The Developmental Testbed Center

HWRF 2011 Baseline Test Report

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Contributors:

The DTC HWRF 2011 Baseline Test was conducted by the team of the Hurricane Task of the DTC, composed by Shaowu Bao, Ligia Bernardet, Timothy Brown, Laurie Carson, Christopher Harrop, and Donald Stark. This test was designed in collaboration with Vijay Tallapragada of NOAA/NCEP/EMC, who provided the HR20 tracks for verification and comparison against HNR2.

All acronyms are defined in Appendix C.

Index

1. Executive Summary
2. Introduction
3. Goals
4. Experiment Design
   a. Codes employed
   b. Domain configurations
   c. Forecast cases and initial and boundary Conditions
   d. Physics Suite
   e. Other aspects of code configuration
   f. Postprocessing and vortex tracking
   g. Model Verification
   h. Graphics
   i. Archives
5. Computer Resources
6. Deliverables
7. Results
   a. North Atlantic Basin
   b. Eastern North Pacific Basin
8. Discussion and Conclusions
9. References

Acknowledgements

Appendix A. Inventory
Appendix B. Archives
Appendix C. Acronyms
1. Executive Summary

- The DTC conducted its first extensive test of a HWRF configuration, demonstrating that the development of a testing infrastructure functionally equivalent to NOAA EMC’s is complete.
- Over 1000 HWRF runs for the Eastern North Pacific and Atlantic basins, for the 2008, 2009, and 2010 seasons were conducted in order to produce a robust Reference Configuration of the community code (HWRF PS:85.98.88.88.88.2.4 nicknamed HNR2).
- Track errors for HNR2 increase linearly with time from near zero at initialization time to 280 nm at the 5-day forecast.
- A negative intensity bias is noted for HNR2 at all lead times, with a marked increase in errors in the first 6-h of the forecast, suggesting a problem with the initialization. More recent results, not presented in this report, indicate that this problem has been mitigated in more recent HWRF configurations.
- Absolute intensity errors increase sharply in the first 6-h of forecast and then grow slowly out to 3-days, after which they remain virtually unchanged.
- The forecast storm size is larger than the observed one for the 34-, 50-, and 64-kt wind radii, with the worst errors occurring for the 34-kt radii.
- A comparison between HNR2 and HR20 (a similar HWRF test conducted by EMC) was conducted for the purposes of assessing how similar the forecasts produced with the community code were to forecasts produced with a similar configuration from the EMC code repository. An exact match was not expected due to differences in computational platform, and a few other minor setup differences noted in Section 3.
- The HNR2 forecast skill is shown to be similar to HR20, with very few statistically significant differences in track and intensity. Several statistically significant differences favoring HNR2 were noted in storm structure but their magnitude is small compared to the actual errors.
- The worst track and absolute intensity forecasts (outliers) were identified so that forecast improvements for these poorly performing cases can be addressed in the future.
- Model output files have been archived and are available to the community for future studies. Forecast maps and verification graphics, along with this report and additional information are available in the DTC website.
2. Introduction

The DTC performed testing and evaluation for the Hurricane WRF system, known as HWRF (Gopalakrishnan et al. 2010). HWRF was configured as close as possible to the operational HWRF model, employing the same domains, physics, coupling, and initialization procedures as the model used at the NOAA NCEP Central Operations and by the model developers at NCEP EMC. The configuration tested matches the 2011 HWRF Baseline, which is the configuration that served as control for all developments at EMC geared towards the 2011 operational implementation.

The HWRF System has the following components: WPS, prep_hybrid (WRF preprocessor for input of GFS spectral data in native coordinates and binary format), vortex relocation and initialization, GSI 3D-Var, WRF model using a modified NMM dynamic core, POM, features-based ocean initialization, WPP, GFDL vortex tracker, GrADS-based graphics, and NHCVx. HWRF is currently designed for use in the North Atlantic and Eastern North Pacific basins. Atlantic forecasts are in coupled ocean-atmosphere mode, while Pacific forecasts use only the atmospheric model.

3. Goals

The overarching goal of the HWRF 2011 Baseline Test Plan was to establish the skill of the community HWRF code for tropical storm forecasting, designating a new DTC RC (Wolff et al. 2010). This RC, formally referred to as HWRF PS:85.98.88.88.88.2.4 and dubbed HNR2, is now a control against which future advancements in HWRF forecast skill can be measured.

Another goal of this test was to compare the forecasts against those obtained at NOAA EMC using the HR20 configuration of HWRF, in order to assess how similar the forecasts produced with the community code are to forecasts produced with code from the EMC repository. It was not expected that HNR2 and HR20 forecasts would match exactly. Work was conducted to merge the EMC and community code repositories for the WPS, prep_hybrid, vortex relocation, POM, POM initialization, and WRF codes, and previous tests have shown that they now produce identical results. However, minor differences remain between the codes for postprocessing and tracking. Additionally, there are differences in computing platform, in the time-invariant snow albedo dataset, and a bug in the scripting for the ocean was discovered after the HR20 runs were complete and has been fixed in the DTC version of the scripts. While differences between HNR2 and HR20 forecasts are expected to be in the noise level for cold start runs, the cycling nature of HWRF will sometimes cause an amplification of the differences for the later initializations of a given storm. It was expected that while HNR2 and HR20 results would differ for specific storms, the forecast skill would be similar over a sufficiently large sample of cases. Table 1 summarizes the differences between HNR2 and HR20.
### Table 1. Differences between HNR2 and HR20

<table>
<thead>
<tr>
<th></th>
<th>HNR2</th>
<th>HR20</th>
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</thead>
<tbody>
<tr>
<td><strong>Institution conducting test</strong></td>
<td>DTC</td>
<td>EMC</td>
</tr>
<tr>
<td><strong>Computer platform</strong></td>
<td>Linux Cluster <em>tjet</em></td>
<td>NCEP IBMs <em>CCS</em> and <em>vapor</em></td>
</tr>
<tr>
<td><strong>Source code repository</strong></td>
<td>Community</td>
<td>EMC</td>
</tr>
<tr>
<td><strong>Scripts</strong></td>
<td>DTC</td>
<td>EMC</td>
</tr>
<tr>
<td><strong>Automation</strong></td>
<td>NOAA GSD Workflow Manager</td>
<td>EMC HWRF History Sequence Manager</td>
</tr>
<tr>
<td><strong>I/O format</strong></td>
<td>NetCDF</td>
<td>Binary</td>
</tr>
<tr>
<td><strong>WPP</strong></td>
<td>WPP v3.2</td>
<td>NAM Post Modified for HWRF</td>
</tr>
<tr>
<td><strong>Tracker</strong></td>
<td>Community repository</td>
<td>EMC operational tracker</td>
</tr>
<tr>
<td><strong>Sharpening procedure in ocean initialization for Atlantic domain</strong></td>
<td>Used in ocean spin up Phases 3 and 4 and in coupled model run</td>
<td>Used in ocean spin up Phase 3 only (known bug)</td>
</tr>
<tr>
<td><strong>Snow Albedo</strong></td>
<td>Older dataset</td>
<td>Newer dataset</td>
</tr>
</tbody>
</table>

### 4. Experiment Design

The end-to-end system was composed of WPS, prep_hybrid, vortex relocation and initialization, GSI, ocean initialization, POM, WRF, coupler, WPP, tracker, graphics generation, data archival, and dissemination of results.

#### a. Codes employed

The software packages utilized were obtained from the community repositories for all codes, except for prep_hybrid and NHCVx, which are not currently supported to the community. NHCVx will be obtained from a DTC in-house code repository. Prep_hybrid, although not supported to the community, is kept in the hwrf-utilities repository. The revisions for all codes are listed below:

- WRF - [https://svn-wrf-model.cgd.ucar.edu](https://svn-wrf-model.cgd.ucar.edu), revision 4594
- WPS – revision 573
- WPP – official release v3.2
- GSI – official release v2.5
- Vortex relocation and initialization, prep_hybrid, miscellaneous libraries and tools: [https://svn-dtc-hwrf-tne.cgd.ucar.edu](https://svn-dtc-hwrf-tne.cgd.ucar.edu), revision 173
b. Domain Configurations

The HWRF domain was configured the same way as used in the NCEP/EMC operational system. The atmospheric model employed a parent and a movable nested grid. The parent grid covered a 75x75° area with 0.18° (approximately 27 km) horizontal grid spacing. There were a total of 216 x 432 grid points in the parent grid. The nest covered a 5.4 x 5.4° area with 0.06° (approximately 9 km) grid spacing. There were a total of 60 x 100 grid points in the nest. Both parent and nest used the WRF-NMM rotated latitude-longitude projection and the E-staggered grid. Indices in the E-staggered grid are such that a square domain has approximately twice as many points in the y-direction than the x-direction. The location of the parent and nest, as well as the pole of the projection, varied from run to run and were dictated by the location of the storm at the time of initialization. Forty-two vertical levels (43 sigma entries) were employed, with a pressure top of 50 hPa.

HWRF was run coupled to the POM ocean model for Atlantic storms and in atmosphere-only mode for East Pacific storms. The POM domain for the Atlantic storms depended on the location of the storm at the initialization time and on the 72-h NHC forecast for the storm location. Those parameters defined whether the East Atlantic or United domain of the POM was used. Both POM domains covered an area from 10.0°N to 47.5°N in latitude, with 225 latitudinal grid points. The East Atlantic POM domain ranged from 60.0° W to 30.0° W longitude with 157 longitudinal grid points, while the United domain ranged from 98.5° W to 50.0° W with 254 longitudinal grid points. Both domains had horizontal grid spacing of approximately 18 km in both the latitudinal and longitudinal directions. The POM used 23 vertical levels and employed the terrain-following sigma coordinate system.

Additional intermediate domains were used for the atmospheric model during the vortex relocation and initialization procedures (see Bao et al. 2010), and during postprocessing (see item 3.g below).
c. Forecast cases and initial and boundary Conditions

Forecasts were initialized every 6 hours for 53 storms and were run out to 126 hours. When no Best Track information was available, verification was not performed. Additionally, forecasts for observed storms classified as a wave or low by the NHC were excluded. Therefore, the number of verified cases is slightly smaller than the total number of cases.

Initial Conditions were be based on pre13d GFS analysis. Pre13d GFS refers to the retrospective runs of the T574 GFS which was implemented operationally on July 28, 2010. The IC and BC for the atmosphere were obtained from the binary spectral GFS files in native vertical coordinates using prepHybrid. The IC for the surface fields were obtained from the 1x1° GFS files in GRIB format using WPS. HWRF used a vortex relocation procedure as described in Bao et al. 2010 and Gopalakrishnan et al. 2010. In the presence of a 6-h forecast from a HWRF run initialized 6-h before the initialization time for a given cycle, the vortex relocation procedure removed the vortex from the GFS analysis and substituted it with the vortex from the previous HWRF forecast, after correcting it using the observed location and intensity. When a previous HWRF forecast was not present, the GFS vortex was removed and substituted by a synthetic vortex derived from a procedure that involves theoretical considerations and HWRF climatology. This procedure is referred to as cold start.

Typically a cold-start initialization was employed for the first NHC Storm Message (INVEST) of each storm, and the HWRF vortex was cycled for all subsequent initialization of each storm. When the NHC storm message was missing during a storm, there was an interruption in the cycling, and a new cold start was done.
For storms classified as *deep* by the NHC at the time of model initialization, the HWRF initialization was updated using GSI. The data supplied to GSI consisted of conventional restricted prepbufr observations, satellite observations from NOAA, metop-a, AQUA, GOES, and AMSU A and B satellites. For any given analysis, only a subset of the observations were employed because of quality and availability of the datasets. No data was assimilated in the inner core of the storm, that is, the GSI modifications to the HWRF initialization were only applied to the storm environment (outside 150 km radius from the storm center).

The inventory of cases used in this test is listed in Appendix A. All the cases listed in the test plan were run. Three cases could not be completed:

- Bill 03L of 2009 initialized at 06 UTC on 08/23. Executable copygb crashed for lead times 84 h and beyond due to a well known deficiency in this program for cases in which the center of the nest is very distant from the center of its projection. After Bill went extratropical and quickly moved to the North and East, copygb failed.
- Gaston 09L of 2010 initialized at 18 UTC on 09/07. This case could not be initialized in cycled mode because storm in the previous case (12 UTC on 09/07) was too weak and the tracker only ran for the first 6 h. A cold start was not attempted.
- Eleven 11E of 2010 initialized at 12 UTC on 09/04. The vortex initialization procedure failed, probably because the storm was over the steep topography of central America.

This failures will be investigated with the intention of making the modeling system more robust. In addition, archives were lost for five cases of Ike 09L of 2008 (00 UTC on 09/13 through 00 UTC on 09/14).

Forecast verification was not performed for all cases run. For some cases Best track information was not available. Additionally, verification was not performed if the storm was classified as a low or wave.

**d. Physics Suite**

The physics suite configuration (Gopalakrishnan et al. 2010) is described in Table 2. The convective parameterization was applied in both the parent and nest domains with momentum mixing (coefficient 1.0) activated in both.
Table 2. Physics Suite for HNR2 test.

<table>
<thead>
<tr>
<th>Microphysics</th>
<th>Ferrier for the tropics (85)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation SW/LW</td>
<td>GFDL/GFDL (98/98)</td>
</tr>
<tr>
<td>Surface Layer</td>
<td>GFDL (88)</td>
</tr>
<tr>
<td>Land Surface Model</td>
<td>GFDL slab model (88)</td>
</tr>
<tr>
<td>Planetary Boundary Layer</td>
<td>GFS (3)</td>
</tr>
<tr>
<td>Convection</td>
<td>Simplified Arakawa-Schubert (4)</td>
</tr>
</tbody>
</table>

**e. Other aspects of code configuration**

The HWRF system was compiled with the environmental variables WRF_NMM_CORE, WRF_NMM_NEST and HWRF set to 1 in order for the executables to contain the HWRF-specific instructions.

As in the operational configuration, a time step of 54 s was used for the parent grid, while a time step of 18 s was used in the nest. Calls to the turbulence, cumulus parameterization and microphysics were done every 4.5 minutes for the parent domain and 54 s on the nest. Calls to the radiation were done every 54 minutes on the parent grid and 9 minutes on the nest. Coupling to the ocean model and nest motion were restricted to a 9-minute interval.

The gravity wave drag parameterization was applied in the parent-domain only, and the advection used the Lagrangian scheme.

**f. Post-processing and Vortex Tracking**

The wrfpost program within WPP was used in the parent and nest domains to destagger the forecasts, to generate derived meteorological variables, including MSLP, and to vertically interpolate the fields to isobaric levels. The post-processed fields included two- and three-dimensional fields on constant pressure levels and at shelter level, all of which are required by the plotting and verification programs.

Using the copygb program contained in WPP, the post-processed parent and nest domains were horizontally interpolated to a latitude-longitude grid with similar domain size to the parent domain and grid spacing similar to the native nested domain. Those two grids with same domain and grid spacings were then combined in order to create a high-resolution grid covering an area similar to the parent domain. Additionally, the post-processed forecast from the nest domain was horizontally interpolated to a high-resolution standard latitude-longitude grid with similar domain to the nest in order to generate graphics.

Tracking was done on the combined domain. For purposes of verification and graphics generation, the input was six hourly postprocessed files. Tracking for the purposes of cycling the HWRF vortex used three-hourly postprocessed files.
g. Model Verification

All verification graphics can be seen at [http://verif.rap.ucar.edu/eval/hwrfrhr2_hr20/verify/](http://verif.rap.ucar.edu/eval/hwrfrhr2_hr20/verify/). The characteristics of the forecast storm (location, intensity, structure) as contained in the HNR2 and HR20 ATCF files produced by the tracker were compared against the Best Track using the NHCVx. The HNR2 ATCF files were produced by the DTC as part of this test, while the HR20 ATCF files were supplied by EMC. The NHCVx was run separately for each case, at 6-hourly forecast lead times, out to 120 h, in order to generate a distribution of errors.

Verification was performed for any geographical location for which Best Track was available, including over land. No verification was performed when the observed storm was classified as a low or wave.

A R-statistical language script was run separately on an homogenous sample of the HNR2 and HR20 datasets to aggregate the errors and to create summary metrics including the mean and median of track error, intensity error, absolute intensity error, and radii of 34, 50, and 64 kt wind in all four quadrants. All metrics are accompanied of 95% confidence intervals to describe the uncertainty in the results due to sampling limitations. The largest outliers (worst forecasts) were identified.

It was originally planned that along- and cross-track errors would be included in this evaluation. However, an error was found in the program after the errors were computed and therefore they are not included in this report.

For the purposes of comparing the HNR2 and HR20 forecasts, pairwise differences (HNR2-HR20) of track error, intensity error and absolute intensity error were computed and aggregated with a R-statistical language script. Ninety-five percent confidence intervals on the median were computed to determine if there is a statistically significant difference between the two configurations.

For the intercomparison between HNR2 and HR20, a homogeneous sample was used. On the other hand, for the analysis of the individual errors of the HNR2 and HR20 configurations, this constraint was not enforced. However, the heterogeneity of the sample is minimal because the HNR2 and HR20 sets cover the same cases.

Verification results are described in Section 7.

h. Graphics

All forecast graphics can be seen at [http://www.dtcenter.org/HurrWRF/graphics/HNR2-HR20](http://www.dtcenter.org/HurrWRF/graphics/HNR2-HR20).

Graphics were generated using GrADS scripts originally developed at EMC. Graphics included line plots of track, maximum winds and mean sea level pressure.

Additionally, the following 4 graphics were produced for six-hourly lead times
- 850-hPa streamlines and isotachs on the combined domain
- 850-hPa streamlines and isotachs on the nest
- MSLP and 10m winds on the nest
- Zonal cross sections of zonal and meridional wind on the nest
- Meridional cross section of zonal wind on the nest

i. Archives

Input and output data files from several stages of the end-to-end system have been archived in the NOAA ESRL/GSD MSS.

The input GFS spectral data in binary format data, along with the observations used in GSI, can be found at /arch3/jet/projects/dtc-hurr/datasets/yyyyymmdd, where yyyyymmdd is the year, month and day of the forecast initialization.

The TCVitals, the A- and B-decks (containing HR20 tracks), the files for ocean initialization (Loop current and warm and cold core rings) along with all the fix (static) files can be found in /arch3/jet/projects/dtc-hurr/HWRF_HNR2_run_archive/dataset.tar.bz2.

The output can be found at /arch3/jet/projects/dtc-hurr/HWRF_HNR2_run_archive/SID_yyyyymmddhh.tar.bz2, where SID is the Storm Identification, expressed as 2 digits plus one letter (L for Atlantic and E for East Pacific). Appendix B lists all the files that are archived for each case.


A file with the output from the NHC Vx for all HNR2 and HR20 cases can be found at /arch3/jet/projects/dtc-hurr/HWRF_HNR2_run_archive/HWRF_HNR2_NHC_files.tar.bz2.

The scripts used in the postprocessing of the NHC Vx data, along with all the logs and images produced, can be found at /arch3/jet/projects/dtc-hurr/HWRF_HNR2_run_archive/HNR2_HR20_Rscript_and_output.tar.bz2.

All source codes and executables are in /arch3/jet/projects/dtc-hurr/HWRF_HNR2_run_archive/TNE_source_files.tar.bz2.

5. Computer resources

- Processing resources

  All forecasts were computed on the HFIP Linux cluster tjet located at NOAA GSD. For the coupled run, 91 processors were used for the atmospheric model, 1 for the coupler, and 1 for POM. GSI was run in 24 processors. All other programs were run in a single processor.

- Storage resources
All archival are on the NOAA GSD MSS.

- Web resources

Model forecast and verification graphics can be accessed through a web interface available on the DTC website.

6. Deliverables

The NOAA GSD MSS was used to archive the files input and output by the forecast system. Appendix B lists the output files that will be archived. Additionally, all code compilation logs, input files and fixed files used in the runs have been archived. These files are available to the community for further studies.

The DTC website is being used to display the forecast and objective verification graphics.

Finally, this report summarizes the results and conclusions from this test.

7. Results

For brevity, this reports gives a summary of the most important results. A comprehensive set of verification figures is available at [http://verif.rap.ucar.edu/eval/hwrf_hnr2_hr20/verify/](http://verif.rap.ucar.edu/eval/hwrf_hnr2_hr20/verify/).

  a. North Atlantic Basin

The mean of the track errors for HNR2 and HR20 indicates that the errors grow in time from near zero at the initialization time to 280 nm at the five-day lead time (Fig. 2). There is only one statistically significant (SS) difference in the median of track errors between HNR2 and HR20, occurring at the 78-h lead time (Fig. 3). This difference favors the HNR2 configuration.
Figure 2. Mean track error (nm) for HNR2 (black) and HR20 (red) as a function of forecast lead time for all cases in the Atlantic basin. The 95% confidence intervals are also displayed. The sample size is listed above the graphic.

Figure 3. Median of the pairwise difference in track error (nm) between HNR2 and HR20 as a function of forecast lead time for all cases in the Atlantic basin. The 95% confidence intervals are also displayed. Positive (negative) values indicate HR20 (HNR2) superior performance. The sample size is listed above the graphic.
The mean of the absolute intensity errors for HNR2 and HR20 displays a sharp growth in the first 6 h of forecast, from near zero to 10 kt. From 6 to 48 h, the error grows more slowly to about 16 kt, and remains relatively unchanged after that (Fig. 4). The mean of the intensity errors for HNR2 and HR20 shows a SS negative bias from the initialization up until the 78-h lead time (Fig. 5). The bias is small (approximately -1 kt) at the initial time, but grows sharply to -4 kt after 6 h, suggesting an imbalance in the initialization. The worst bias are seen after 1 day of forecasting, after which the bias diminishes and becomes near zero by the end of the forecast period. There are no SS differences in the median of absolute intensity errors between HNR2 and HR20 (Fig. 6).

Figure 4. Same as Fig. 2, except for absolute wind error (kt).
Figure 5. Same as Fig. 2, except for intensity error (kt).

Figure 6. Same as Fig. 3, except for absolute intensity error (kt).
The mean absolute errors for the 34 kt radii are in order of 45 nm, while they are on the order of 30 kt for the other radii (not shown). In general the errors tend to be higher at the beginning and at the end of the forecast period, pointing to deficiencies in the initialization of storm structure. In a couple of cases (34 kt radii for the SE and SE quadrants), the error grows sharply in the first 6 h, then decays, and finally increases towards the end of the forecast, suggesting that the model goes through an adjustment period in the first six hours which is not in alignment with the observed storm structure. The mean error is positive for all quadrants and wind thresholds, indicating that the forecast storm is always larger than the observed one.

The lead times in which SS differences between HNR2 and HR20 in track, intensity and storm structure occur are listed in Table 3. In all cases, the SS differences have small magnitude compared to the errors of the individual models.

While the 34 kt wind threshold in the SW quadrant of the storm does not exhibit any SS difference between HNR2 and HR20, differences are noted in the other quadrants in 33 instances (Table 3) Note that there are a total of 252 instances (21 lead times, 4 quadrants, 3 radii) that can exhibit differences. All differences favor the HNR2 configuration, except for the 50 and 64 kt radii in the NE quadrant at the initialization time, which favor HR20.
Table 3. Statistical significances in the mean of various errors as a function of forecast lead time for all cases in the Atlantic basin. The lines correspond to track error (Tk), intensity (Wd), radii of the 34, 50, and 64 kt wind threshold in the NE, SW, SE, and SW quadrants of the storm (34NE, 50NE, 64NE, 34NW, 50NW, 64NW, 34SE, 50SE, 64SE, 34SW, 50SW and 64SW, respectively). Statistically significant differences that favor the HNR2 or HR20 configurations are indicated as "N" or "R", respectively. A dash indicates that no SS difference exists.

|       | 0  | 6  | 12 | 18 | 24 | 30 | 36 | 42 | 48 | 54 | 60 | 66 | 72 | 78 | 84 | 90 | 96 | 102 | 108 | 114 | 120 |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Tk    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Wd    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NE34  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NE50  | R  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NE64  | R  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NW34  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NW50  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NW64  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| SE34  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| SE50  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| SE64  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| SW34  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
Figure 7 displays the outliers in track forecasting for the Atlantic Basin for the HNR2 configuration. The worst forecasts in the first two days of forecast are from Nicole, while Thomas is responsible for several outliers on days 3 and 4. Finally, the worst 5-day forecasts are from Fay.

Even though the largest track error outliers happened for Nicole, Thomas and Fay, those are not necessarily the worst storms on average. When the error is computed individually for each storm, the largest mean track errors are for Erika in which the error reached 300 nm in 48 h, Ida with 550 nm in 5 days, Matthew with 300 nm in 60 h, and Nicole with 400 nm in 42 h.

![Image](image.png)

**Figure 7.** Boxplots of mean track errors for the HNR2 (black) and HR20 (red) configurations. The median is the waist of the plot and the 95% confidence intervals are the notches. The bottom and top of the boxplots denote the 25 and 75% percentiles, respectively. Outliers are represented as circles. A star represents the mean.

The outliers for absolute intensity can be seen in Fig. 8. A large number of outliers is seen in general for the intensity forecasting, indicating that there is a strong variability in the forecast skill from run to run. The worst forecasts in the first two days are from Igor, while large outliers for Gustav, Ike, and Richard are seen later in the forecast period. The intensity MAE did not present a large variability between storms, that is, it was not possible to identify individual storms that had much worst absolute intensity forecast than the other storms.
Similarly to the results in the Atlantic basin, the track errors in the Eastern North Pacific basin increase linearly with time during the forecast period, from near zero at the initial time to approximately 200 nm for the 5-day forecast (Fig. 9). Therefore, the Pacific errors are smaller than the Atlantic ones, indicating that the forecast challenge is easier in the Pacific. Statistically significant differences in track error between HNR2 and HR20 appear at 48- and 60-h lead times, both favoring HR20, but in both cases with magnitude smaller than 3 nm (Fig. 10).
Figure 9. Mean track error (nm) for HNR2 (black) and HR20 (red) as a function of forecast lead time for all cases in the North Pacific basin. The 95% confidence intervals are also displayed. The sample size is listed above the graphic.

Figure 10. Median of the pairwise difference in track error (nm) between HNR2 and HR20 as a function of forecast lead time for all cases in the North Pacific basin. The 95% confidence intervals are also displayed. Positive (negative) values indicate HR20 (HNR2) superior performance. The sample size is listed above the graphic.
The mean absolute intensity error is also similar to the Atlantic basin, with errors increasing very rapidly in the first 6 h, then grows slowly until the third day of the forecast, becoming stable after that (Fig. 11). The mean intensity errors (Fig. 12) indicate that the error is near zero at the initial time, and grows sharply in the first six hour of forecast to develop a negative bias which remains throughout the entire forecast period. Statistically significant differences in storm intensity (Fig. 13) only occur at the 48- and 72-h forecasts, favoring HR20 and HNR2 respectively. The magnitude of the difference does not exceed 1 kt.

All SS differences between HNR2 and HR20 are summarized in Table 4. Numerous SS differences occur between HNR2 and HR20 in the radii of the various wind thresholds (Table 4), indicating that there might be a systematic difference in storm structure between the two configurations. However, the differences are of small magnitude when compared to the actual errors. All differences except one favor the HNR2 configuration, indicating that HNR2 produces a more compact storm than HR20.
Figure 12. Same as Fig. 6, but for intensity errors (kt).

Figure 13. Same as Fig 7 but for absolute intensity errors.
Figure 14 displays the outliers in track forecasting for the Eastern North Pacific Basin for the HNR2 configuration. The worst forecasts in the first two days of forecast are from Olaf, while Darby is responsible for several outliers on days 3 through 5.

When the errors are aggregated for individual storms, the largest mean track errors are for Olaf in which the error surpassed 250 nm in 48 h, Rick and Darby with more than 450 nm in 5 days, and Estelle, which reached 300 nm in 102 h.

The outliers for absolute intensity can be seen in Fig. 15. The worst forecasts in the first two days are from Rick, Celia, and Guillermo, while large outliers for Celia dominate later in the forecast period. When the MAE is computed separately for each storm, the worst intensity forecasts are for Rick, in which the error reaches 40 kt in 48 h, and for Celia, that surpasses 30 kt in the first day of day forecast (not shown).

Figure 14. Boxplots of mean track errors for the HNR2 (black) and HR20 (red) configurations for the Eastern North Pacific Basin. The median is the waist of the plot and the 95% confidence intervals are the notches. The bottom and top of the boxplots denote the 25 and 75% percentiles, respectively. Outliers are represented as circles. A star represents the mean.
Figure 15. Same as Fig. 14 but for the absolute intensity errors.
Table 4. Same as Table 3, except for the Eastern North Pacific basin.

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8. Discussion and Conclusions
This was the first extensive test of HWRF configurations conducted by the DTC, and it demonstrated the DTC's ability to efficiently conduct extensive HWRF experiments in an environment that is functionally equivalent to EMC's. The runs were very robust, however three crashes occurred. For storm Bill 03L of 2009, initialized at 08/23 at 06 UTC, copygb crashed at the 84-h and later lead times. At this time, Bill had undergone extratropical transition and had quickly moved north and east, placing the center of the nest far from the center of the parent grid projection. This is a known challenge for the copygb program, which we recommend be amended to better handle this situation. The second crash occurred for storm 11E, initialized at 09/04 at 12 UTC. The center of the storm at the time of initialization was over land and high topography, which caused the vortex initialization procedure to produce unrealistic results. It would be worth it to revise the vortex initialization procedure to better handle the vortex relocation and correction procedure over complex topography. Finally, the Gaston (09L of 2010) forecasts initialized at 09/07 at 18 UTC and 09/08 at 00 UTC did not run because the storm in the forecast initialized at 09/07 was too weak to be tracked and produce results to be used in the subsequent cycled start.

The forecast results indicate that the HNR2 configuration run by DTC produced similar results to the HR20 configuration run by EMC, with a minor number of SS differences in track and intensity. A larger number of SS differences between HNR2 and HR20 was found in the radii of the 34-, 50-, and 64-kt wind thresholds, mostly favoring the HNR2 configuration, indicating that there may be a systematic difference between the two configurations. However, given the small magnitude of the differences, exploring this issue was not given a high priority.

The main purpose of the test, the benchmarking of the HWRF community code, was achieved and the HWRF PS:85.98.88.88.88.2.4 RC, nicknamed HNR2, was created and results were published. This RC will serve as a baseline against which future RCs will be compared to assess the improvement of the HWRF model.

9. References


Acknowledgements
The Developmental Testbed Center is funded by the National Oceanic and Atmospheric Administration, Air Force Weather Agency and the National Center for Atmospheric Research. This work was supported by the NOAA Hurricane Forecast Improvement Project
Appendix A: Inventory

Table 3. Inventory for HNR2 Test. Columns on the table refer to the storm name, storm number, beginning and ending case (month, day and time UTC in format mmddhh), number of cases for which the NHCVx was run, and number of cases for which the NHC Vx contains valid data. Typically the first case of a storm was initialized as a cold start and subsequent cases are cycled. When the NHC storm message was missing during a storm, there was an interruption in the cycling, and a new cold start was done. This is indicated on the table by using multiple lines for a single storm.

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<td><strong>Total Pacific</strong></td>
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Appendix B: Archives

Output files

- Messages
  - domain_center
  - Tcvital
- geogrid output
  - geo_nmm*
  - namelist.wps
- real output
  - namelist.input
  - fort.65
  - wrfinput_d01
- WRF ghost output
  - ghost_d02_0000-00-00_00:00:00
- WRF analysis output
  - wrfanl_d02_yyyy-mm-dd_hh:00:00
- Vortex relocation output
  - wrfinput_d01
  - wrfghost_d02
- GSI output for parent and ghost domains
  - wrf_inout
  - ${SID}L.${yyyymmddhh}.gsi_cvs[1,2].biascr
  - logs
    - stdout
    - fort.201 through fort.215
- Ocean Initialization output
  - ocean_region_info.txt
  - getsst/mask.gfs.dat
  - getsst/sst.gfs.dat
  - getsst/lonlat.gfs
  - phase4/track
  - logs
    - getsst/getsst.out
    - phase3/phase3.out
    - phase4/phase4.out
- Coupled WRF-POM run input and output
  - RST.final
  - wrfinput_d01
  - wrfbdy_d01
  - wrfanl_d02
  - EL.*
  - GRADS.*
  - OHC.*
  - T.*
  - TXY.*
  - U.*
  - V.*
  - WTSW.*
  - rsl.*
- Postprocessing output
- WRFPRS*
  - Tracker output
    - Short track (12 h forecast) from forecasts at 3-h intervals
      - Combined domain
        - gvt_combined_12hr_3hrly_HNR2_$(SID)_(yyyymmddhh).txt
      - Parent domain
        - gvt_parent_12hr_3hrly_HNR2_$(SID)_(yyyymmddhh).txt
    - Long track (126h forecast) from forecasts at 6-h intervals
      - Combined domain
        - fort.64
    - Long track (126h forecast) from forecasts at 3-h intervals
      - Combined domain
        - gvt_parent_12hr_3hrly_HNR2_$(SID)_(yyyymmddhh).txt

- Graphics Output
  - hwrf_plots/$(SID)_(yyyymmddhh)/*gif

- Verification Output
  - nhc_HNR2_$(SID)_(yyyymmddhh).txt

- logs
  - All files
Appendix C: List of Acronyms

3D-Var – Three dimensional Variational Analysis
ATCF – Automated Tropical Cyclone Forecasting
BC – Boundary Conditions
DTC – developmental Testbed Center
EMC – Environmental Modeling Center
GFDL – Geophysical Fluid Dynamics Laboratory
GFS – Global Forecasting System
GSD – Global Systems Division (of NOAA Earth System Research Laboratory)
GSI – Global Statistical Interpolator
GRIB – Gridded binary data format
HNR2 – HWRF configuration used in this test (stands for HWRF njet R2 code)
HR20 – HWRF configuration similar to HNR2 used in a previous test
HWRF – Hurricane Weather Research and Forecasting
IC – Initial Conditions
MSLP – Mean Sea Level Pressure
MSS – Mass Storage System
NAM Post – North American Model Post-processor
NCEP – National Centers for Environmental Prediction
NHC – National Hurricane Center
NMM – Non-hydrostatic Mesoscale Model
NOAA – National Oceanic and Atmospheric Administration
POM – Princeton Ocean Model
Pre13d GFS – Retrospective runs made with GFS implemented operationally on June 29, 2010
RC – reference Configuration
SID – Storm Identification
WPP – WRF Post-Processor
WPS – WRF Preprocessing System
WRF – Weather Research and Forecasting
yyyymmddhh – Year, month, day and hour of forecast initialization