# Achieving Superior Tropical Cyclone Intensity Forecasts by Improving the Assimilation of High-Resolution Satellite Data into Mesoscale Prediction Models

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## LONG-TERM GOALS

Forecasts of TC intensity change are often lacking in skill due in part to the paucity of conventional observations over the oceans that are assimilated into the operational models. The inability to accurately map the three-dimensional atmosphere and the underlying upper ocean has also constrained our understanding of how intensity fluctuations are governed by internal and environmental processes. Remotely-sensed observations from multiple satellite sources have become more routinely available as part

of the atmospheric/oceanic observing system. As an important input to global numerical data assimilation and forecast systems, these data are providing crucial large-scale environmental information for better predicting such parameters as TC steering flow fields. However, in regards to TC intensity change, it is clear that a dedicated research effort is needed to optimize the satellite data processing strategies, assimilation, and applications within a higher resolution modeling framework. Contemporary strategies developed for assimilating satellite data into global NWP systems appear to be inadequate for retaining information on the scales of processes pertinent to TC analysis and intensity change. Our study attempts to focus on and evaluate the impact of integrated, full resolution, multi-variate satellite data on TC intensity forecasts using advanced data assimilation methods and coupled ocean-atmosphere mesoscale forecast models. The development of successful strategies to optimally assimilate satellite-derived data should ultimately lead to improved numerical forecasts of TC intensity.

## OBJECTIVES

The ultimate goal of this project is the development and refinement of a capability to supplement the contemporary atmospheric observation network with optimal configurations and assimilation of advanced satellite-derived observations, to improve high-resolution operational analyses and intensity forecasts of TCs.

The primary objectives are to prepare a comprehensive database of full-resolution observations from multiple satellite platforms for selected TC case studies, for provision to the Navy, NOAA and NCAR collaborators in this study and other NOPP-funded studies. Then quantify how best to utilize the multiple satellite datasets in applications to TC structure/intensity prediction, using advanced data assimilation and high-resolution forecast models. Finally, provide a pathway towards advanced satellite data assimilation in the emerging operational TC forecast models (i.e. HWRF, COAMPS-TC).

## APPROACH

Our approach is to first investigate and optimize the assimilation of the satellite data in the WRF ensemble-based assimilation system. The COAMPS-TC system will also be employed in later efforts. In the evaluation phase, the investigators are analyzing the parallel model forecasts that assimilate and do not assimilate the satellite data. In this manner, the utility of the various satellite data in improving TC intensity predictions is being assessed. The main science focus is on investigating and understanding how the assimilation of the satellite data modifies the model analyses and forecasts of TC structure. Moreover, the improvement in model representation of important synoptic features such as adjacent trough interactions, outflow channels, and available environmental moisture is expected to benefit the numerical forecasts of TC intensities. The effects of assimilating data from multiple satellite platforms will be investigated for each individual platform, and for combinations of platforms. Typhoon Sinlaku and Hurricane Ike, both from 2008, are being targeted as first-look cases, but other TCs during our study period that undergo rapid intensity change will become candidates for further investigations.

**WORK COMPLETED**

In Year 1, we set out the following tasks (responsible team members in parentheses):

1) Confirm identity of initial case studies and possible follow-ons. (All)
2) Proposal team meeting/teleconference to iron out details of strategies. (All)
3) Collect and prepare satellite datasets. (CIMSS, NRL-H, RAMMB)
4) Refine the CHISR algorithm for processing advanced IR sounder data and characterize errors of retrievals for TC applications. (CIMSS)
5) Prepare EnKF and WRF systems for satellite data ingest and trials. (NCAR)
6) Run WRF Control (NoSat) forecasts on selected cases. (NCAR)
7) Advanced vortex initialization; initial hypotheses for intensity change. (UMiami)


Tasks 1-3 have been completed. The team identified Typhoon Sinlaku (occurred in the western North Pacific during TCS-08) and Hurricane Ike (also 2008, Atlantic) as initial case studies. Proposal team coordination meetings and/or telecons were held when necessary to strategize and update progress. The enhanced satellite datasets we hope to explore have been collected, processed, and archived (more detail on these below). Tasks 4-7 are addressed in the work summaries by team members below.

CIMSS-Velden

Addressing Task 3: As part of the TCS-08 field program, CIMSS processed enhanced fields of atmospheric motion vectors (AMVs) from the JMA MTSAT geostationary satellites during Typhoon Sinlaku. These datasets were derived at hourly intervals, over the entire western North Pacific west of the dateline. In addition, JMA made MTSAT rapid scans available for a several day segment of Sinlaku. These more frequent images result in higher quality vectors over a limited domain around the typhoon. CIMSS also processed AMVs from these images. As part of this proposal, CIMSS added new quality indicators to the AMV datasets, which can be employed as observation confidence estimates or forward operator error estimates in data assimilation. Similar AMV datasets with the new quality indicators were derived for our other case case study, Hurricane Ike. These datasets are being used in assimilation experiments with our NCAR collaborators.

CIMSS-Li

Addressing Task 4: Full spatial resolution (or single field-of-view, SFOV) Atmospheric Infrared Sounder (AIRS) temperature and moisture profiles have been processed for Hurricane Ike and Typhoon Sinlaku, allowing for improved spatial/temporal coverage (Figure 1).  The SFOV sounding physical retrieval algorithm has also been adapted to process IASI data, with the algorithm refined and adjusted to include many more IASI channels in the retrieval process. An initial evaluation for IASI clear sky soundings is promising.  Full spatial resolution AIRS sounding data for Typhoon Sinlaku and Hurricane Ike have been provided to NCAR partners for assimilation experiments, and after processing and evaluation, IASI clear sky sounding data will also be provided. Finally, a dual regression algorithm is being developed to accurately retrieve sounding

profiles from hyper-spectral infrared radiances under cloudy skies at SFOV resolution. This algorithm will expand the sounding coverage from clear skies to cloudy skies. After the cloudy soundings have been refined, the AIRS and IASI data for the Hurricane Ike and Typhoon Sinlaku cases will be processed.

(a)
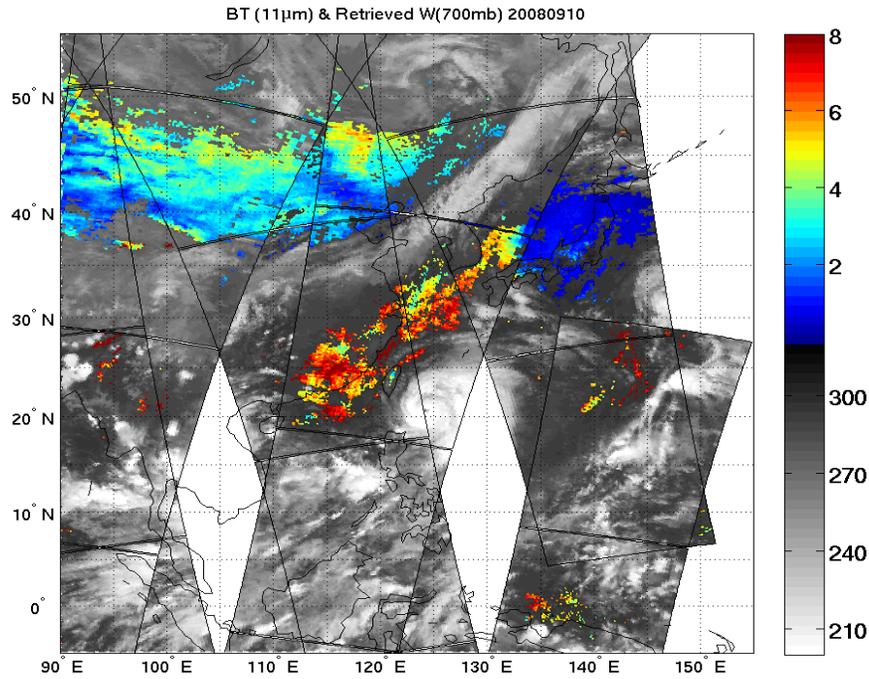


(b)
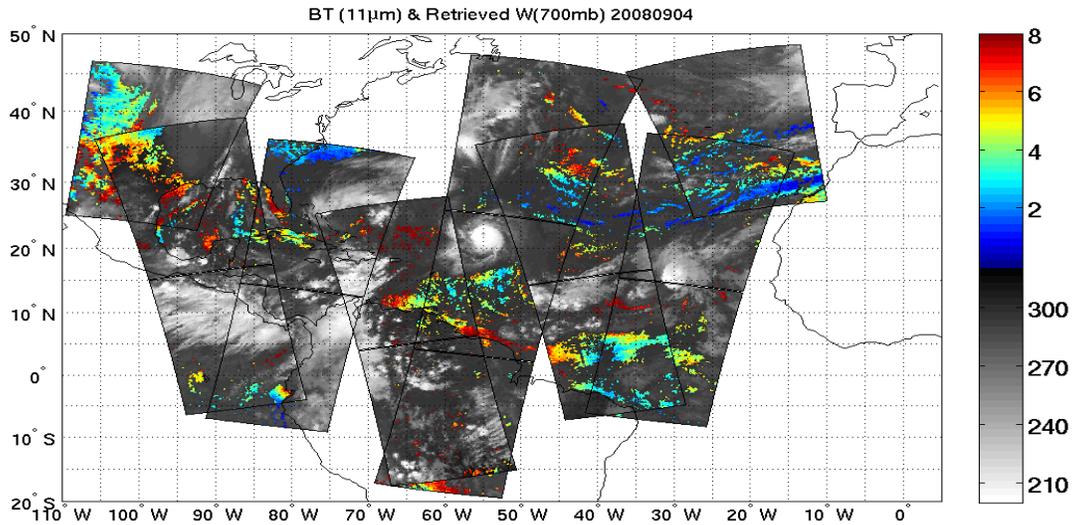


*Figure 1.  Clear sky 700 hPa AIRS SFOV water vapor mixing ratio (color) overlaid on 11 μm IR image (B/W), for (a)Typhoon Sinlaku on 10 September 2008 and (b) Hurricane Ike on 04 September 2008. Each color pixel provides vertical temperature and moisture soundings.*

In addition to the above identified work completed, the proposal team is also collaborating with scientists at NESDIS-RAMB and NRL-MRY (not funded directly by this award). Their brief work completion summaries are included in the next 2 pages.

NESDIS-RAMMB

Addressing Task 3: Two satellite-based datasets were prepared as intended input to our modeling experiments for both Hurricane Ike and Typhoon Sinlaku, along with FORTRAN 90 software designed to read the ASCII files. These datasets include six-hourly Multi-platform Tropical Cyclone Surface Wind Analysis fields, and AMSU-based tropical cyclone data and products consisting of antenna temperatures, corrected (for ice and cloud liquid water) statistical temperature retrievals and non-linear balance approximation winds at standard pressure levels. These datasets will be used in data assimilation experiments in the next reporting year.

NRL/MRY-Hawkins

Addressing Task 3: All proposed surface wind-related variables were retrieved from satellite microwave measurements for two storm cases (Hurricane Ike and Typhoon Sinlaku) from seven different agencies/groups. Some of these datasets were reprocessed and reformatted to create desired images or file formats for further team analysis and/or model assimilation. The datasets were documented, and made available to the data assimilation team members. A list of the datasets is shown in Table 1.

### Table 1: Microwave-based dataset list and associated variables

| Data Name | Variables | Resolution | Coverage | Source |
|---|---|---|---|---|
| ASCAT Wind | Lat, lon, time, wind speed and direction, ECMWF wind speed & direction, wind flag | 25 km | orbit | EUMETSAT |
| BYU QuickSCAT Wind | Lat, lon, time, wind speed & direction, surface type | 2.5 km, 25 km | 20x20 deg box following TC | BYU |
| UCF QuickSCAT Wind | Lat, lon, time, wind speed & direction, RR_flag, TB | 1/8 degree grid | 10 lat x 20 lon box following TC | UCF |
| NOAA Windsat EDR | Lat, lon, time, wind speed & direction, SST, TPW, CLW, RR, surface type | Pixel | orbit | NOAA |
| NRL Windsat EDR | Lat, lon, time, SST, TPW, CW, RR, WSP_err, TPW_err, CLW_err | 25X35 km 35x53 km 50x71 km | orbit | NRL |
| SSM/I EDR | Lat, lon, time, TPW, CLW, wind speed, RR, Wind_flag, surface type | Pixel and 1/3 degree grid | orbit | NOAA/NESDIS |
| SSMIS EDR | Lat, lon, time, TPW, CLW, wind speed, RR, wind_flag, surface type | 1/3 degree grid | orbit | NOAA |
| RSS EDR (AMSR | Lat, lon, time, SST, Wind | 0.25 deg grid | Daily | RSS |

| | speed, TPW, CLW | | ascending & descending | |
|---|---|---|---|---|
| RSS EDR (MWSST) | Lat, lon, SST | 0.25 deg grid | daily | RSS |
| RSS EDR (QuikSCAT) | Lat, lon, time, wind speed & direction, RR, flag | 0.25 deg grid | daily | RSS |
| RSS EDR (SSMI-F13) | Lat, lon, time, wind speed, TPW, CLW, RR | 0.25 deg grid | daily | RSS |
| RSS EDR (TMI) | Lat, lon, time, SST, wind 11GHz, wind37GHz, TPW< CLW, RR | 0.25 deg grid | daily | RSS |

NRL/MRY-Doyle

Typhoon Sinlaku was simulated using COAMPS-TC run at 45-, 15-, and 5- km resolution with two moving nests automatically following the storm centers. The lateral boundary conditions were provided by the forecast from NOGAPS, while the initial first guess field used a 12-hour COAMPS-TC forecast from a previous update cycle. Synthetic observations based on the current warning messages were analyzed with other conventional observations by a 3DVAR scheme called NAVDAS. Parameterizations were used for all sub-grid scale processes except for convection in the innermost domain, which used explicit microphysics. The simulation was started at 12 UTC 12 September 2008, after Sinlaku had turned westward toward the island of Taiwan. The model track captures several of the relevant features seen in the JTWC best track: both storms move in an initial WNW direction, they pass over the northern part of Taiwan, and they begin to recurve immediately after passing over the island. The most significant difference between the two tracks results from a southward deflection just upstream of the island that occurs in the model simulation, but not in the actual case. Future work will be performed on Typhoon Sinlaku to test the impact of enhanced satellite observations on the track, intensity, and structure for this storm.

In parallel, the Data Assimilation Research Testbed (DART) was fully implemented into the COAMPS during FY2010. This system includes the ability to assimilate real-data observations into the COAMPS NWP model in quasi real time and to perform probabilistic ensemble forecasts of mesoscale phenomena in the tropics and mid-latitudes. Lateral boundary conditions for the limited area COAMPS domains are generated by a global model ensemble and can be run on demand. Initial tests for well-observed mid-latitude domains are promising and will lead to our planned future work for tropical cyclone data assimilation.

NCAR

Addressing Tasks 5 and 6: Assimilation experiments in DART have commenced, using the Ensemble Kalman Filter (EnKF) to assimilate processed conventional data, CIMSS AMVs, and AIRS soundings for Ike and Sinlaku. More specifically, the observations comprise radiosonde wind, temperature, and humidity, operational AMVs taken from the NCEP GFS bufr files (control analyses) or CIMSS (3-hourly or rapid-scan), aircraft flight-level wind and temperature, and NHC/JTWC advisory TC positions. A 9km

moving nested grid with feedback to the 27km analysis grid in the 6-hourly (or 3-hourly) forecast is employed when a tropical cyclone is present. Otherwise, assimilation and analyses are all conducted on the 27 km grid. Ensemble (32 member) initial and boundary conditions were generated for these cases. It was found that starting the assimilation one week before tropical cyclogenesis was sufficient for the initial track analysis of Sinlaku and Ike. One initial experiment involved the revision of NHC/JTWC advisory position errors, and testing these for TC analysis sensitivity to the errors. In another intial trial, it was found that for 3-hourly analyses at 27km grid using the CIMSS enhanced AMV datasets, a shorter WRF time step was needed (120 seconds). Finally, a WRF model top cold bias was identified and fixed during assimilations.

Control analyses of Typhoon Sinlaku and Hurricane Ike have been finished. For Sinlaku, radiosondes, operational MTSAT AMVs, aircraft data, and JTWC advisory TC position data were assimilated at 6-hourly intervals. Advisory position errors were 90, 60 and 40 km for tropical cyclones possessing maximum sustained winds of <34, 34-85 and >85 kts respectively. It was found that the analysis track and intensity of Sinlaku can be sensitive to this input.  For Ike, the same observational input as Sinlaku was used for the control, except that the advisory position errors were 75km, 50km, 30km, and were provided by NHC.

Preliminary analyses using CIMSS enhanced AMVs have been completed for Ike, and some of these are presented in the Results section below. The enhanced AMV datasets for Ike produced by CIMSS consist of hourly files of AMVs derived from GOES satellites, and the AMV algorithms employ rapid scan imagery (7-min intervals) over a majority of the covered domain. In the CIMSS-RS6h and CIMSS-RS3h trials, CIMSS AMVs replace the operational AMVs in 6-hourly and 3-hourly analyses respectively. Only the AMV datasets at exact analysis times are assimilated in these initial experiments.

University of Miami

Addressing Task 7: Vortex initialization has been advanced via a separate ONR grant (N00014-08-1-0250), with the capability to insert synthetic high-resolution vortices into the WRF model domain. The main effort of the U. Miami team on this grant in Year 1 has been to investigate tropical cyclone structure in WRF analyses and forecasts.  First, triply-nested (18/6/2 km) WRF simulations of Typhoon Sinlaku have been conducted on the same domain as used by NCAR, with operational ECMWF analyses as initial and boundary conditions. These simulations can serve as a benchmark upon which the new simulations will need to improve. Horizontal and vertical cross-sections of the intensifying typhoon were analyzed, and will be compared against the COAMPS-TC simulations produced at NRL. The infrastructure is now in place to run high-resolution simulations from the WRF/EnKF analyses in Year 2.  Second, the characteristics of the WRF/EnKF analyses provided by NCAR are being compared against observations, to determine whether the gross characteristics of the tropical cyclone have been captured adequately. Data used for comparison so far include those from TCS-08 dropwindsondes, BYU QuikSCAT post-processed surface winds (listed in Table 1), JTWC estimations of

gale force wind radii, and a new "best track" produced by CIMSS with values of mean sea level pressure, maximum surface winds, radius of maximum winds and wind radii based on a blend of satellite and aircraft data. The model-data comparison diagnostic tools have been developed for use with any set of WRF/EnKF analyses, such as those described above.

**RESULTS**

The initial NCAR group data assimilation experiments involve the incorporation of enhanced AMV observations provided by CIMSS, as explained in the Work Completed section. An example of the impact of the extra AMV data on an upper-level analysis is shown in Fig. 2. The data are clearly enhancing the 300 hPa anticyclonic outflow in the region of Ike, relative to the control. This will increase the ventilation and upper-level divergence over the storm, and should enhance the prospects for capturing TC intensification within the model. Figure 3 shows time series of the 3-hourly and 6-hourly assimilation experiments for Ike. While the analysis TC position error results are mixed, the intensity analyses with the enhanced 6-hourly AMV data show a clear improvement in capturing the intensification of Ike, at least initially. When the assimilation of enhanced AMVs are conducted at 3-hourly intervals, the initial intensification is not as dramatically resolved as the 6-hr assimilation cycle, although subsequent intensity analyses are improved slightly.

Comparisons are underway between the WRF/EnKF analyses and estimations of the best track. As an example, it is evident that the radius of 50-knot winds around Sinlaku tend to be too large in the model analyses compared with best track estimates by JTWC and CIMSS early in the life cycle of Sinlaku, but the radii become more consistent later on (Fig. 4a). The surface wind field structure of the high-resolution (2 km) WRF simulations has also been compared qualitatively against corresponding QuikSCAT passes (Fig. 4b). An examination of the vertical structure of tangential winds reveals that the WRF/EnKF analyses tend to vary between the ensemble members, and most of the members produce a deeper wind structure than that in the ECMWF analysis. The high-resolution WRF forecast, initialized from the ECMWF analysis, produces a deeper cyclone. An investigation of the respective intensification processes in the analyses and forecasts is underway, and will be extended to the CIMSS/RS6h and CIMSS/RS3h analysis fields to determine the role of assimilating the additional AMVs.
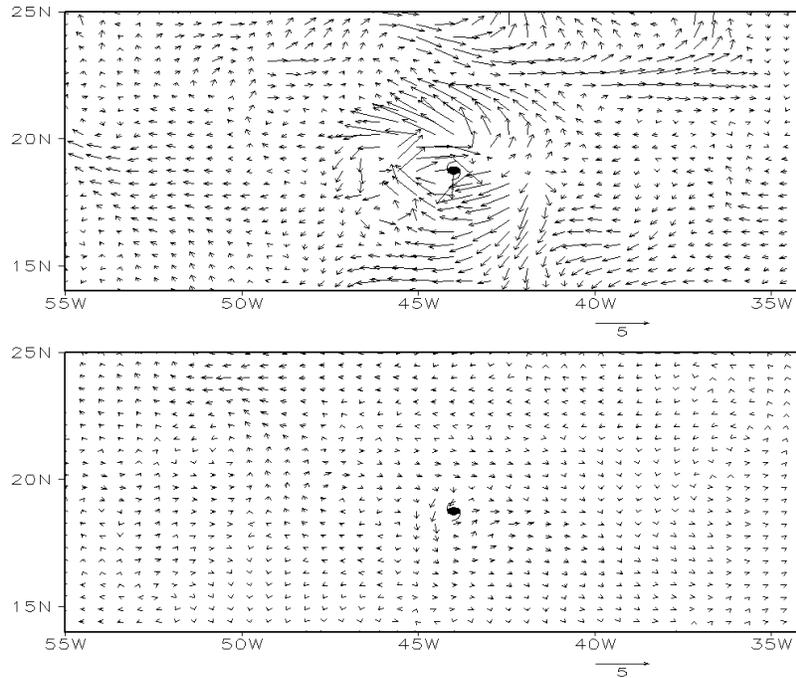
*Figure 2: Hurricane Ike wind analysis increments using the CIMSS-RS6h AMV dataset (upper panel) vs. control (lower panel) at 300 hPa (m/s) for 12Z Sep 02, 2008.*
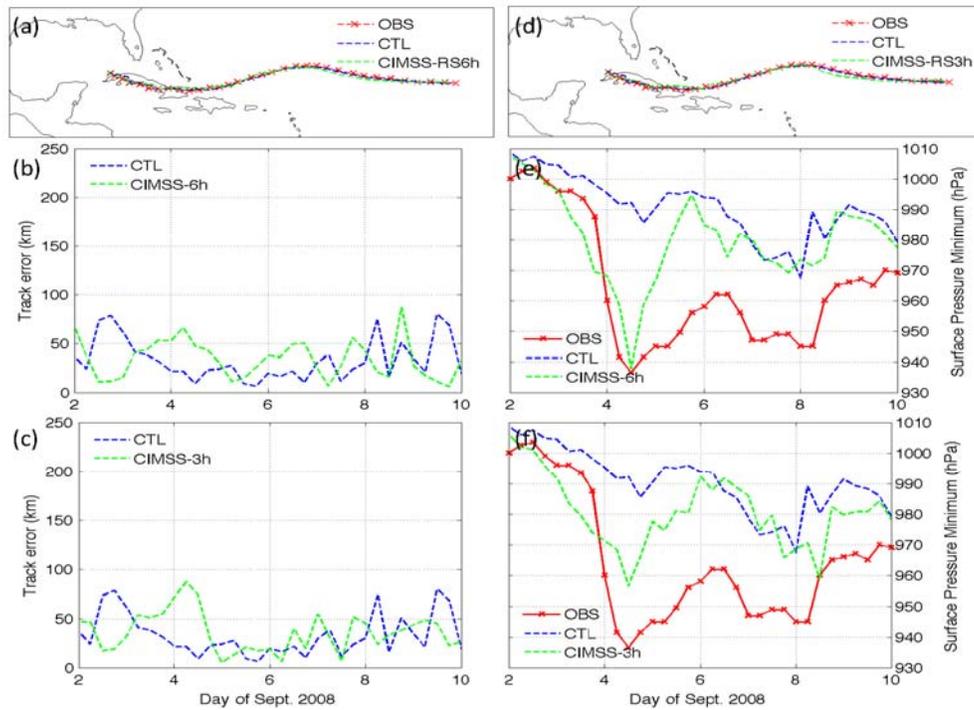


*Figure 3: Analyses for Hurricane Ike, for (a-c) 6-hour intervals and (d-f) 3-hour intervals. The graphs represent analysis differences (not forecasts) at these intervals for 8 days of the experiment. NHC Best Track data is used in the validation.*
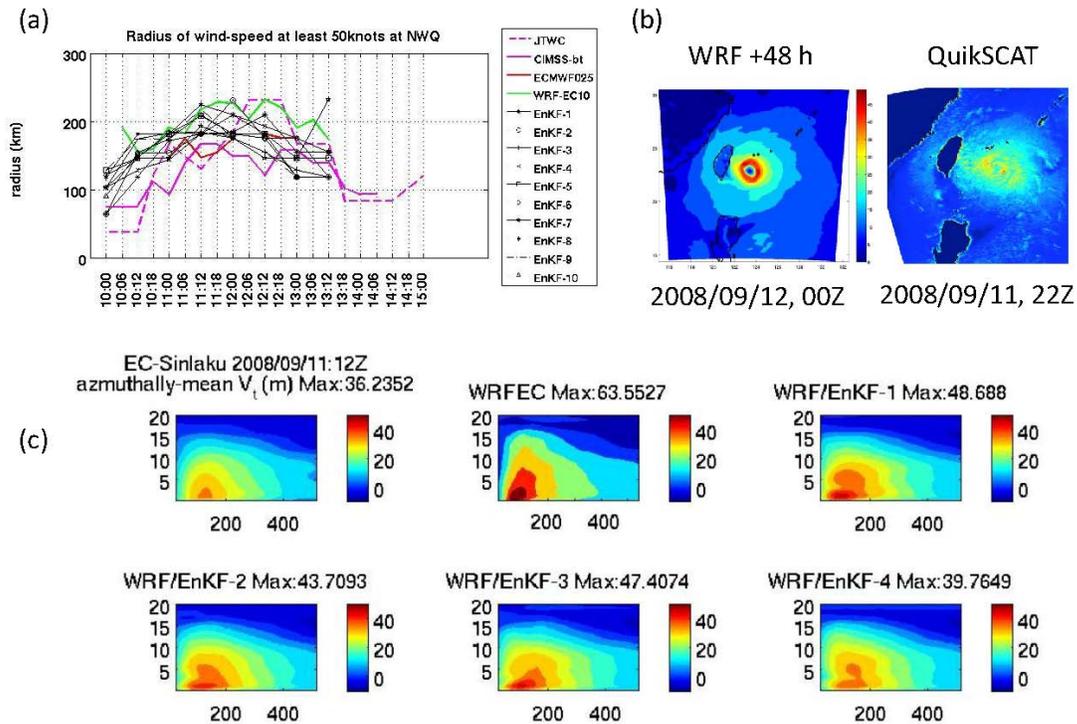
*Figure 4: (a) Radius of 50 kt winds in the northwest quadrant of Typhoon Sinlaku, between September 10-15 2008, for ten members of the WRF/EnKF analysis, a high-resolution WRF forecast (WRF-EC10), the ECMWF analysis, and best tracks from JTWC and CIMSS. (b) Surface wind speed for 48-h WRF forecast and QuikSCAT-BYU. (c) Vertical cross-sections of azimuthally averaged tangential wind speed, for the ECMWF analysis, 2-km resolution WRF (WRFEC), and four WRF/EnKF analyses.*

## IMPACT/APPLICATIONS

The longer-term impact of this study will be derived from the improved assimilation of high-resolution satellite observations in Navy (and other) mesoscale models. These improvements should translate into superior numerical forecasts of TC track, structure and intensity. The result of improved TC forecasts should positively impact all four of the NOPP evaluation factors.

## TRANSITIONS

**None in this reporting period. However, in the longer term, results of this study should provide for excellent transition opportunities into NWP operations, and positively impact all four of the NOPP evaluation factors.**

## RELATED PROJECTS

This project is related to that funded to CIMSS by ONR grant N00014-08-1-0251: "Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies

During TCS-08 for Developing Improved Operational Analysis and Prediction of Western North Pacific Tropical Cyclones" (PIs Velden and Majumdar).

Another project at CIMSS that is related is "High impact weather studies with advanced IR soundings", funded by the NOAA GOES-R program office (PI Li).

Work at NCAR is related to a NASA GNSS proposal: "Improving Tropical Prediction and Analysis using COSMIC Radio Occultation Observations and an Ensemble Data Assimilation System with Regional and Global Models (PI Anderson). Also, a NCAR-CWB (Taiwan Central Weather Bearou) cooperative project "The Enhancement of the CWB Data Assimilation System (PI: Bill Kuo). Finally, a related NASA proposal submitted and in review "Evaluation of Hyper-spectral IR Data in Storm Forecast with Regional WRF/DART Ensemble Data Assimilation System" (PIs Liu and Li).

This project is also related to that funded to the University of Miami by ONR Grant N00014-08-1-0250: "Using NOGAPS Singular Vectors to diagnose large scale influences on tropical cyclogenesis". Dynamic initialization methods for tropical cyclones developed on that grant will be examined for use on this project.

Work at NRL Monterey is related to three projects: (i) ONR PMW-120: "Prediction of Tropical Cyclone Track and Intensity Using COAMPS-TC"; (ii) the COAMPS-TC component of the NOAA Hurricane Forecast Improvement Project, and (iii) a NOPP (NOAA/ONR) award on Air-Sea Interaction.


## PUBLICATIONS

Li, J., H. Liu, and T. Schmit, 2010: Advanced Infrared Water Vapor Measurements Improve Hurricane Forecasts. SPIE, 012337/FAE9473B/000053. (published, not refereed)


## HONORS/AWARDS/PRIZES

PI Velden elected as Co-Director of the Seventh WMO International Workshop on Tropical Cyclones to be held in November, 2010. PI Velden also nominated for Councilor of the American Meteorological Society.

Co-PI Doyle has been elected a Fellow of the American Meteorological Society, effective from 2011.