Final Report

Project Title: Validation of HWRF Forecasts with Satellite Observations
PI: Tomislava Vukicevic, AOML/HRD, NOAA
Co-PI: Tom Greenwald, UW/CIMSS
Project period: 09/01/2011 - 08/31/2013

Report data : 12/30/2013

As presented in the Midyear Report in April 2013, the work in the second year has been focused on the following main tasks

1. Completing the new verification software fully compatible with operational environment
2. Developing and testing the verification diagnostics for immediate and future implementation

All of the planned work has been completed

The following is the summary of deliverables to the EMC and NHC

1. HWRF-SatV software for potential operational use

Software package for on-line implementation within HWRF operational system or as stand-alone tool for retrospective diagnostic verification of HWRF forecasts using satellite observations (HWRF-SatV stands for HWRF- Satellite Verification). The software consists of a driver script and a number of modules, including source codes and libraries (described below), all of which are fully compatible with HWRF operational environment. This software could be used either in stand-alone mode or within HWRF system as part of post-processing.

HWRF-SatV includes the following capabilities (schematic is shown in Figure 1):

- *Ingest of satellite observations* from the operational on-line data archive in BUFR format (GDAS data archive)
- *Selection of subsets of these data* within storm regions based on operational TC-vitals data
- *Creation of ordered geo-referenced observation data* for the selected region using WCT (Weather and Climate Toolkit : http://www.ncdc.noaa.gov/wct). This capability is necessary for reordering the BUFR data which are referenced by individual (lat,lon) coordinate, into ordered lat-long grid reference for purpose of mapping using GRADS, as well as for comparison with simulated satellite data from HWRF forecasts. In HWRF-SatV implementation WCT is used in batch mode, tested on NOAA-HFIP *jet* computing platform.
- *Re-mapping of simulated HWRF satellite data* for the need to compare high resolution HWRF simulated brightness temperatures fields to lower resolution satellite observations. This tool, written in FORTRAN convolves, or averages over, the simulated brightness temperature field using the

antenna pattern of the microwave sensor as it maps to the sensor's coordinate system. We currently support the SSMIS, SSM/I, TMI, and AMSR-E.

- *Computation of storm-relative diagnostics* using either FORTRAN or GRADS. For the operational implementation the following diagnostics are currently included: a) brightness temperature (BT) maps (e.g., 92H GHz), b) colorPCT (color composite from H and V BT) and c) warm core temperature anomaly using 54 GHz. The visual
- *Graphical display of diagnostics* using GRADS. The color tables used in the graphics for (a) and (b) (Figure 3) are exactly matching the standard used for NRL's Tropical Cyclone Page (http://www.nrlmry.navy.mil/tc-bin/tc_home2.cgi) .

HWRF-SatV makes use of the following libraries already included in the operational environment:

- CRTM
- UPP
- GRADS
- BUFR

2. HWSS (HWRF Satellite Simulator) research software package

This software was developed for the purpose of testing further advancements to simulating satellite observations using HWRF forecast data that could be implemented in UPP the future. The advanced features include

- QuickBeam radar simulator to simulate the TRMM Precipitation Radar (PR) and CloudSat . The implementation includes capability to collocate a given CloudSat track or TRMM PR swath with the simulated radar reflectivity field as well as output north-south or east-west cross-sections of the simulated reflectivities centered about the storm center.
- Accounting for multi-dimensional radiative transfer effects in microwave radiance calculations by using a slant path approach. These effects are particularly important at higher microwave frequencies. Version 2.1 of the CRTM was successfully modified to do slant path calculations

HWSS uses Pearl script driver with user defined control files for simulation of micro-wave and infra-red frequencies of choice.

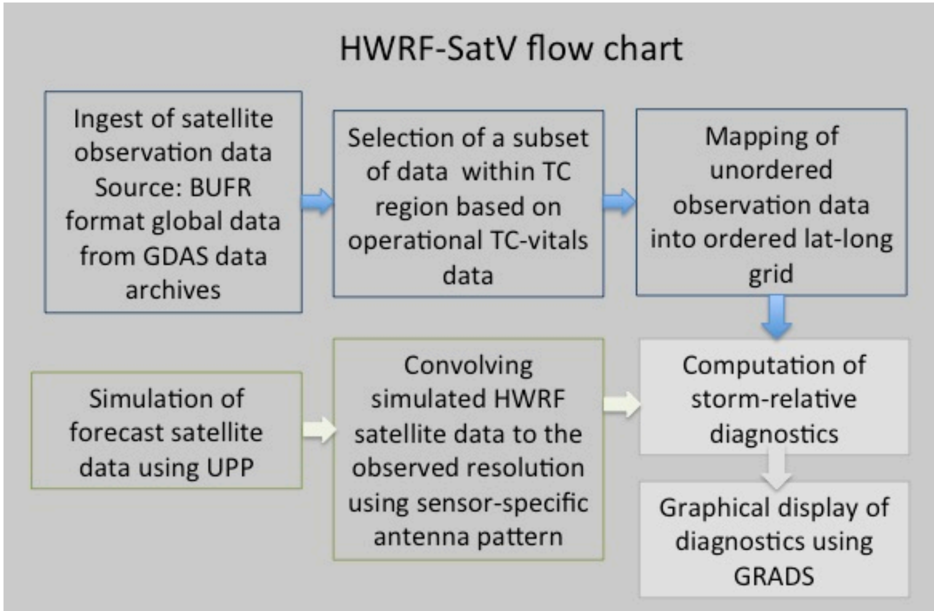


Fig. 1. Major modules and data flow in HWRF-SatV

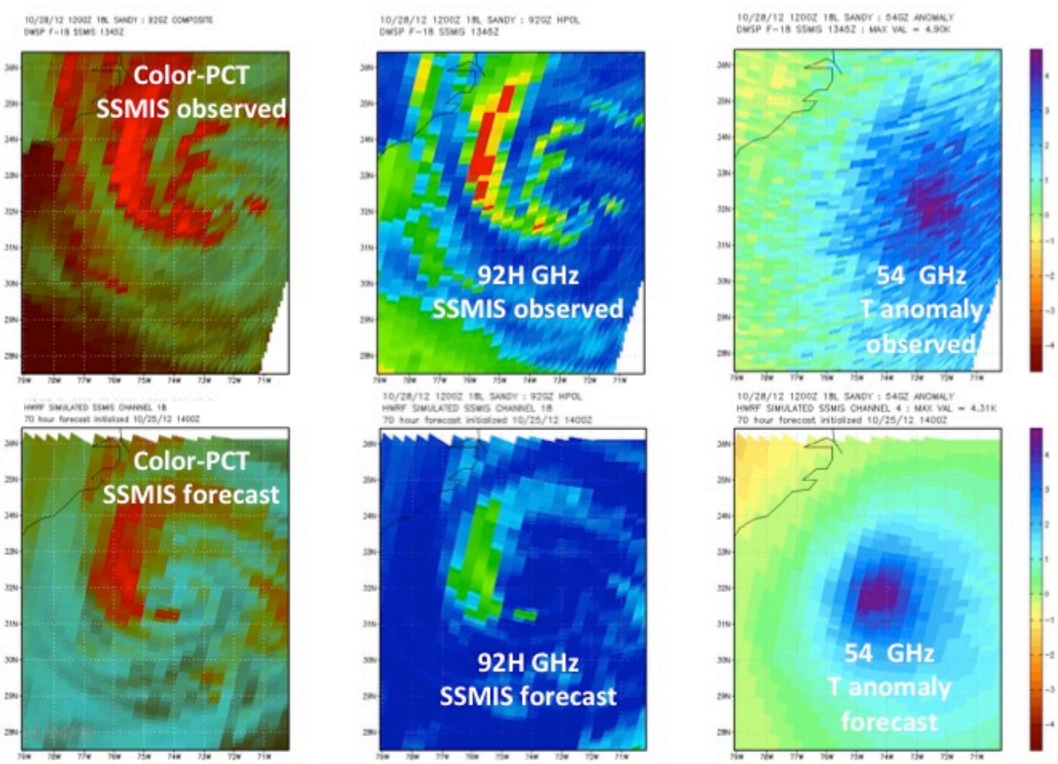


Fig. 2. Verification product from HWRF-SatV. Example is for Hurricane Sandy Aug. 28, 2012

3. **Advanced diagnostic analysis for model evaluation**

This deliverable is still under construction at CIMSS, led by Tom Greenwald. It is being developed for purpose of in-depth quantitative verification of different aspects of the forecast. So far the following diagnostic functions have been developed. Tom Greenwald has received no-cost extension for completing this work

- Evolution of the inner core (< 100 km) rain field. The mean 19 GHz brightness temperature of the inner core can serve as a proxy for rain intensity and latent heat release in the lower atmosphere. The maximum 19 GHz brightness temperature, on the other hand, provides a measure of the maximum intensity of localized heavy rainfall regions. To examine this, we gathered all available observations (ranging from 18.7-19.35H GHz) from numerous sensors and platforms (SSM/I, SSMIS, AMSR-E and TMI). The synthetic brightness temperature data were all remapped to the actual satellite swaths. Such diagnostic analysis offers insights into model capability to simulate storm structure as in the following example

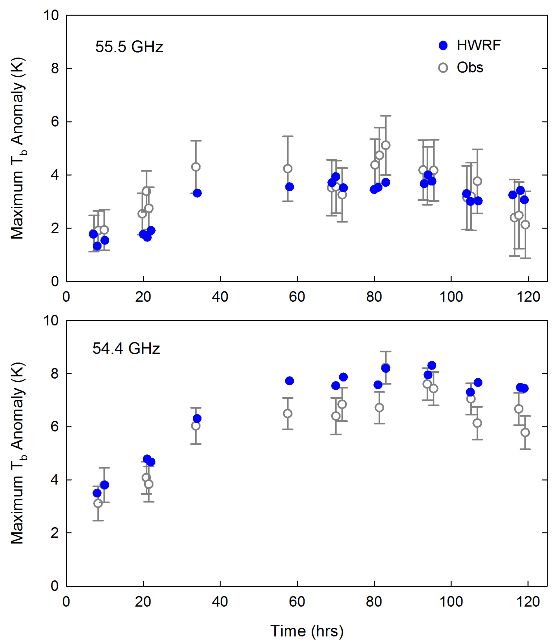


Fig. 3. Time series of HWRF simulated (open gray circle with error bars) versus observed (blue filled circles) maximum brightness temperature anomalies derived from the SSMIS 54.4 GHz channel for hurricane Earl. Error bars include instrument noise and variation in the estimated background brightness temperature.

Interesting conclusions for the example forecast are: While the mean 19H GHz brightness temperatures (i.e., rain intensity) for both observations and forecast increase in time as the storm strengthens, there exists a large cold bias (10-20 K) in the forecast (Figure 4). Much of this bias could be caused simply by the fixed raindrop effective diameter assumed for the CRTM calculations. HWSS has an option for applying a fixed raindrop number concentration, which allows the effective diameter to increase with increasing rain mixing ratio. Redoing the analysis using a fixed number concentration accounts for some of these biases (results not shown). The mean 19H GHz observations also show a significant drop in the final 24 hours of the forecast, while the forecast does not. This drop is caused by a large *increase in size of the hurricane's eye and signals a weakening of the storm, consistent with the observed warm core anomaly results. In terms of the maximum 19H GHz brightness temperatures, the observations and the forecast are consistent with one another, where both show little trend.*

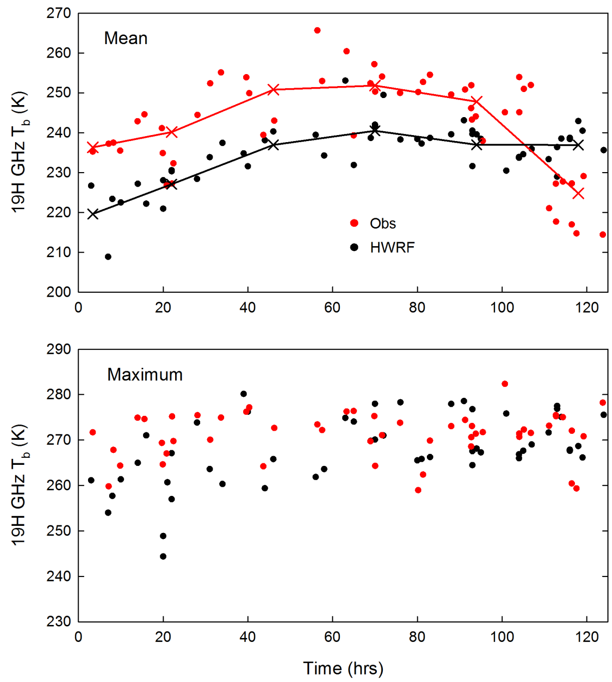
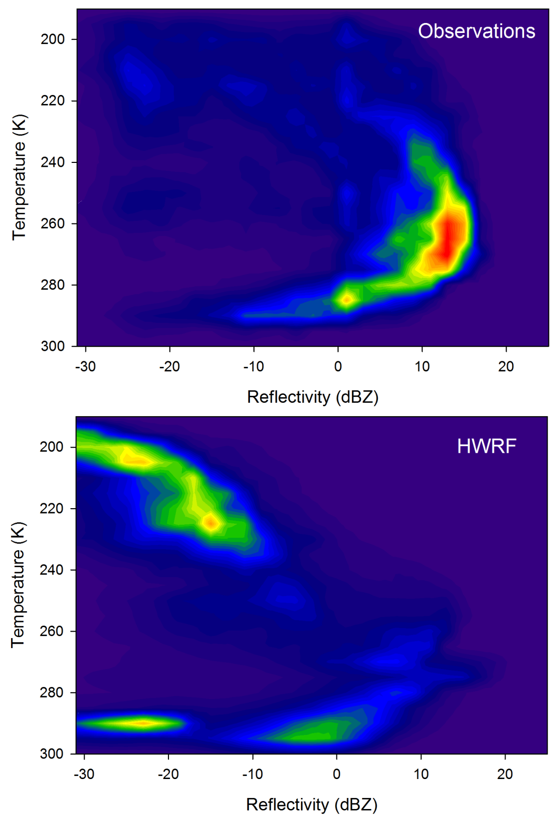


Fig. 4. Time series of HWRF simulated (black dots) versus observed (red dots) mean (top panel) and maximum (bottom panel) 19H GHz maximum brightness temperatures in the inner core of the storm. Solid lines depict the 24-hr smoothing.

- Ice microphysics verification. The observations that we believe have the highest potential for evaluating ice microphysics in the HWRF come from the CloudSat Cloud Profiling Radar (CPR). For hurricane Earl we were fortunate to have one CloudSat overpass that came very close to the eye at 0610 UTC on Aug 31, 2010 when Earl was a weak category 4 storm. One way to evaluate the simulation is to compare joint PDFs of temperature and radar reflectivity with observations. Figure 6 shows such a comparison, where the PDF for HWRF includes data from the entire model domain to provide more representative results. Two major differences are seen. First, cloud ice (occurring at temperatures of 240-200 K) is much more frequent in the simulation than in the observations. Second, the simulation lacks frequent large reflectivities (probably caused by snow) that are observed at colder temperatures (220-250 K). Further comparisons like these for other hurricanes can give further insight into how well different ice species are partitioned as diagnosed from the HWRF model.

Satellite observations above 80 GHz are also very useful for evaluating ice microphysics diagnosed from HWRF, especially large ice associated with strong convection. Results of our comparisons at 85-91H GHz have shown consistently that synthetic imagery produced from HWRF and the CRTM exhibit cold biases of 20-40 K in the strongest convective regions of the storm. To examine this in more detail we plotted simulated 91H GHz brightness temperatures against 150H GHz brightness temperatures and compared them to SSMIS (Special Sensor Microwave Imager Sounder) observations (Figure 5). It is seen that the simulated brightness temperatures at these two frequencies are similar in magnitude, indicating exceptionally strong scattering. This behavior may be caused by the overestimation in mass and/or size of large ice particles and/or deficiencies in ice optical properties within the CRTM.

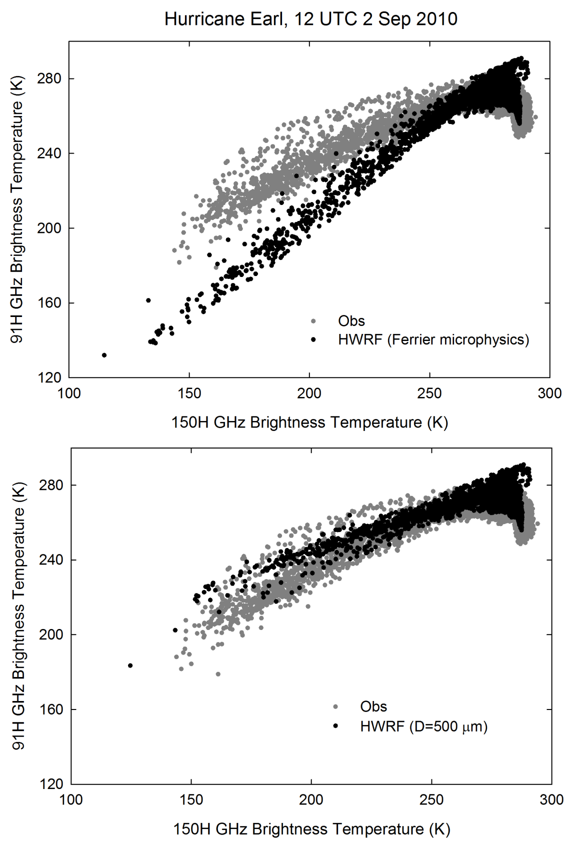
Fig. 5. Joint PDFs of temperature and CloudSat radar reflectivity for the CPR observations (top panel)



and forecasted by the HWRF (bottom panel) for hurricane Earl, 0600 UTC 31 Aug 2010.

To see how sensitive this bi-spectral relationship is to snow particle size (snow is the most common ice species in the simulation), we set the effective diameter to a constant value of 500 μm. Results show (see Fig. 7) much better agreement between the simulations and the observations. However, more work is needed to determine whether it's the ice microphysical parameters or the CRTM scattering properties that are the main cause of the simulated brightness temperature errors.

Fig. 6. SSMIS 91H GHz observed (gray dots) and simulated (black dots) brightness temperatures using the Ferrier microphysics parameterization in the HWRF (top panel) and assuming a fixed snow particle diameter (bottom panel).



- <u>Structure verification using ARCHER:</u> The program operates on multi-spectral satellite imagery and objectively analyzes structure to estimate TC storm center, eyewall diameter, and spiral banding structure/organization. ARCHER is currently being used on satellite observations at 85-91H GHz and provides an intensity score, which is then related to thresholds of maximum winds (but only meant for intensifying storms). For demonstration, ARCHER was applied to simulated 85-91H GHz brightness temperature fields that coincided with observations for the 124-hr hurricane Earl run. This work was done by Tony Wimmers (UW-CIMSS), the main developer of ARCHER. The spiral and ring analyses can be used to compare and quantify the integrity of the HWRF forecasts to the verifying microwave imagery. Results for a selected case are shown in Figure 8. However, additional work is needed since the ARCHER score and intensity thresholds, which were calibrated for the observations, may not be suitable for simulated data.

Fig. 7. Application of ARCHER to TMI observations (left four panels) and HWRF-simulated TMI data (right four panels) on 31 Aug 2010 for the hurricane Earl forecast.