**Project Progress Report**

**Title:** Validation of HWRF Forecasts with Satellite Observations and Potential Use in Vortex Initialization
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**Co-PI:** Tom Greenwald, UW/CIMSS
**Reporting period:** 09/01/2012 - 02/28/2013 (second year)

Work in second year is focused on the following main tasks:

1. **HWSS development**: Enhance the capabilities of the Hurricane Weather Research & Forecasting (HWRF) Satellite instrument Simulator (HWSS) that was built during the first year's work.
2. **Transition to operations**: Incorporate selected capabilities of the HWSS into the operational HWRF unified post-processing system (UPP) and compare synthetic satellite imagery generated by the UPP and HWSS.
3. **HWRF verification**: Develop new ways of evaluating the HWRF forecasts using satellite data.

**Work accomplished:**

*1. HWSS development ( performed at CIMSS led by Co-I Greenwald)*

Our significant accomplishments since the first-year report:

- A new feature was added that allows for a storm relative analysis; i.e., the model grid is moved so that the center of the forecasted storm is collocated with the observed storm center. However, an estimate of the observed storm center is required.
- Two capabilities were added to the QuickBeam radar simulator. We can now simulate the TRMM Precipitation Radar (PR). Also, we can 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.
- A remapping tool was developed for the need to compare high resolution HWRF simulated brightness temperatures fields to lower resolution satellite observations. This tool 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. Figure 1 shows an example for the SSMIS 54.4 GHz channel.

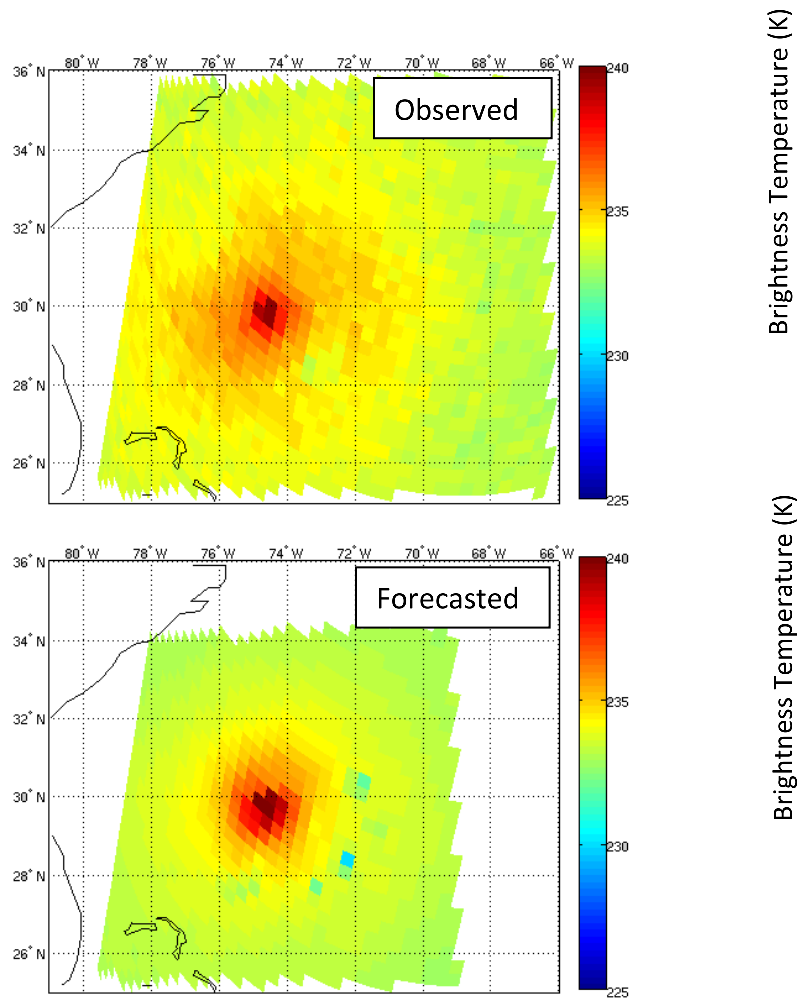


Fig. 1. Observed and remapped/translated HWRF forecasted 54.4 GHz SSMIS data for hurricane Earl.

- The last achievement was making it possible to account for most 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.

## *2. Transition to operations (collaboration with Sam Trahan and Dave Zelinsky)*

Comparisons were done between synthetic AMSR-E brightness temperature fields produced by the UPP v1.1 and HWSS. The purpose was to identify and explain any possible differences and provide feedback to the UPP and CRTM development teams. Figure 2 shows a comparison for the 37H GHz and 89H GHz channels. At 37H GHz the main differences occur in clear regions, most likely due to differences in the versions of the sea surface emissivity models, and in some of the convective areas, which may be due to the UPP including a subgrid-scale water/ice condensate term for convective clouds that the HWSS does not. Similar differences are seen in the 89H GHz fields in regions of strong convection and ice scattering. Again, these differences are probably related to the subgrid-scale condensate term.

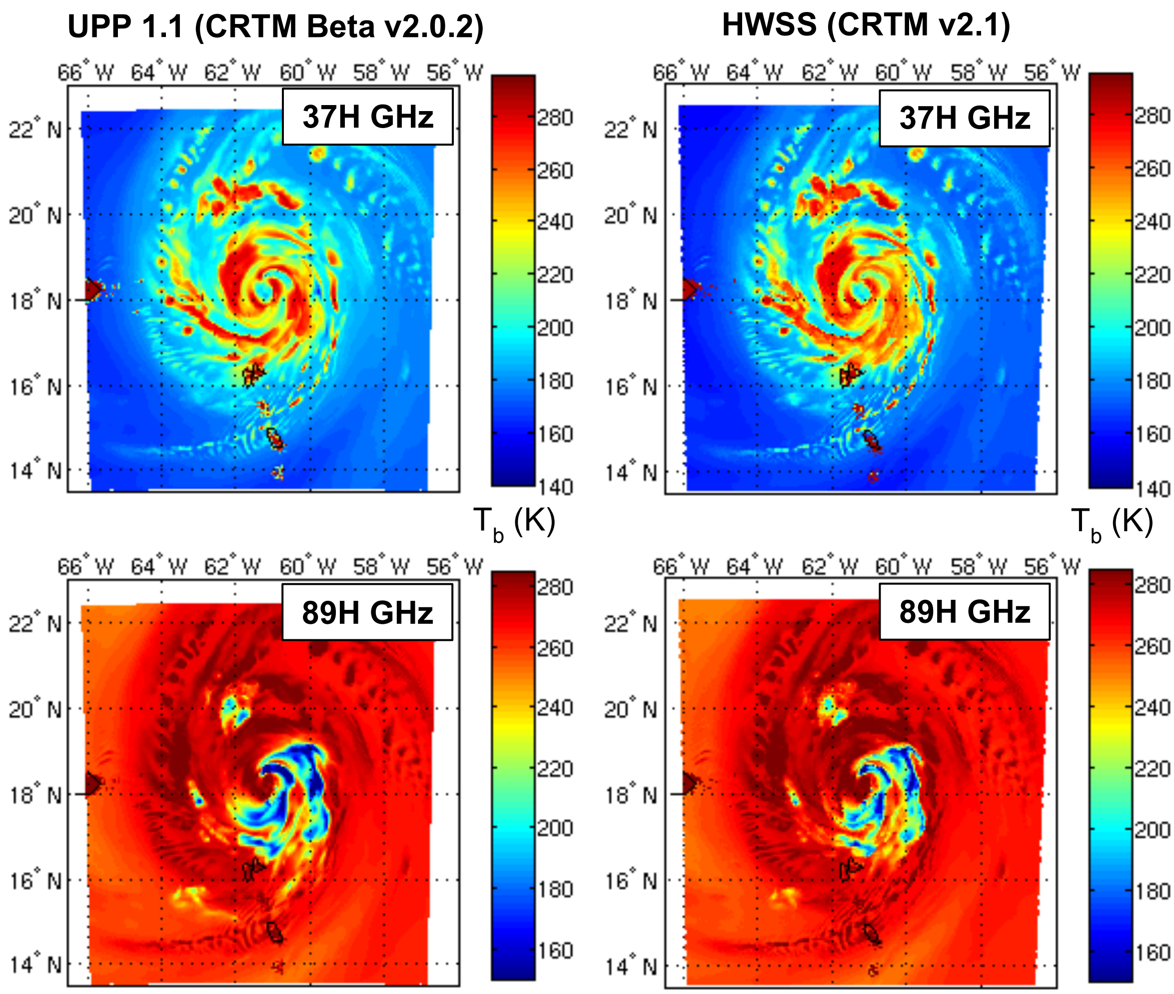


Fig. 2. Comparison of AMSR-E 37H GHz and 89H GHz brightness temperature fields as produced by the UPP v1.1 (left panels) and the HWSS (right panels) for hurricane Earl.

Our plan for transitioning to operations includes enhancing the synthetic satellite imagery produced by the UPP. We are preparing to add a new product that provides forecasters with HWRF-forecasted anomalies of upper tropospheric temperature as derived for the 54.4 GHz channel on the Special Sensor Microwave Imager Sounder (SSMIS). These anomalies are related to hurricane intensity and can be compared against observations. Sam Trahan (EMC) has provided us with modified UPP code that allows this channel to be output in the GRIB file. However, it has yet to be tested. We have also been collaborating with Dave Zelinsky (NHC) to provide synthetic imagery that looks more like what would be seen by the satellite sensor using our recently developed remapping tools. Code for remapping synthetic SSMIS 91H GHz data to the SSMIS spatial resolution was delivered to Dave in February.

## 3. HWRF verification

We developed several new ways of evaluating HWRF forecasts using satellite data, each of which tests different aspects of the hurricane. A new model run for the hurricane Earl case was made by AOML/HRD using their new data assimilation system (HEDAS) and the latest operational version of the HWRF. The forecast evaluated here was initialized at 14 UTC 29 Aug 2010 and run for 124 hours. The innermost nested grid domain had a horizontal grid spacing of 3 km.

To evaluate how well HWRF predicted the upper tropospheric warming in the inner core of hurricane Earl, we compared simulated SSMIS 54.4 and 55.5 GHz maximum brightness temperature anomalies to those observed by the SSMIS on the F-16, F-17, and F-18 platforms. This sensor has suffered numerous large calibration anomalies, so it was important to find highly recalibrated data. Our source was the Fundamental Climate Data Record (FCDR) microwave brightness temperature products provided by Colorado State University (courtesy of Wesley Berg).

Anomalies were derived for both simulated and observed data using a background brightness temperature computed as the average value more than 500 km from the storm center and subtracting it from the maximum brightness temperature in the core. It's important to note that the simulated data were remapped to the SSMIS swath using our recently developed remapping tool (as shown in Fig. 1), which had a significant impact on the magnitude of the maximum anomalies. Observations were chosen within ½ hr of the HWRF model output.

Results are summarized in Fig. 3 as time series for each SSMIS channel. The 54.4 GHz channel has a weighting function that peaks at around 175 hPa, while the 55.5 GHz channel's weighting function peaks at about 70 hPa. Results show that HWRF performs very well, especially early on in the forecast (< 50 hrs). But differences appear between hours 60 and 75. We can't eliminate the possibility, however, that the observed maximum anomalies were underestimated due to scattering by nearby large hydrometeors. There is also an indication in the observations in the final 24 hrs of the forecast that the storm has weakened, though this is not the case in the forecasted anomalies.

Another aspect of the forecast that can be evaluated is the 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.

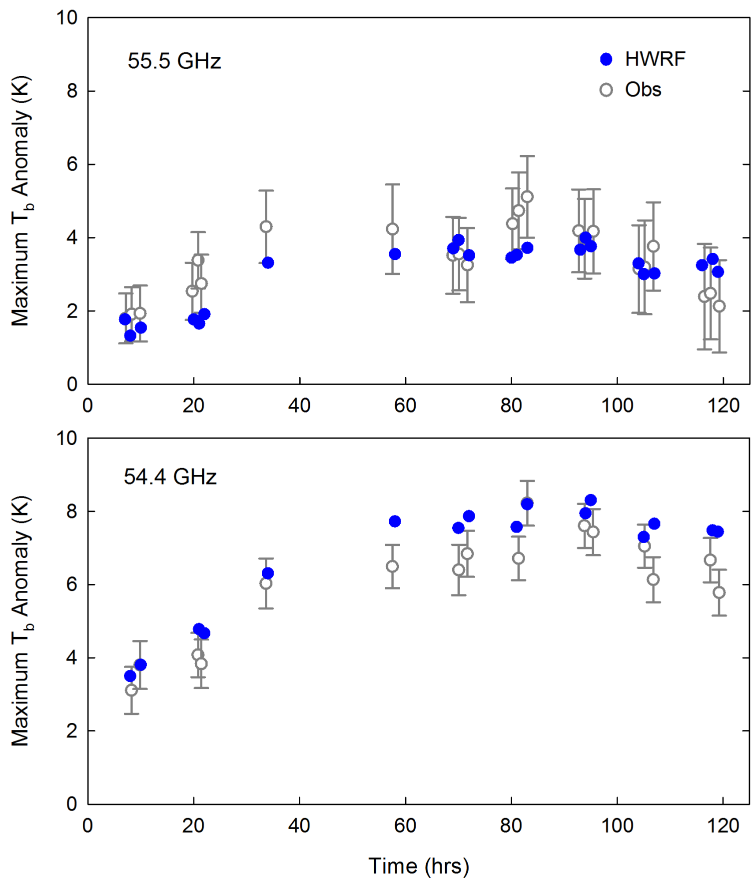


Fig. 3. Time series of HWRF simulated (open gray circle with error bars) versus observed (blue filled circles) maximum brightness temperature anomalies derived from the SSMIS 54.4 GHz channel for hurricane Earl. Error bars include instrument noise and variation in the estimated background brightness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

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.

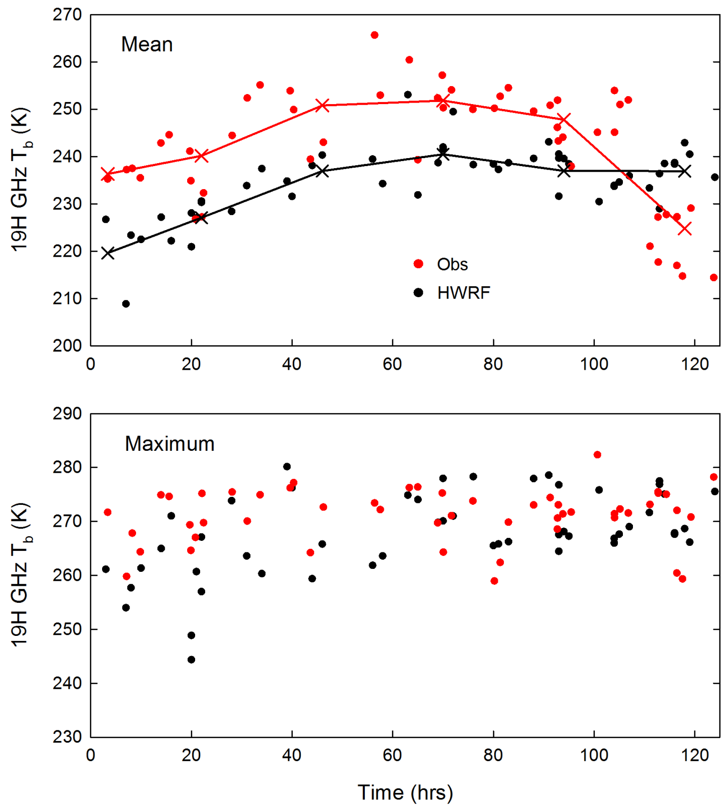

Fig. 4. Time series of HWRF simulated (black dots) versus observed (red dots) mean (top panel) and maximum (bottom panel) 19H GHz maximum brightness temperatures in the inner core of the storm. Solid lines depict the 24-hr smoothing.

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 5 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 6). 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.

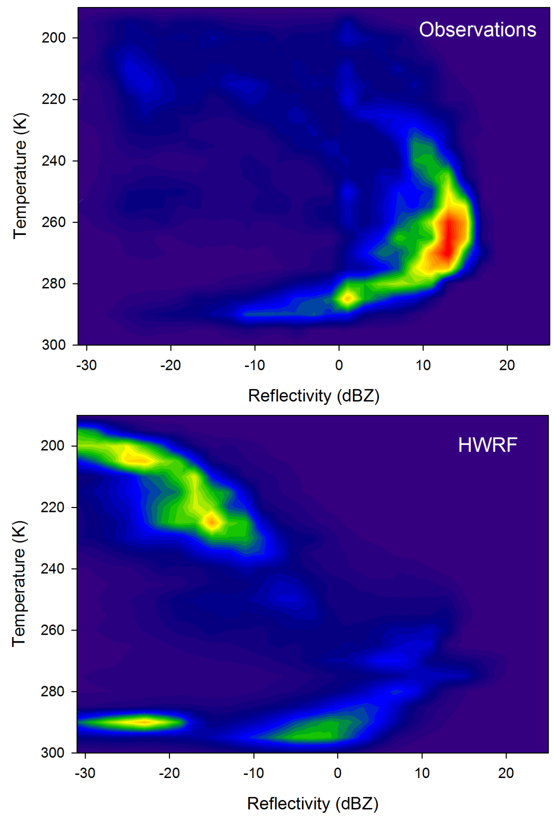


Fig. 5. Joint PDFs of temperature and CloudSat radar reflectivity for the CPR observations (top panel) and forecasted by the HWRF (bottom panel) for hurricane Earl, 0600 UTC 31 Aug 2010.

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. 6) 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.

Another way of validating HWRF forecasts that holds great promise is ARCHER, an algorithm developed by UWisc-CIMSS that 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).

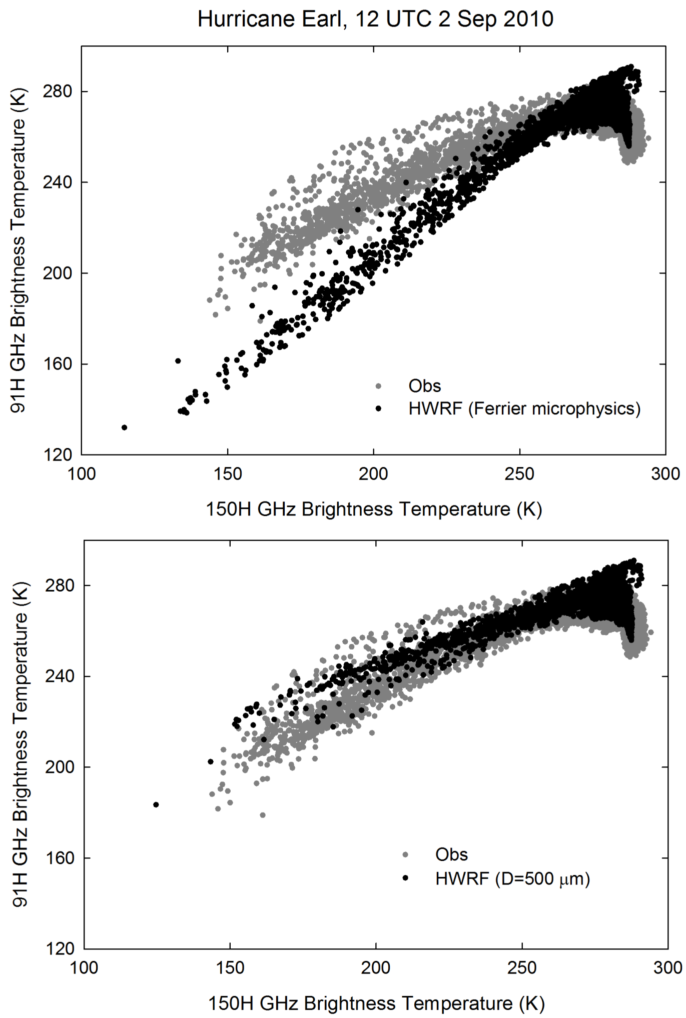


Fig. 6. SSMIS 91H GHz observed (gray dots) and simulated (black dots) brightness temperatures using the Ferrier microphysics parameterization in the HWRF (top panel) and assuming a fixed snow particle diameter (bottom panel).

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 7. 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.

**Plans for next 6 months:**

- Improve the synthetic imagery produced by the latest version of the UPP by modifying its code. Some of the improvements include updating to the latest version of the CRTM (v2.1.2), outputting SSMIS channel 4 (54.4 GHz) imagery, correcting for biases in the 85-91H GHz imagery, determining the effects of slant path calculations, and using the remapping tool to make the imagery more consistent in spatial scale with the observations

- Develop software for on-line diagnostic verification. That would include the following capabilities: a) ingest of satellite observations from the operational on-line data archive (bufr data) and selection of subsets of these data within storm regions, b) computation of the aforementioned diagnostics and c) display of products
- Begin writing a manuscript that would present technical and scientific accomplishments of this project

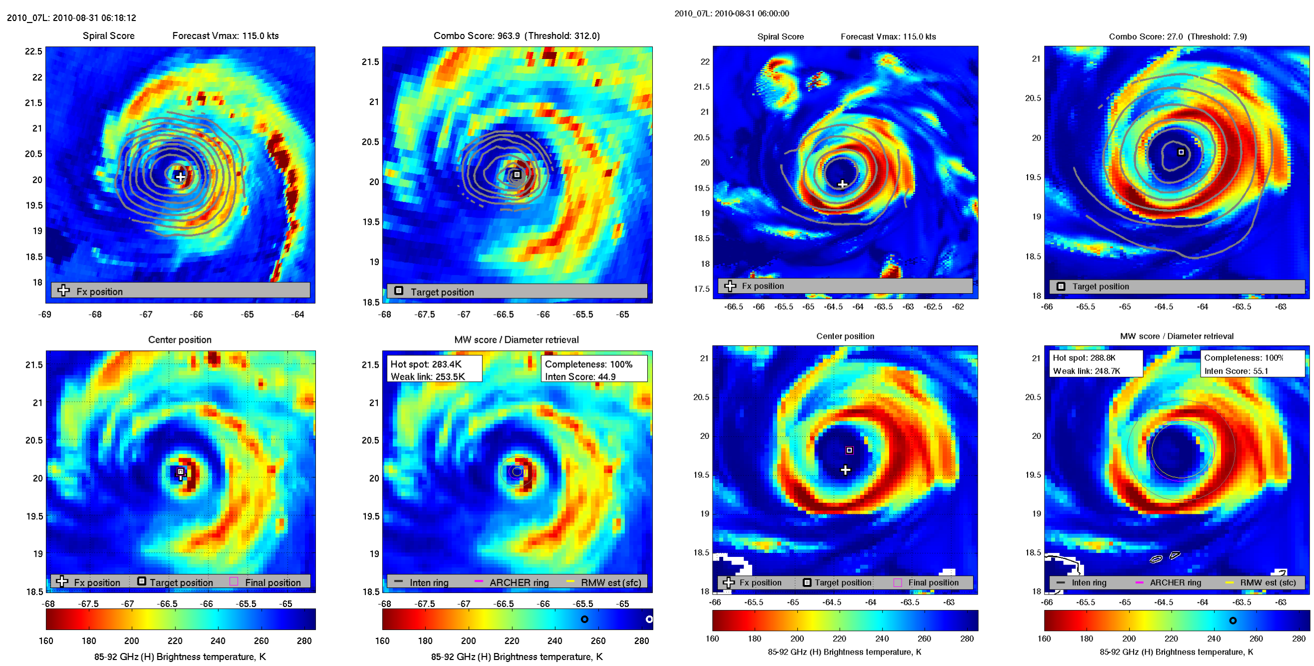


Fig. 7. Application of ARCHER to TMI observations (left four panels) and HWRF-simulated TMI data (right four panels) on 31 Aug 2010 for the hurricane Earl forecast.