DTC Visitor Project Report: Evaluation of Two Microphysics and Radiation Schemes in HWRF Using Remote Sensing Data

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1. Background

NWP model forecasts are sensitive to the choice of the microphysics scheme, which is a large source of forecast uncertainty. For hurricane forecast, it was demonstrated that microphysics schemes could impact the hurricane track (Fovell and Su, 2007) and intensity (Pattnaik, S. and T.N. Krishnamurti, 1 and 2, 2007) forecasts. Because the hydrometeors have different radiative and reflective properties that could affect radiation processes, microphysics, and radiation schemes are closely related and should be studied together. The operational Hurricane WRF model (HWRF) (Bernardet et al., 2014, Biswas et al., 2015 and Tallapragada et al. 2014) was originally designed to use a fixed suite of physics parameterization schemes, with the microphysics scheme being the Ferrier scheme developed at the National Centers of Environment Prediction (Ferrier 1994) and the radiation scheme being GFDL scheme (Lacis and Hansen, 1974). However, the community WRF model, the atmospheric component of HWRF, has multiple physics parameterization schemes available that could potentially improve the HWRF forecast skills. The Developmental Testbed Center has conducted several extensive Testing and Evaluation (T&E) activities in an effort to increase the HWRF's physics schemes interoperability and examine the impacts of several alternative physics schemes on HWRF forecast skill. The results of a recent test for the 2012 hurricane season showed that replacing the operational Ferrier microphysics and GFDL radiation schemes with the Thompson microphysics (Thompson et al. 2004) and RRTMG radiation (Mlawer et al. 1997) schemes significantly affected the seasonal track and intensity forecast skill (personal communication). Thompson/RRTMG degraded the track and intensity forecast skills for hurricanes in the Eastern North Pacific (EP) basin. In the North Atlantic (AL) basin, the track forecast was improved. There was a degradation in the AL basin intensity forecast in the early stage of the forecasts, until 48 hrs, but the intensity forecast after 60 hrs showed smaller errors than the operational configuration with Ferrier/GFDL schemes.

Compared to earlier microphysics schemes, the relatively new Thompson scheme incorporates a number of advanced features to the physical processes. Unlike any other bulk microphysics schemes, the assumed snow size distribution depends on both ice water content and temperature and is represented as a sum of exponential and gamma distributions. Furthermore, snow assumes a non-spherical shape with a bulk density that varies inversely with the diameters as found in the observations and in contrast to nearly all other bulk microphysics schemes that assume spherical snow with constant density (Thompson et al. 2004).

Therefore, the DTC T&E test result raised an important and intriguing question: Why did the test runs with Thompson/RRTMG schemes have mixed impacts on the forecast skill? To answer this question, we must first know if the Thompson/RRTMG schemes more realistically represented the microphysics processes in the hurricane forecast than its operational counterpart, the Ferrier/GFDL schemes. If the answer is *yes*, this could explain the improvement in the AL basin track forecast; and the degradation of the Eastern Pacific (EP) forecast and the early stage of the AL basin intensity forecast could have resulted from other factors such as the previous tuning of other model physics schemes or the ocean component, among other factors.

The goal of this study is to evaluate HWRF microphysics/radiation scheme's skill in realistically simulating hurricane clouds, focusing on the current operational Ferrier/GFDL and the alternative Thompson/RRTMG. The objective of this study is to quantitatively compare the HWRF forecast microphysics hydrometeors and cloud brightness temperature against those observed by remote sensing satellite. This study will identify and compare the deviations of the Ferrier/GFDL and Thompson/RRTMG schemes from the remote-sensing observations. The result of this study could also potentially help the diagnosis of the other parts of HWRF as well; therefore help identify avenues to improve the model's forecast skills.

This report is constructed as follows. In section 2 we will describe the data used in the evaluation. Section 3 describes the model configurations, the simulated cases and the method to generate synthetic satellite images. Section 4 presents the analysis method used in comparing the model synthetic satellite images with the observed ones. Section 5 shows the results. Section 6 describes the products and activities delivered for this project. Section 7 gives the summary.

2. Observational Data

Remote sensing data are chosen because the conventional ground-based in-situ observations are limited since tropical cyclones spend most of their lifetime over open oceans. Remote-sensing data can fill many gaps by covering large areas including open oceans with high-resolution and therefore can be used in model diagnostics (Jin et al. 2014 and Cintineo et al. 2014).

In this study, we used the brightness temperature in the infrared channel (band-4) data measured by the Geostationary Operational Environmental Satellite (GOES) operated by the United States National Environmental Satellite, Data, and Information Service (NESDIS). Dr. Greg Thompson recommended the use of the infrared channel brightness temperature data because it can best represent the cloud-top temperature without interference due to diurnal variations in other channels.

The observed GOES satellite data were obtained from the online archive at NOAA's Comprehensive Large Array-Data Stewardship System (CLASS) at http://www.class.ngdc.noaa.gov. Due to the large size of the global data, we only retrieved the data within a fixed sub-set that covers the majority areas of both the AL and EP basins where most hurricanes occur (Fig. 1). Note that when GOES satellite data set was not measured at a whole hour, it was assigned to the nearest whole hour (e.g., if a data set was measured at T=17:45 UTC, it was compared with model synthetic brightness temperature product valid at T=18:00 UTC)

A total of 1269 datasets, based on the dates and times of the hurricane cases (**Error! Reference source not found.**) that were tested in this study, were downloaded from NOAA's CLASS system. They were then converted from GIS shape-file to the NetCDF format for easier comparison. All the downloaded and converted data are achieved on NOAA's Jet computer.

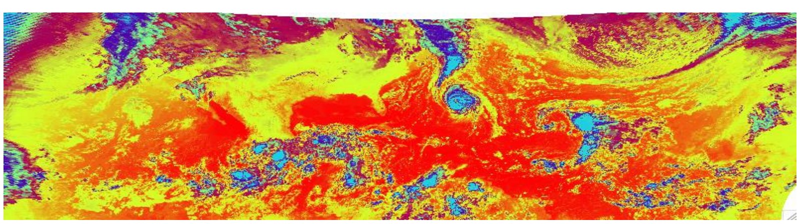

Figure 1. An example (for October 17th, 2014) of the retrieved GOES infrared channel brightness temperature data from NOAA's CLASS system. All the GOES data retrieval used the same domain grid.

3. HWRF Experiments

1. Model configurations

We used three microphysics and radiation scheme configurations (Table 1) of the 2014 operational version of HWRF in this study, which was the latest version at the time this study started.

Table 1. Model configurations in the HDGF, HDRF and HDRT experiments.

Configurations	Radiation scheme	Microphysics scheme	Method to generate synthetic satellite
HDGF	GFDL	Ferrier	UPP
HDRF	RRTMG	Ferrier	UPP
HDRT	RRTMG with partial cloudiness	Thompson (2014)	Otkin, Jason

The DTC conducted a test in early 2014 using the HDGF and HDRF configurations (Holt et al. 2015). That test included about 220 5-day hurricane forecast cycles for the following hurricanes (Table 2**Error! Reference source not found.**).

Table 2. Hurricanes used in the HDGF, HDRF and HDRT tests.

09e 2011 (HILARY)	04e 2012 (DANIEL)
09l 2011 (IRENE)	05e 2012 (EMILIA)
12l 2011 (KATIA)	07e 2012 (GILMA)
16l 2011 (OPHELIA)	12l 2012 (LESLIE)
03l 2012 (CHRIS)	18l 2012 (SANDY)
04e 2012 (DANIEL)	03l 2013 (CHANTAL)
05e 2012 (EMILIA)	17e 2013 (RAYMOND)
07e 2012 (GILMA)	18e 2013 (SANIA)
12l 2012 (LESLIE)	06l 2014 (EDOUARD)
18l 2012 (SANDY)	08l 2014 (GONZALO)
09l 2011 (IRENE)	13e 2014 (MARIE)
12l 2011 (KATIA)	14e 2014 (NORBERT)
16l 2011 (OPHELIA)	15e 2014 (ODILE)
03l 2012 (CHRIS)	

The results from the DTC's HDGF and HDRF tests were also used in this study.

HDGF is used as the control configuration, which is also the 2014 operational configuration. It used GFDL radiation and Ferrier microphysics. The other two configurations, namely, HDRF and HDRT, used the same configuration as HDGF except that different microphysics and/or radiation were used. HDRF used RRTMG radiation and Ferrier microphysics; HDRT used RRTMG radiation and Thompson microphysics.

Previous DTC T&E tests showed the HDRF and HDGF configurations produced similar results for both track and intensity forecasts. In this study, we generated synthetic GOES brightness temperature from the HDRF and HDGF model output and compared them against the observed satellite images. The comparison confirmed that the HDRF and HDGF model results closely resemble each other not only in their track and intensity forecasts but also in their simulated synthetic cloud-top brightness temperatures. Therefore, this study focused on comparing the results for the Thompson scheme (HDRT) configuration with that for the two Ferrier scheme configurations (HDRF and HDGF).

Additional model runs were conducted using the HDRT configuration. All the cases and cycles used in DTC's HDGF and HDRF experiments were planned for the HDRT run. But in the middle of the HDRT experiment runs, some input data were deleted by NCEP/EMC. Therefore, the HDRT experiment was only able to finish 166 5-day forecast cycles, compared with the 220 in HDGF and HDRF. In the subsequent evaluation, we conducted homogeneous comparisons, using the model output available for all of the HDGF, HDRF, and HDRT experiments.

Each of the 5-day forecast cycles generated 20 6-hourly model synthetic satellite brightness temperature images. A total of more than 3000 synthetic images from each experiment were generated and used in the evaluation. The large sample size enabled a systematic and reliable evaluation of the strength and weakness of the two microphysics schemes by avoiding the possible inconclusive, statistically insignificant evaluation influenced by a small number of outliers estimation in small-sample-sized studies.

2. Track and intensity verification

The track and intensity forecasts from HDGF, HDRF and HDRT were verified against the best track data (Figure 2). The HDGF and HDRF experiments produced very similar track and intensity simulations, as mentioned above. For the cases that occurred in the AL basin, the HDRT experiment also generated mixed results (Figure 2 (a) and (c)). However, for the cases that occurred in the EP, HDRT produced degraded forecast for both track and intensity (Figure 2 (b) and (d)) for almost all the lead-times.

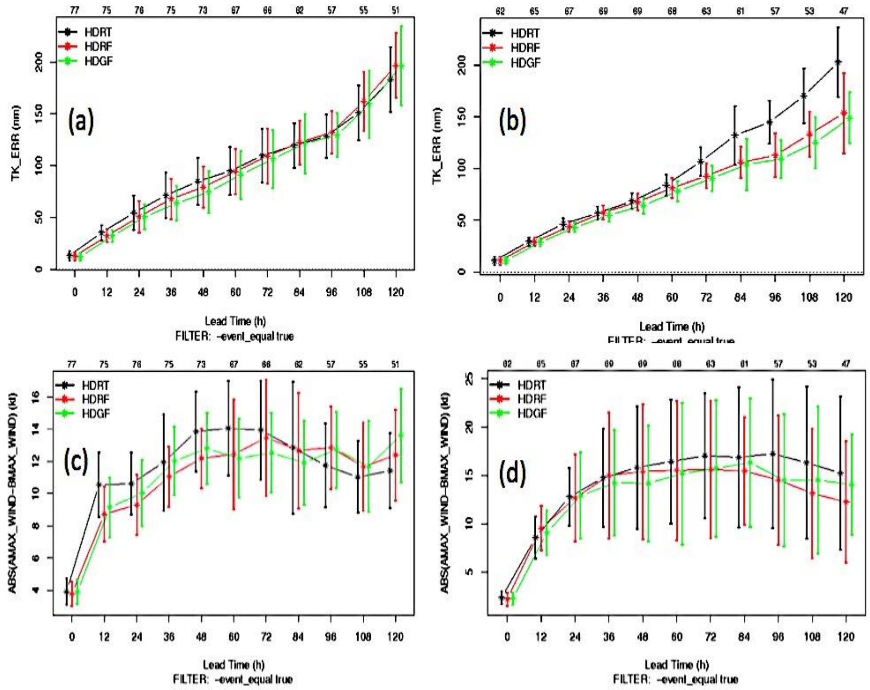

Figure 2. Track and intensity verification of the HDGF (green), HDRF (red) and HDRT (black) experiments. (a) the Atlantic basin cases track error, (b) the Eastern Pacific basin cases track error, (c) the Atlantic basin cases intensity error, and (d) the Eastern Pacific basin cases intensity error.

All the HDGF, HDRF, and HDRT experiments displayed a right-side cross-track bias for EP cases (Figure 3), but the HDRT has the most noticeable tendency to deviate to the right side of the observed tracks. For Hurricane Daniel (2012), the two Ferrier microphysics runs had an average of right-side track bias of 30 nautical miles (nm), but the cross-track bias of HDRT runs reached over 100 nm.

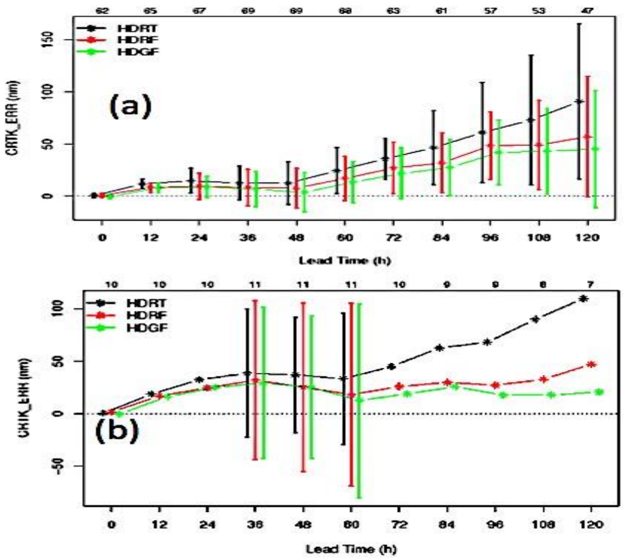

Figure 3. Cross-track errors for (a) all EP cases and (b) Hurricane Daniel (2012). A positive cross-track bias indicates systematic tendency to deviate to the right side of the best track.

3. Method of generating synthetic images

For model forecast with the Ferrier microphysics scheme (i.e. the HDRF and HDGF), the HWRF post-processor, or Unified Post-Processor (UPP), has the capability of deriving synthetic cloud-top brightness temperature satellite images from the model simulated hydrometeor quantities at the infrared channel.

Note that the Ferrier scheme does not output a quantity called radiative effective size, which is used in UPP to produce the synthetic satellite images. The radiative effective size used in UPP, therefore, is specified in UPP, not as a part of the HWRF model result. This scenario introduced some uncertainty in the evaluation of the HWRF Ferrier scheme results, especially for the high clouds areas.

When the study was conducted, UPP could not process WRF model output for non-Ferrier microphysics scheme configurations. Therefore, a software package obtained from Jason Otkin at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) of University of Wisconsin-Madison was used to post-process HDRT's model output. It is acknowledged that the capability of post-processing non-Ferrier microphysics scheme WRF model output to generate synthetic satellite images was recently incorporated into UPP recently.

For each forecast snapshot, the model-generated synthetic satellite cloud-top brightness temperature images and the downloaded observed ones were interpolated onto a common domain grid. An example is shown in Figure 4, which corresponds to the downloaded satellite data in Figure 1. The common domains are case specific. For each simulated case, its common domain is defined as the area where the four data sources—the observed satellite image, the model synthetic satellite images from HDRT, HDRF and HDGF—all have valid non-missing data coverage.

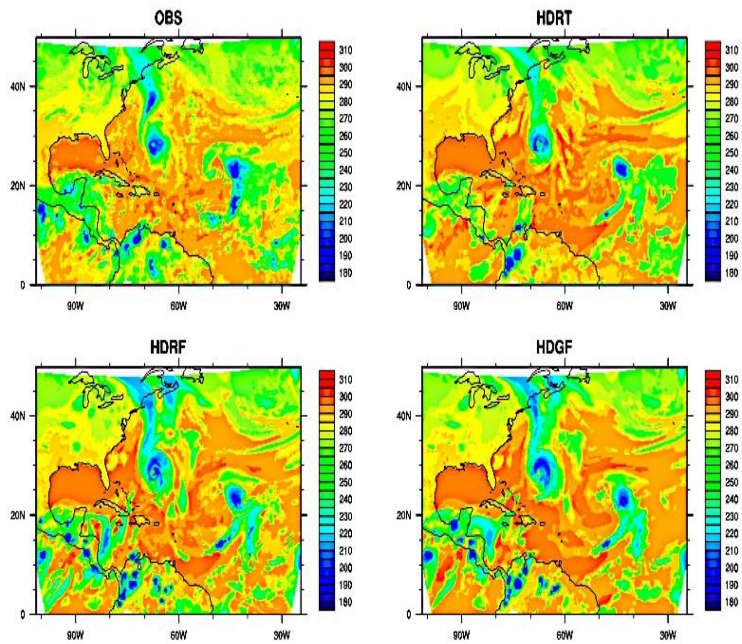

Figure 4. An example of the observed (labeled "OBS") model-generated synthetic satellite images (labeled "HDRT", "HDRF" and "HDGF") interpolated onto a common domain grid.

4. Analysis Methods

Since the HDRT result showed larger track error than HDRF and HDGF, if we compare the three model-generated synthetic satellite images of the cloud structure with the observed ones using an exact point-to-point method, the larger track error in HDRT result will lead to worse scores for HDRT. Therefore, in this study we used methods that do not penalize or penalize less the large track errors in HDRT, so we can focus on examining the cloud structures and their cloud-top temperatures. The two methods we used are the <u>Probability density distribution functions (PDF)</u> and the <u>Fraction Skill Score (FSS)</u> (Roberts & Lean, 2008)

1. PDF.
   The PDF function uses a satellite cloud-top brightness temperature image, either observed or model-generated synthetic, as input. The brightness temperature range of 180K to 310K was equally divided

into 50 bins as X-axis values. Each of the grid points (or pixels) in the dataset was counted into one of these 50 bins based on the cloud-top brightness temperature of that grid point. In the end, the probability (in percentage %), as the ratio of the number of grid points in a bin over the total number of grid points in the entire satellite image, was calculated for all the bins and plotted as Y-axis values. The PDF function analysis provides the information about the relative amount of the high clouds (with cold cloud-top temperature), low clouds (with less cold cloud-top temperature) and non-clouds (warm land or ocean surface). Since the locations of the grid points are not considered in the PDF function, the HDRT experiment is not penalized due to its larger tracker errors.

2. The FSS is a neighborhood statistic method. For each grid point in the data, the FSS method examines a number of its neighbors (including the grid point itself). The number of its neighbors that are examined is determined by a user-provided "neighborhood size" parameter. The *fraction* is defined as the ratio of the number of the examined neighboring points that meet a certain *condition* (e.g. exceeding a certain threshold) over the total number of the examined neighboring points. The fractions for the model-generated and the observed data are calculated separately and compared to give a model performance metrics for its ability to simulate the values specified in the *condition*. FSS ranges from 0 to 1, with 0 being no skill and 1 perfect skill.

5. Results

The main goal of this study was to evaluate the Thompson scheme's cloud simulation skill and how it compared with the operational Ferrier scheme. We assumed the cloud-top brightness temperature is a good metric that reflects the cloud simulation skill of the model's microphysics schemes. If the Thompson scheme's cloud simulation showed degradation compared with the Ferrier scheme, that may explain its track and intensity degradation and work is needed to improve the Thompson scheme itself; if the Thompson scheme's cloud simulation showed better skill than the Ferrier, then its track and intensity degradation might be attributed to other factors in the model. Therefore, in the following analysis we focus on comparing HDRT vs. HDGF/HDRF in their PDF and FSS statistics.

First we analyzed the individual hurricane model synthetic and the satellite observed cloud-top brightness temperature images using the methods mentioned above, the PDF and FSS. To obtain a systematic and objective evaluation, we then created the composite evaluations that include the individual PDF and FSS results.

We focus on the range of temperature from (a) 180K to 240K, which corresponds to the high clouds with strong convection, such as areas near the eye-wall, and (b) 240K-285K, which corresponds to the low clouds such as stratus and stratocumulus often found in the environment outside of the hurricane vortex.

Figure 5 shows the composite PDF distribution of the model synthetic and satellite observed cloud-top temperature that included all the hurricanes that occurred in the AL Basin. The curves indicate the percentage of the areal coverage (in %) for a particular temperature bin. For HDGF and HDRF, the two Ferrier microphysics scheme experiments, their results closely resemble each other for both the high clouds and low clouds areas, consistent with their similar track and intensity evaluations.

For the high clouds areas, the HDGF and HDRF have a bump-shaped high-rise area near 220K, which does not exist in the satellite observed or the HDRT model synthetic data. This signature indicates the Ferrier scheme results might have too much strong convection and thus the high clouds resulting from them. The HDRT result showed less high clouds than the satellite observed data. Overall the HDRT is closer to the satellite observed than the HDRF and HDGF.

For the low clouds areas, the three experiments showed no significant difference. This might be because that compared to the EP basin, the AL basin does not have as much stratus.

Figure 6 shows the FSS for hurricanes that occurred in the AL basin. The FSS scores used the thresholds of cloud-top temperature that fall in a series ranges. For cloud-top temperature ranges of 230K-250K (Figure 6b), 250K-270K (Figure 6c) and 270K-290K (Figure 6d), HDRT FSS is slightly better than that for the two Ferrier scheme experiments. For the high clouds areas with a cloud-top temperature of less than 230K (Figure 6a), HDRT's FSS is not as good as HDGF/HDRF. This may be due to the HDRT's degraded track forecast. Although FSS is a neighborhood method, the grid points' locations are considered in the score. A part of the high clouds areas with a cloud-top temperature of less than 230K are the small areas near the hurricane's eye walls; therefore a degraded track forecast could be partially penalized in the FSS score.

In general, for the hurricanes that occurred in the AL basin, the HDRT result showed a slightly better composite cloud-top brightness temperature simulation than the HDGF and HDRF.

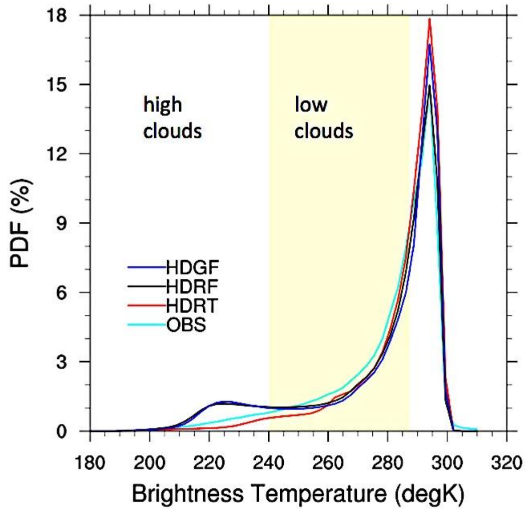

Figure 5. Composite probability density distribution of the model synthetic and satellite observed cloud-top brightness temperature for the hurricanes that occurred in the Atlantic basin.

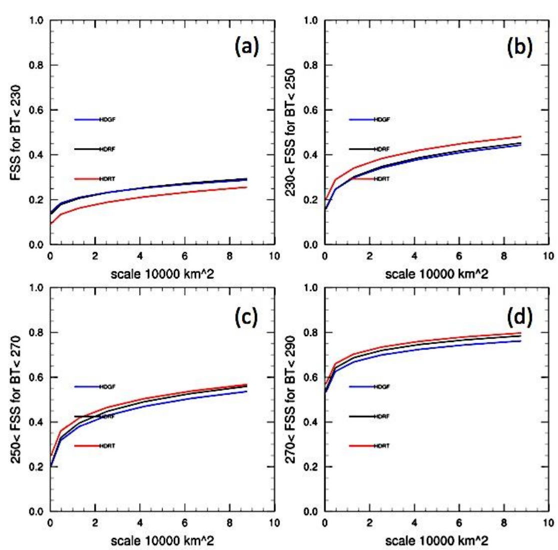

Figure 6. Fractions Skill Scores for hurricanes that occurred in the Atlantic Basin. The FSS scores used the thresholds of cloud-top temperature that fall in (a) T<230K (b) 230K< T < 250K (c) 250K < T < 270K (d) 270K < T < 290K.

Figure 7 shows the composite PDF distribution of the model synthetic and satellite observed cloud-top temperature that included all the hurricanes that occurred in the EP basin. Similar to the AL basin, the two Ferrier microphysics scheme experiments, HDRF and HDGF, produced very similar results in both the high clouds and low clouds areas, consistent with their similar track and intensity evaluations. In the EP basin, the HDGF and HDRF also have a bump-shaped high-rise area near

220K, which does not exist in the satellite observed or the HDRT model synthetic data. This scenario indicates the Ferrier scheme results might have too much strong convections and thus the high clouds resulting from them, in both AL and EP.

From Figures 5 and 7, the HDRT result showed smaller coverage of high clouds than the satellite observed data in both the AL and EP basins. This might be related to the overall weak intensity bias found in the HDRT forecasts. However, it is not clear if the weak intensity bias in HDRT forecast caused the smaller high clouds coverage, or the vice versa, which is worth further investigation. Nevertheless, overall, the HDRT result is closer to the satellite observed than the HDRF/HDGF.

For the low clouds areas, unlike in the AL basin, in the EP basin, the HDRT and HDGF/HDRF have significant differences. This might be because compared to the AL basin, the EP basin often has more low-level stratus clouds. And the Thompson scheme with partial cloudiness is more skillful in simulating those low-level stratus clouds.

Figure 8 shows the FSS for the hurricanes that occurred in the EP. For cloud-top temperature ranges of 250K-270K (Figure 6c) and 270K-290K (Figure 6d), the HDRT FSS are significantly better than those from the two Ferrier scheme experiments, which is consistent with the PDF shown in Figure 7. For the cloud-top temperature range of 230K-250K, the three experiments have almost identical FSS. And for high clouds areas with a cloud-top temperature of less than 230K (Figure 6a) HDRT's FSS is not as good as HDGF/HDRF. Again, this may be due to the HDRT's degraded track forecast.

In general, for the hurricanes that occurred in the EP, the HDRT result showed a slightly better composite cloud-top brightness temperature simulation than the HDGF and HDRF.

But note, in both AL and EP, there is uncertainty in the evaluation of the HWRF Ferrier scheme results, especially for the high clouds areas, because the radiative effective size is not a direct output from HWRF model simulation but a quantity that is specified in UPP. Although at the time this study was conducted, the radiative effective size values used in UPP was considered optimal, the choice of the different radiative effective size values can significantly change the cloud-top brightness temperature for the same HWRF Ferrier scheme output.

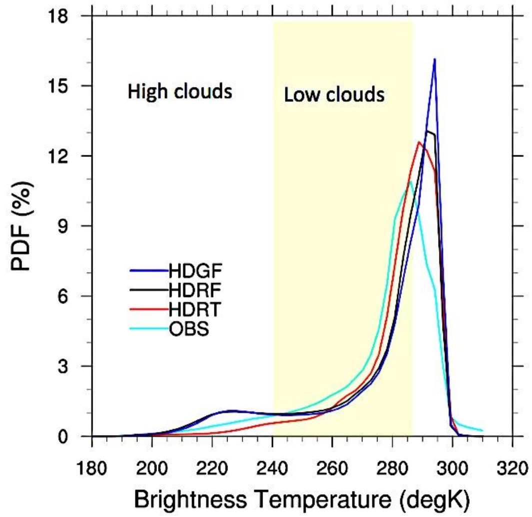

Figure 7. Composite probability density distribution of the model synthetic and satellite observed cloud-top brightness temperature for the hurricanes that occurred in the Eastern Pacific basin.

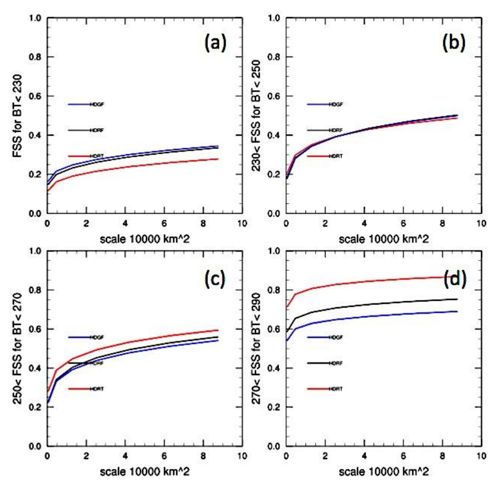

Figure 8. Fractions Skill Scores for hurricanes that occurred in the Eastern Pacific Basin. The FSSs used the thresholds of cloud-top temperature that fall in (a) T<230K (b) 230K< T < 250K (c) 250K < T < 270K (d) 270K < T < 290K.

Figure 9 shows a snapshot of Hurricane Daniel satellite observed as well as the HDRT, HDRF, and HDGF experiments model synthetic cloud-top brightness temperature images. This example illustrates the characteristics revealed by the PDF distribution shown in Figure 7. In the satellite observed image, there are large areas of low-level stratus cloud marked in yellow. The HDRF and HDGF images have much smaller coverage of these stratus clouds. In the HDRT images the area of the low-level stratus is also smaller than the satellite observed image but much larger than the HDGF/HDRF and agrees better with the satellite observed. For the high clouds area near the vortices, marked in blue, the HDRF and HDGF have larger coverage than the satellite observed, whereas the HDRT has smaller coverage.

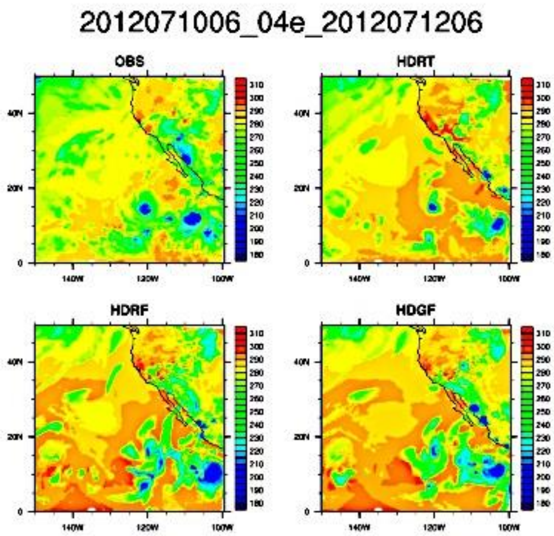

Figure 9 An example of EP hurricane cloud top brightness temperature, Daniel 04E 2012

6. Deliverables

In addition to this report, the PI and his collaborators delivered the following products and activities:

1) A database was created that contained the GOES-13 satellite *observed* brightness temperature data for the hind-cast hurricanes. The data are all interpolated to a common grid covering the AL and EP basins where most of the historical hurricanes are observed to occur. The data files were converted to NetCDF format for easy use. They have been archived on NOAA's High-Performance Computers and are available to other researchers.

2) Similarly, a database was created that contained the *model synthetic* GOES-13 satellite brightness temperature data, for all the three experiments (HDGF, HDRF and HDRT) for the hind-cast hurricanes. The data files were converted to NetCDF format for easy use. They have been archived on NOAA's High-Performance Computers and are available to other researchers.

3) Several software scripts were created for this project including those that create satellite image NetCDF files, produce and plot the PDF functions

and the FSS, etc. These software scripts are being further tested by DTC scientists and will be incorporated into HWRF contributed code (hwrf-contrib) repository.

4) The PI visited the DTC in Boulder, Colorado, in June 2015 and the NOAA's NCEP Environmental Modeling Center in College Park, Maryland, in September 2015. He presented his work in two seminars, one at NCAR and the other at NCEP EMC.

5) One publication to describe the result of this work is in preparation.

7. Summary

Three multi-year HWRF T&E tests (two of them from previous DTC T&E tests and the other for this study) were conducted using different microphysics and radiation schemes. The tests were post-processed to create model synthetic satellite cloud-top brightness temperature. GOES remote-sensing data were also collected and processed for the modeled hurricane cases. The model synthetic cloud-top brightness temperatures were evaluated using the satellite observed data. Probability density distribution function (PDF) and Fraction Skill Scores (FSS) were used as the main analysis methods. The evaluation revealed that when the same microphysics scheme is used, the difference between results using RRTMG (in HDRF) and GFDL (in HDGF) radiation schemes were small. The difference between the results using the Thompson (in HDRT) and the Ferrier (HDGF/HDRF) schemes were significant, especially in the EP. For the low-level stratus cloud simulation, the Thompson scheme was more skillful. For the high clouds areas with a very cold cloud-top temperature, the Ferrier scheme overestimated the cloud's area and the Thompson scheme underestimated it. The reason for the latter might be due to the weak intensity bias in the forecast using the Thompson scheme. Overall, the evaluation showed that the Thompson scheme did not degrade cloud simulation performance, compared with the Ferrier scheme. Therefore, the track and intensity degradation in the forecast using the Thompson scheme might be related to other factors in the HWRF model system.

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