sea-level pressure for typhoon Sinlaku at 0000 UTC 5 September 2008 from the (a) NAVDAS analysis, (b) first time step from the control forecast and (c), first time step from the simulation performed with the TC relocation reformulated.

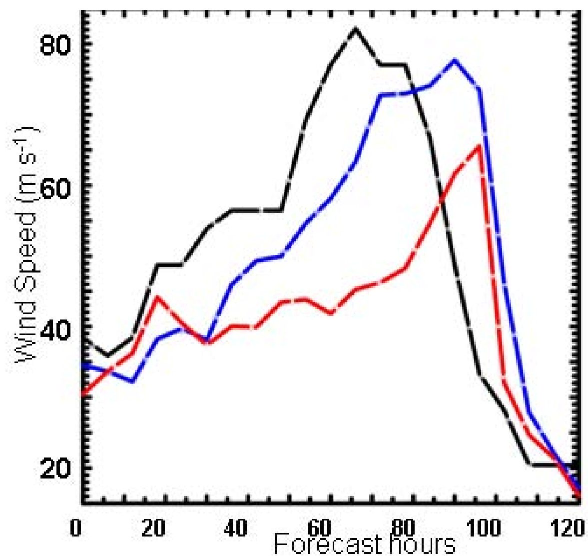

Figure 3: COAMPS forecast surface maximum winds in the 3-km resolution domain for Katrina initialized at 0000 UTC 26 August 2005 with (blue) and without (red) the sea spray parameterization. The best track is shown in black.

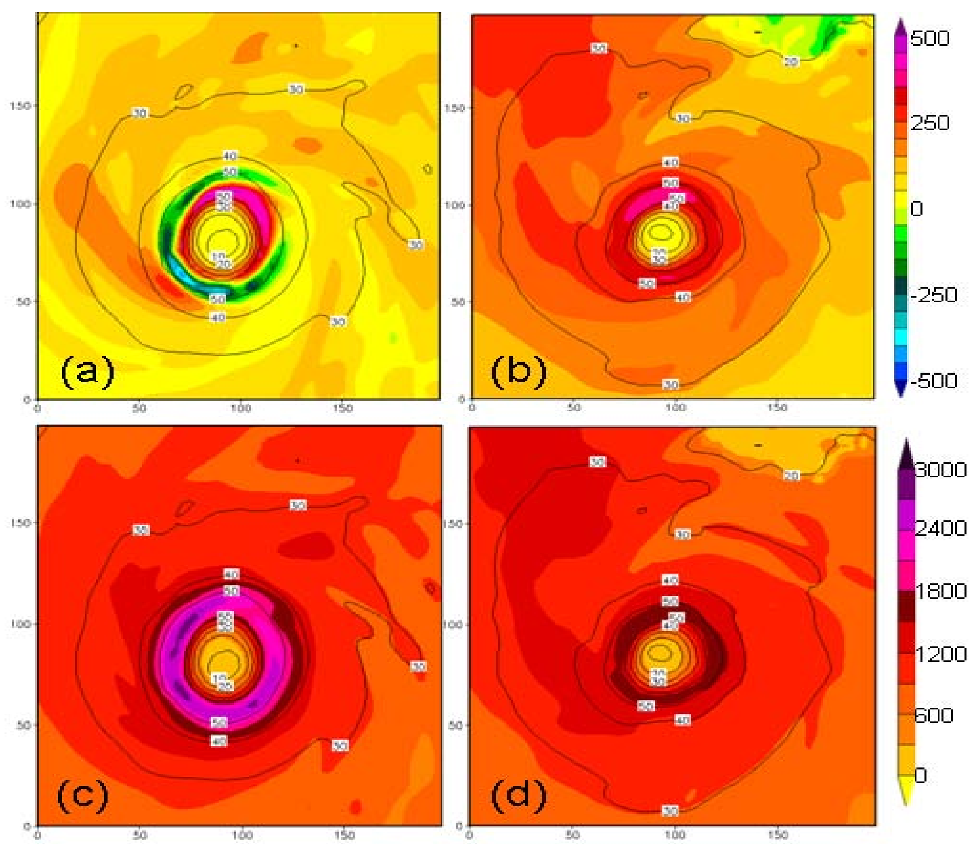

Figure 4: COAMPS 3-km resolution domain 72-h forecast surface sensible heat flux (W m^{-2}) with sea spray (a) and without sea spray (b), and latent heat flux (W m^{-2}) with sea spray (c) and without (d) valid at 0000 UTC 29 August for hurricane Katrina.

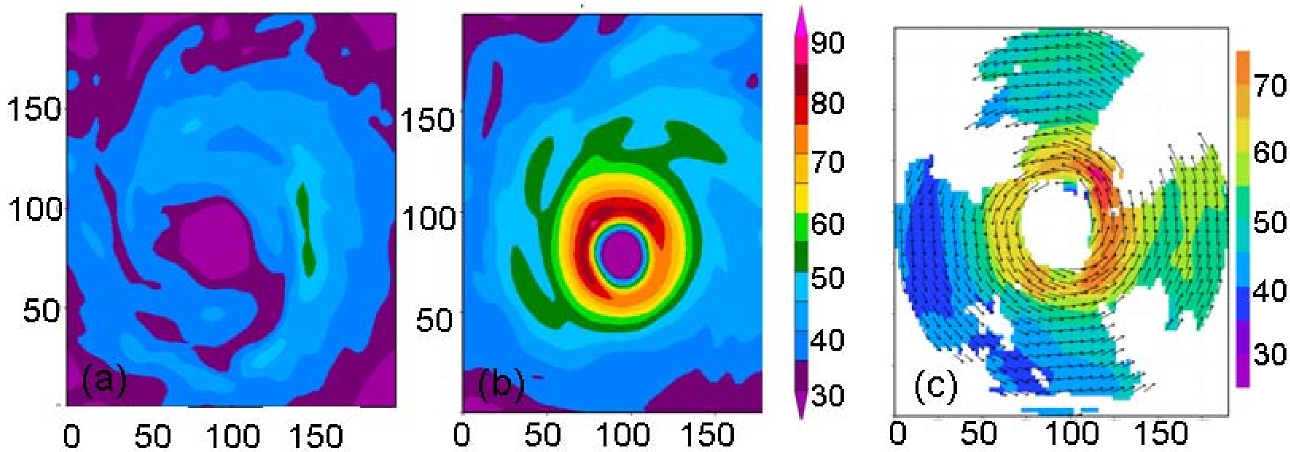

Figure 5: COAMPS-TC 3-km domain 72-h forecast surface wind speed (m s^{-1}) using the original COAMPS-TC version (a) and the new version (b) of the model. The Doppler radar observation is show in (c) (Courtesy of R. Rogers of Hurricane Research Division of NOAA).

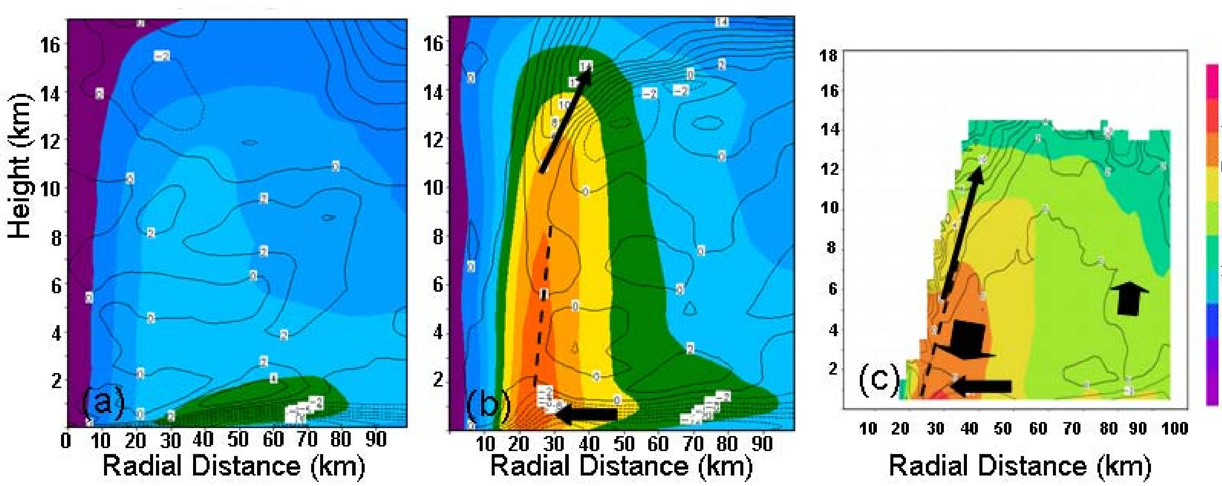

Figure 6: Radial-height distributions of tangential winds (shaded, m s^{-1}) and radial winds (contoured at 2 m s^{-1}) from the COAMPS-TC fine mesh (3-km) domain 72-h forecast using the original COAMPS-TC version (a) and the new version (b) of the model. The Doppler radar observation is show in (c) (Courtesy of R. Rogers of Hurricane Research Division of NOAA).

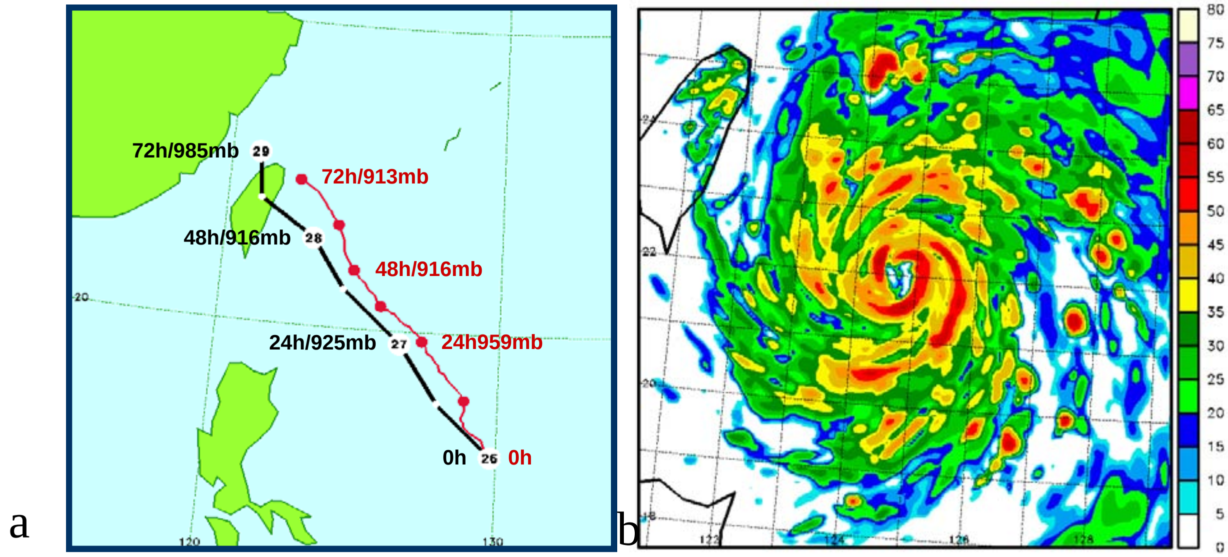

Figure 7: COAMPS-TC real time forecast initialized on 00Z 26 September 2008 for super-Typhoon Jangmi. The 72-h forecast tropical cyclone track (red) and best track (black) are shown in (a) along with the estimated central pressures and model predicted central pressure. The dots represent the tropical cyclone position at a 12-h interval. The larger white circles in the best track indicate the 00Z position with the date denoted in the circle. The model forecasted radar reflectivity at 2 km valid at 00Z 28 September (48 h) for the 5 km mesh is shown in (b).

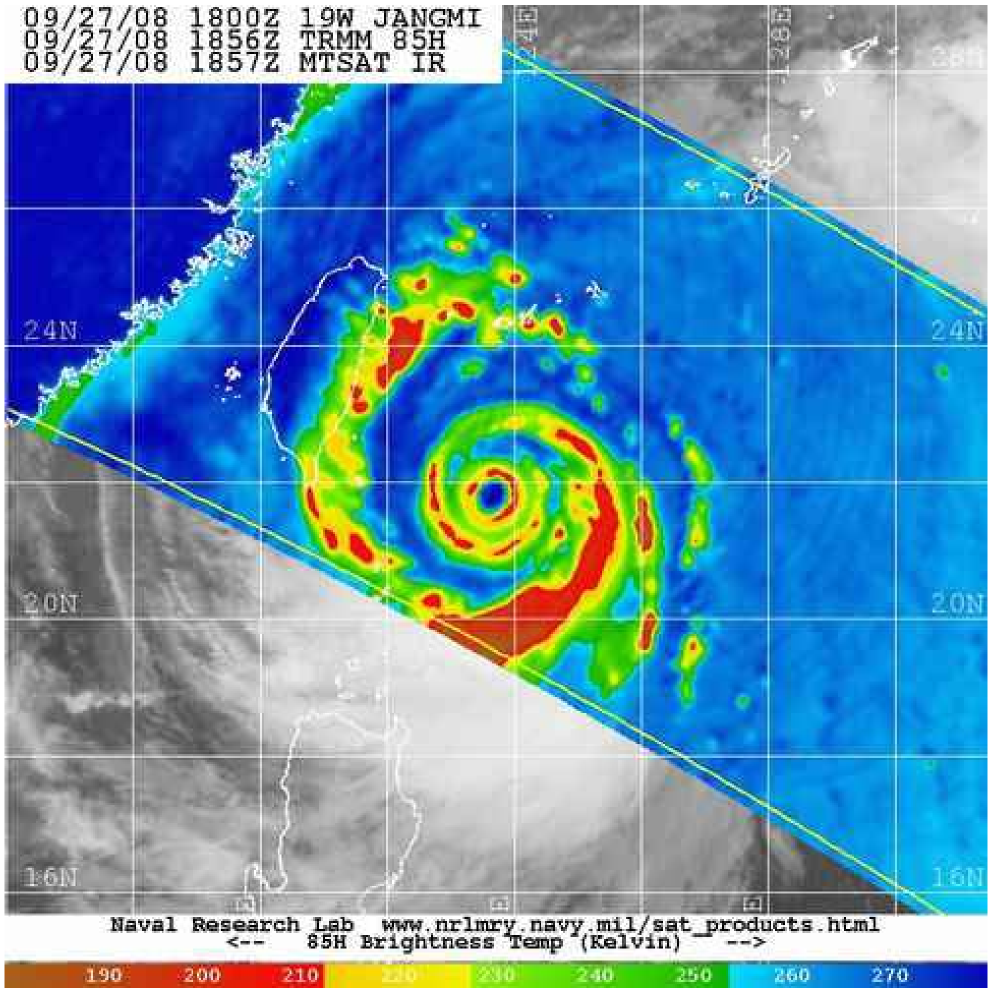

Figure 8: TRMM 85-GHz and MTSAT IR imagery for Jangmi valid at 1856 UTC 27 September with the color shading corresponding to the 85Ghz brightness temperature (scale in Kelvin).

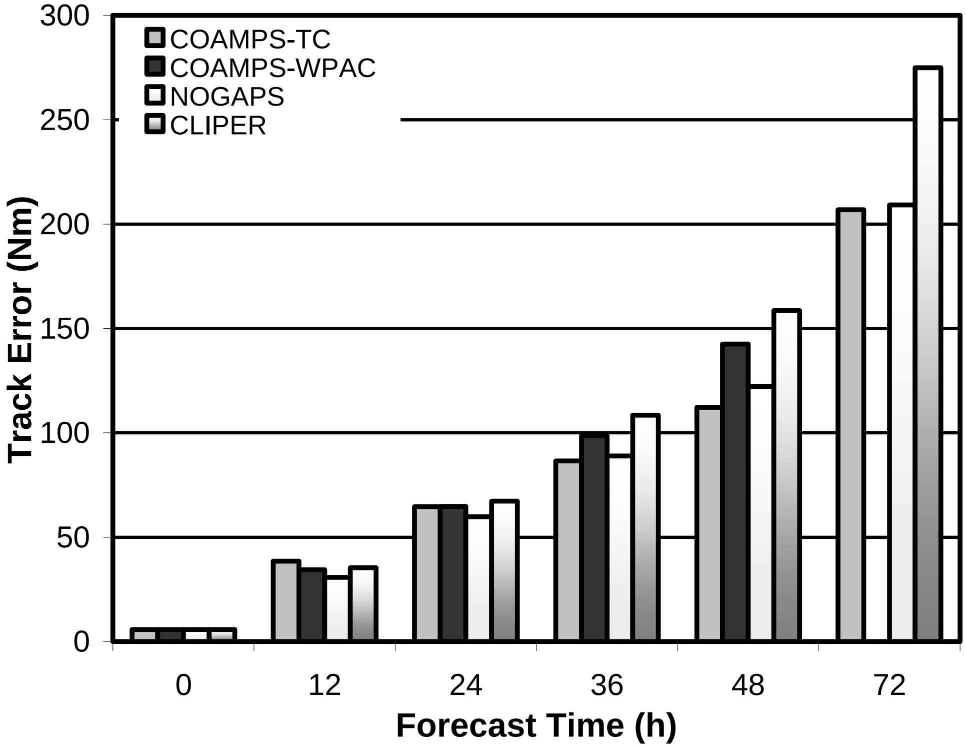

Figure 9. Tropical cyclone track error statistics for COAMPS-TC, COAMPS-WPAC, NOGAPS, and CLIPER.

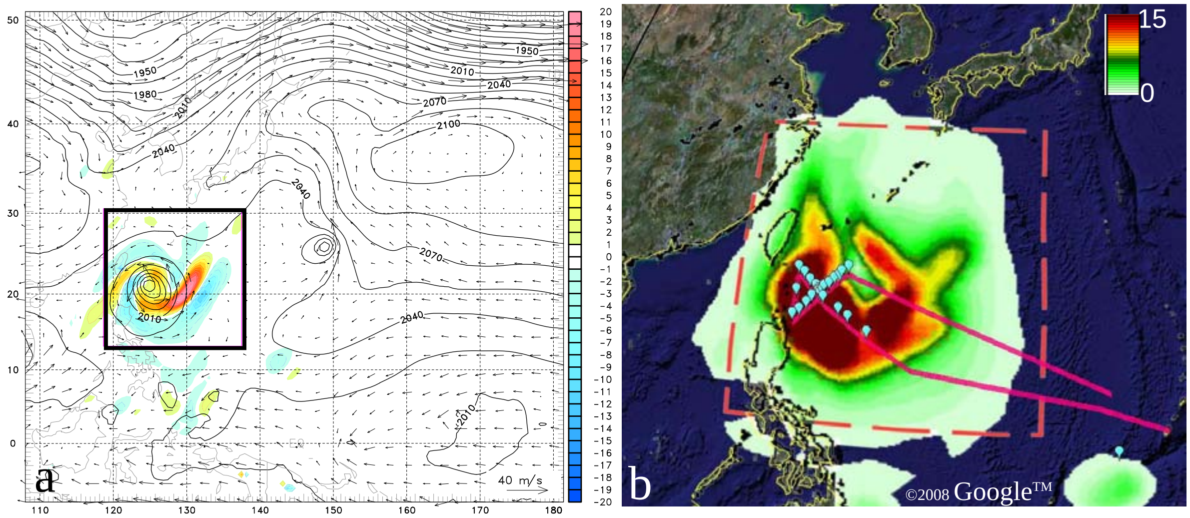

Figure 10. The COAMPS (a) adjoint sensitivity fields for the 800-hPa vorticity (10^{-5} m^2 s^{-1}) (color shading) and forward model 800-hPa geopotential heights (isopleths every 10 m) and wind vectors, and (b) vertically integrated total energy (J kg^{-1}) based on the adjoint optimal perturbations valid at 1200 UTC 10 September 2008 for typhoon Sinlaku using a 36-h lead time. The C130 flight track is shown by the solid magenta line and the dropsonde deployment locations are represented by the turquoise balloon symbols in (b). The boxes in (a) (black) and (b) (red dashed) indicate the region over which the response function is applied. Image for (b) created using Google^{TM} Earth.

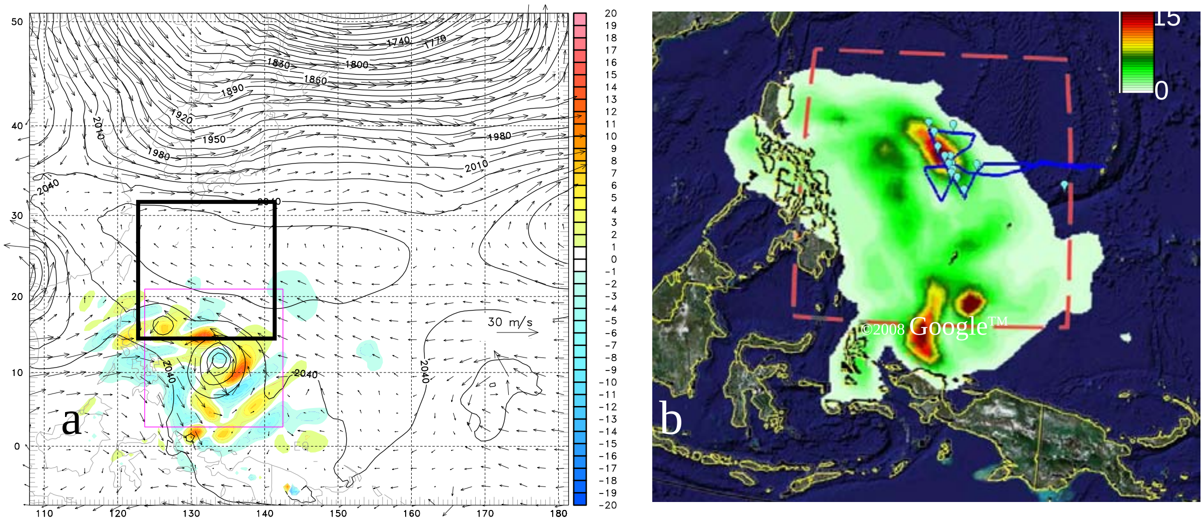

Figure 11. The COAMPS (a) adjoint sensitivity fields for the 800-hPa vorticity ($10^{-5}\ m^2\ s^{-1}$) (color shading) and forward model 800-hPa geopotential heights (isopleths every 10 m) and wind vectors, and (b) vertically integrated total energy ($J\ kg^{-1}$) based on the adjoint optimal perturbations valid at 00Z 25 Sep 2008 for typhoon Jangmi using a 36-h lead time. The C130 flight track is shown by the blue line and the dropsonde deployment locations are represented by the turquoise balloon symbols in (b). The boxes in (a) (black) and (b) (red dashed) indicate the region over which the response function is applied.
Image for (b) created using Google™ Earth

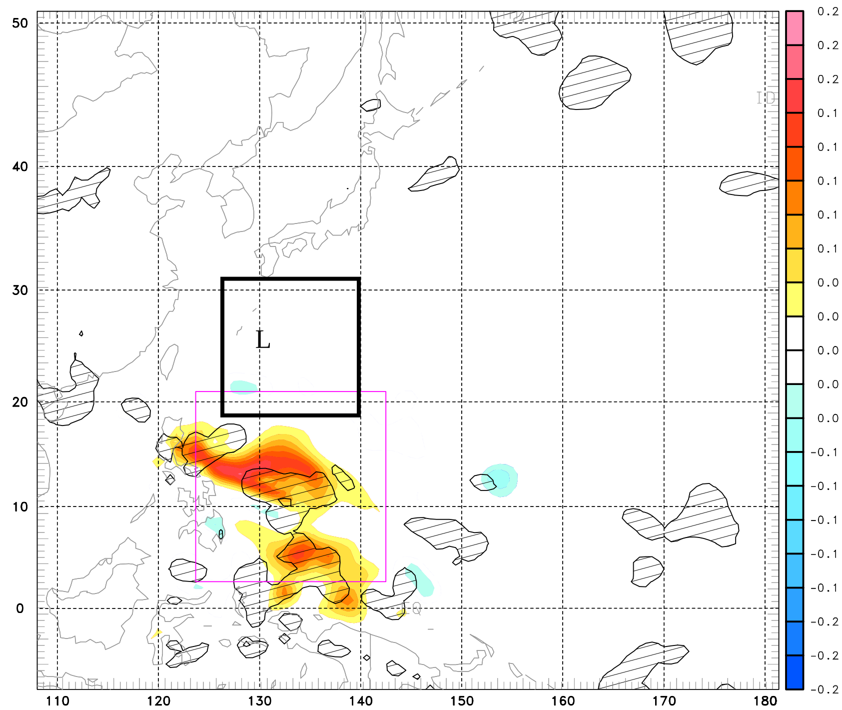

Figure 12. The COAMPS adjoint sea and land surface sensitivity field (K^{-1} m^2 s^{-2}) valid at 00Z 25 Sep 2008 for typhoon Jangmi using a 36-h lead time. The hatched regions denote heavy precipitation regions in excess of 20 mm during the 60 h forecast. The two low pressure symbols denote the forecast position of the tropical cyclone center at the 36-h (eastern most) and 60-h (western most) forecast times. The black box indicates the region over which the response function is applied.

TRANSITIONS

The tropical cyclone application of COAMPS will transition to 6.4 projects within PE 0603207N (managed by PMW-120) that focus on the transition of COAMPS to Fleet Numerical Meteorology and Oceanography Center.

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. This project is also closely coordinated with the COAMPS-TC Rapid Transition Process jointly supported by ONR and PMW-120.

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