69 **THE VALUE OF A BASIN-SCALE DOMAIN TO IMPROVE TROPICAL CYCLONE TRACK FORECASTS IN HWRF**

Ghassan Alaka Jr.[1,2], Xuejin Zhang[1,2], Sundararaman G. Gopalakrishnan[2,*], Frank Marks Jr.[2]
[1]*Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, Florida*
[2]*NOAA/Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division, Miami, Florida*

1. INTRODUCTION

Tropical cyclone (TC) track forecasts are critical tools that help forecasters, emergency managers, and citizens prepare for potentially devastating landfall events. Model improvements, including improved data assimilation techniques and upgraded model physics (Torn and Davis 2012), have significantly reduced TC track errors in the last few decades, especially at shorter lead times (Rappaport et al. 2009). As a result, some research efforts have shifted to focus on the improvement of track forecasts at greater lead times (e.g., > 72h), which were in excess of 150 km in 2014 for Atlantic basin TCs (http://www.nhc.noaa.gov/verification/verify5.shtml). TC tracks are dominantly determined by the large-scale environment, especially wind fields (e.g., DeMaria and Kaplan 1994). Therefore, it is crucial to accurately simulate the large-scale environment in order to reduce track errors at lead times greater than three days. A byproduct of poor track forecasts is that the corresponding intensity forecasts are generally unreliable, given that the TC may be interacting with the wrong large-scale features altogether.

The effort to reduce TC track errors is one of the Hurricane Forecast Improvement Project (HFIP; Gall et al. 2013) goals, in addition to the broader mission of improving community comprehension of the fundamental and complex processes at work within a TC. One important aspect of HFIP is to improve TC forecasts made by the operational Hurricane Weather Research and Forecasting (HWRF) model, which is updated every year to reflect the latest research advances made by the HFIP community. The HWRF model has been a critical tool to help improve TC track forecasts. For example, Goldenberg et al. (2015) demonstrated improved track skill by adding a convection-permitting third nest in the 2012 operational HWRF. However, even as the efforts of HFIP collaborators are integrated into each new version of HWRF, broader shortcomings have been identified with the current system. These shortcomings must be addressed in order to continue reducing track and intensity errors and to meet HFIP goals.

One of the most significant limitations of the operational HWRF is its inability to simulate multiple TCs simultaneously with high-resolution inner nests. In addition to the one storm limitation, the operational HWRF features an outer domain that lacks the horizontal expanse to capture critical multi-scale interactions that influence TC tracks, especially in greater lead times. Currently, the location of the operational HWRF outer domain is determined by the initial location of the TC, such that the domain will capture the TC motion throughout its 120h forecasted trajectory. Unfortunately, the operational HWRF outer domain location differs from one forecast cycle to the next, which complicates analysis efforts. Additionally, this variable outer domain location sometimes results in the less than ideal placement of the model boundaries over topography or land-sea interfaces, which introduces errors that grow throughout an HWRF forecast. Therefore, a critical component of this study will be to address the sensitivity of HWRF track skill to the location of the outer domain.

In an effort to build a more robust operational HWRF system for the future, a parallel version of the HWRF model, called the basin-scale HWRF (Zhang et al. 2015b), has been developed in the Hurricane Research Division (HRD) at the Atlantic Oceanographic and Meteorological Laboratory (AOML). The basin-scale HWRF, which features a large domain that covers most of the Northeast Pacific and North Atlantic basins, is capable of including several moving nests (i.e., more than one TC). Therefore, the basin-scale HWRF addresses some of the shortcomings of the current operational HWRF configuration and is a valuable tool to test the importance of multi-storm and multi-scale interactions. Of particular importance to Atlantic and East Pacific TCs is the fact that the basin-scale HWRF domain includes most of the North American continent, which may reduce errors related to topography, land-atmosphere interactions, and the timing/amplitude of mid-latitude weather systems. The basin-scale HWRF could be especially beneficial at longer forecast lead times, when the TC is still incubated from boundary-induced errors consistent with a large outer domain.

* *Corresponding author address*: Dr. Sundararaman G. Gopalakrishnan, NOAA/AOML/Hurricane Research Division, 4301 Rickenbacker Causeway, Miami, FL 33149.
E-mail: sundararaman.g.gopalakrishnan@noaa.gov

The goal of this study is to compare the track skill of the 2013 basin-scale HWRF to the track skill of the operational HWRF versions from 2013, 2014, and 2015 in order to assess the value of a basin-scale domain. A case for the basin-scale HWRF is the argument that TCs interact with the large-scale atmosphere like a cork bobs in the flow of a river. In other words, the basin-scale HWRF captures more of the large-scale environment, which is a crucial to simulate accurate TC tracks (and, ultimately, TC intensity). Thus, we are primarily concerned with track skill in this study so that modeled TC intensity and inner core structure may be diagnosed in the correct environment.

Section 2 introduces the various HWRF model configurations investigated in this study and additional data used to supplement our analysis. In Section 3, track skill scores from the 2013 basin-scale HWRF are compared to those from the operational HWRF versions for several years in the Atlantic and East Pacific basins. Section 4 focuses on the sensitivity of HWRF track skill scores to the initial location of the TC, which is used as a proxy for the operational model outer grid location. In Section 5, the track of Hurricane Isaac is compared for the 2013 basin-scale HWRF and the 2015 operational HWRF for two different forecast cycles. In Section 6, the sensitivity of the 2015 operational HWRF to land surface models is analyzed in an effort to understand how important land-atmosphere interactions are to TC tracks. Finally, we summarize the results of this study in Section 7.

2. MODEL CONFIGURATIONS AND DATA

The HWRF system was developed at the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) to improve community understanding of TCs and has served as an operational track and intensity guidance tool since 2007 (Gopalakrishnan et al. 2012). A version of this evolving system is available at the Developmental Testbed Center (DTC) of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, which maintains a version of the HWRF system and the corresponding scientific documentation (Gopalakrishnan et al. 2010). All models described here are a particular version of the HWRF system. While some similarities exist between all versions, such as the use of Global Forecast System (GFS) boundary conditions, there are important distinctions between the HWRF versions used in this study (Table 1).

The versions of the operational HWRF used in this study are: the 2013 operational HWRF (H213), the 2014 operational HWRF (H214), and the 2015 operational HWRF (H215). Several features of the operational HWRF system are consistent in H213, H214, and H215. The operational HWRF is a triply-nested system with a parent outer domain that spans about 80° in both the latitude and longitude directions. Two inner nests, which are much smaller than the outer domain, are centered over the TC of interest to better resolve its inner core and associated mesoscale features. The operational HWRF system has ocean coupling for the outer two domains, with downscaling in the innermost domain. All versions of the operational HWRF system used in this study include data assimilation. In addition, the planetary boundary layer (PBL) and convection schemes have not changed since 2013. The PBL scheme is a modified version from the Global Forecast System (GFS), used in all model domains (Hong and Pan 1996). Convection is simulated by a Simplified Arakawa-Schubert (SAS; Pan and Wu 1995) scheme for the two outermost domains. The SAS scheme is turned off for the innermost domain, where clouds may be explicitly resolved.

Upgrades to the operational HWRF versions are highlighted in red in the last three columns of Table 1. H213 is the most basic of these versions, with relatively coarse horizontal and vertical resolutions in addition to older physics packages. In 2014, the vertical dimension of H214 was modified so that the model top was raised from 50 hPa to 2 hPa and the vertical levels were increased from 42 to 61. The physics and horizontal resolution were unchanged in H214. In 2015, both the physics and horizontal resolution were upgraded in H215. In particular, the horizontal resolution increased from a 27:9:3 km setup, for each domain, respectively, in 2014 to 18:6:2 km in 2015. Additionally, four physics packages were upgraded in H215: microphysics, radiation, surface layer, and land surface model. The microphysics package was upgraded from a modified Ferrier scheme (Ferrier et al. 2002) to a modified Ferrier-Aligo scheme (Aligo et al. 2014). The shortwave and longwave radiation packages were upgraded from GFDL schemes to RRTMG (Iacono et al. 2008). The surface layer package was upgraded from a GFDL scheme to a modified version of that scheme. Finally, the land surface model was upgraded from a GFDL slab scheme to the National Centers for Environmental Prediction–Oregon State University–Air Force–Hydrologic Research Laboratory (Noah) land surface model (Ek et al. 2003). Also noteworthy is the fact that data assimilation schemes have been upgraded in each version since H213, as well. Developments have taken data assimilation from the Gridpoint Statistical Interpolation (GSI; Wu et al. 2002) system in 2013 to a more robust hybrid method in 2014. In 2015, the hybrid data assimilation method was maintained and an HWRF data assimilation ensemble for tail Doppler radar (TDR) from HRD aircraft missions was implemented.

The 2013 basin-scale HWRF (H3HW; Zhang et al. 2015b) is a simpler version of the operational HWRF system, with no data assimilation or ocean coupling. However, H3HW has two important distinctions from the operational HWRF versions: 1) a larger outer domain and 2) multi-storm capability. Here, we focus on the value provided by this larger outer domain. The outer domain of the basin-scale HWRF spans almost 180° in longitude and covers close to a quarter of the globe. Unlike in the operational HWRF, the outer domain in H3HW is static from one forecast cycle to the next, which translates into the same outer domain being available for analysis. In terms of the vertical dimension, H3HW is on par with H214 and H215, with 61 vertical levels and a model top of 2 hPa. In fact, H3HW was the first version of HWRF to increase the vertical resolution and motivated the implementation of these settings in H214 and H215. The physics packages in H3HW are exactly the same as for H213 and H214.

The 2015 basin-scale HWRF (H5HW), the next-generation version of H3HW that is nearly ready for implementation, will feature the same physics as H215 (see Table 1) and similar ocean coupling. Thus, H5HW and H215 will differ only in horizontal resolution, data assimilation, outer domain size, and multi-storm capability. Future work will also isolate each aforementioned model aspect in sensitivity tests to see which is responsible for the biggest difference between H5HW and H215. None of the results in this study are from H5HW.

Data from the Global Forecast System (GFS) Analysis (http://www.emc.ncep.noaa.gov/GFS/doc.php) is incorporated to represent a best guess of concurrent observations at all model valid times. The GFS Analysis has a horizontal grid spacing of 0.5°, which is coarser than all versions of the HWRF used in this study. This data will aid in the analysis of large-scale errors in the outer domain model output. The National Hurricane Center (NHC) best track is used as the "true" TC location in this study to assess track errors from the HWRF versions included in this study. Track skill scores are computed by comparing HWRF track errors with track errors from the CLIPER5 model (CLP5; Aberson 1998).

3. BASIN-SCALE HWRF VERIFICATION

Verification is a statistical tool that evaluates the quality of model forecasts by identifying systematic flaws in vital TC characteristics (e.g., track and intensity). Verifications are a crucial component in the evaluation of TC structures, track, and intensity in the operational HWRF model as the system is upgraded (e.g., Aberson et al. 2015; Chen and Gopalakrishnan 2015; Goldenberg et al. 2015; Zhang et al. 2015a). Such evaluations are vital to understand if upgrades are, in fact, improving the HWRF modeling system.

The first step of this analysis is to prove the quality of H3HW track forecasts by directly comparing track skill scores from this version of the model to track skill scores from operational HWRF versions. In particular, the 2013, 2014 and 2015 operational HWRF models are scrutinized here (H213, H214, and H215, respectively). In all cases, track skill scores are computed against CLP5 (see Section 2). Retrospective forecasts allow for evaluation of each HWRF version for all Atlantic and East Pacific TCs from 2011-2013. In this verification, we stratify by ocean basin, in acknowledgement of the vastly different environments that the two basins offer. As evidence of this basin difference, track skill scores are higher in the Atlantic (Fig. 1a) than in the East Pacific (Fig. 1b). It is immediately obvious that H3HW produces more skillful tracks than H213 (Fig. 1), which highlights the importance of the increased vertical levels and model top (see Table 1). Despite H3HW not including data assimilation or ocean coupling, as all of the operational versions do, the basin-scale version is better than or competitive with all three operational HWRF versions. Although the track skill improves in subsequent versions of the operational HWRF (e.g., H214 and H215), likely due to improvements to the model physics, data assimilation, ocean coupling, and resolution (see Table 1), H3HW remains competitive with (or better than) these versions at most forecast lead times.

This verification motivates the need to understand why H3HW is competitive or better than the operational HWRF versions. One potential reason that H3HW track skill scores are competitive with those from H214 and H215 is the importance of vertical resolution (all three have 61 levels and a model top of 2 hPa). Another potential reason is that the benefits of multi-scale interactions in the larger H3HW outer domain help to offset upgrades in H214 and H215. In the next section, we investigate the sensitivity of track skill to the location of the operational HWRF outer domain, with the initial TC location used as a proxy.

4. TRACK SKILL SENSITIVITY TO TC INITIAL LOCATION

When running the operational HWRF, a TC is initialized near the center of the outer domain so that the TC motion is optimally captured (Gopalakrishnan et al. 2010). Therefore, the operational HWRF outer domain is not static from one forecast cycle to the next. Occasionally, the operational HWRF outer domain is situated so that critical errors may be introduced into the simulation through the boundaries, such as topography and land-sea interfaces. We hypothesize that the placement of the operational HWRF outer domain is especially problematic for TCs initialized in the West Atlantic Ocean and Caribbean Sea, which are critical regions for diagnosing potential landfall threats to the United States. In these cases, the northern and/or western boundaries of the outer domain often reside near the Rocky Mountains. It is important to note that the basin-scale HWRF does not have this topography-driven problem, with a large, static outer domain that covers the Northeast Pacific Ocean, North America, and the North Atlantic.

Given the potential problems encountered by the location of the operational HWRF outer domain, we test the sensitivity of HWRF track skill to the initial (0hr) TC location, which is used as a proxy for the outer domain location. By dissecting the Atlantic basin into 10°x10° boxes, track skill scores from H3HW are compared with the three versions of the operational HWRF in each respective box. These results are sensitive to the box size, since smaller regions result in too few cases to have confidence in the results and larger regions fail to capture critical differences between different sub-regions within the Atlantic basin. For 24h forecasts, H3HW tracks are up to 80% more skillful than CLP5 (Fig. 2a). Overall, H3HW is skillful for TC tracks over the entire Atlantic basin for 24h forecasts. When compared to the operational HWRF versions (Fig. 2b-d), H3HW outperforms these models in the East Atlantic. It is interesting to note that each successive operational HWRF version performs a little better than the last, which gives confidence that operational HWRF upgrades are adding skill to TC tracks (see Section 3). It is not entirely clear why H3HW performs so well in the East Atlantic for small forecast lead times (e.g., Fig. 2), but one reason could be the influence of higher latitude features that are better captured in the basin-scale HWRF outer domain.

For 120h forecasts, the picture is much different (Fig. 3). For one, H3HW track skill scores and the number of cases (Fig. 3a) are lower for 120h than for 24h, as expected. When comparing H3HW to the operational HWRF versions (Fig. 3b-d), the basin-scale HWRF is more skillful in the West Atlantic and Caribbean Sea. Given the proximity of TCs in the West Atlantic and Caribbean Sea to the U.S. coastline, the improvement of track skill is especially important to in these regions would greatly benefit society. As we mention earlier in this section, model initialization in these regions often results in the boundaries of the operational HWRF outer domain being located near the Rocky Mountains. This boundary location introduces errors into the model domain, likely from vertical coordinate interpolations from GFS fields. By 120h into the forecast, these boundary-induced errors have grown to the synoptic scale and have propagated through the operational model outer domain. However, for 24h forecasts, boundary-induced errors are not expected to have a significant impact on track skill. H5HW, the next version of the basin-scale HWRF, will be a vital tool to test the robustness of this location-based sensitivity analyzed here.

5. ISAAC (AL092012) CASE STUDIES

Given the multi-season statistics analyzed in Sections 3 and 4, a specific case is chosen for further study into the value of the basin-scale HWRF. Hurricane Isaac, the ninth Atlantic TC in 2012, is a particularly interesting case, with false alarms of various types that perplexed forecasters. For one, the operational HWRF erroneously forecasted a rapid intensification when Isaac entered the Gulf of Mexico. No such rapid intensification occurred and is a focal point of current research. For example, Jaimes and Shay (2015) found that wind-driven downwelling impacted the ocean heat content available to Isaac as it tracked though the Gulf of Mexico, which may have been a factor in the delayed intensification that Isaac exhibited. In addition, the operational HWRF continually tracked Isaac to the east of Florida when the TC was initialized in the Caribbean Sea, when the TC actually made landfall in Louisiana. As mentioned in Section 1, a primary goal of this study is to prove the value of the basin-scale HWRF in producing more skillful track forecasts. After all, TC intensities are very sensitive to the large-scale environment, so the track errors must be reduced in order to properly address intensity errors.

Overall, H3HW produces consistently better tracks than H215 for Hurricane Isaac (Fig. 4). For example, H215 forecasted Isaac to erroneously move east of Florida for several successive cycles before adjusting to a more correct westward track (Fig. 4a). On the other hand, H3HW forecasted a westward track for many more forecast cycles, although it does have a small westward bias at landfall (Fig. 4b). To understand why H215 has such large track errors relative to H3HW, two forecasts cycles, one with large H215 track errors and the other with relatively small H215 track errors, are analyzed in further detail below: a) 12Z, 24 August 2012 and b) 12Z, 26 August 2012. Note that these forecast cycles are both initiated at 12Z, which eliminates any sensitivity to the diurnal cycle.

5.1 *Isaac – 12Z, 24 August 2012*

For the 12Z, 24 August 2012 forecast cycle, Isaac was initialized in the Caribbean Sea near 10°N, 70°W. Throughout the first 48h of the forecast, H3HW and H215 produce tracks that are very consistent with the NHC best track. After 48h, however, H3HW and H215 simulate very different tracks for Isaac. H3HW continues to track Isaac to the west-northwest, consistent with the best track. On the other hand, H215 turns Isaac sharply to the north and propagates the TC east of Florida, which produces track errors greater than 1000 km by the end of the forecast period. The obvious question here is: why does H3HW produce a good track forecast while H215 produces a poor track forecast?

For one, errors to the trough by the U.S. East Coast result in a dramatically different track for Isaac in H215. Fig. 5b shows that the trough is too strong and the central U.S. ridge is too weak at 48h in H215 when compared with the GFS Analysis. Although Isaac interacted with the trough in reality, the central U.S. ridge was the main steering flow for this TC. However, in H215, Isaac interacts too strongly with the trough, is not steered by the central U.S. ridge, and moves east of Florida as a result. Note that Isaac moves just to the east of the negative 200 hPa geopotential height errors, which approach -100 m, between 48h and 72h (Fig. 6b,d,e), which highlights the dominance of the East Coast trough in the steering flow near Isaac in H215. On the other hand, 500 hPa and 200 hPa geopotential heights show that H3HW does a much better job at handling the strength and position of the ridge and the trough to the north of Isaac (Figs. 5a, 6a,c,e). The western and northern boundary of the H215 outer domain, which resides near the Rocky Mountains, may be a crucial error source for this case. We hypothesize that small-scale errors grow from the model boundary and play a role in large-scale errors 2-3 days into the model forecast. Recent research showed that small amplitude errors on large scales have similar negative impacts as large amplitude errors on small scales (Durran and Gingrich 2014). Therefore, small-amplitude errors in the large-scale flow near the Rocky Mountains may be as important as small-scale errors in the same region. In the interest of disclosure, we have included the full outer domains for both H3HW and H215 to emphasize the difference in area-coverage between the two.

Although errors to the trough-ridge over the continental U.S. pattern are significant factors to the track of Isaac, TC propagation speed is also important. In the H3HW forecast, the forward speed of Isaac is very close to that analyzed in the NHC best track. However, in the H215 forecast, Isaac is much slower and lags behind the NHC best track by ~200 km by 48h. This slower forward speed in H215 may also be a factor in the erroneous Isaac-trough interaction, since the TC is not far enough West to be influenced by the ridge steering, as observed in H3HW and the GFS Analysis.

Concurrent research into other problematic TC track forecasts in this region is ongoing to understand how the robustness of large TC track errors in H215 for TCs initiated in the West Atlantic and Caribbean Sea. For example, H215 exhibited similarly poor track forecasts for Hurricane Ernesto (2012). When Ernesto was initialized in the western Caribbean Sea, H215 forecasted the system to turn to the north and hit the U.S. Gulf Coast (not shown). In reality, Ernesto traversed the Yucatan Peninsula and never turned to the north.

5.2 *Isaac – 12Z, 26 August 2012*

If H215 is initialized two days later (12Z, 26 August 2012), the track forecast for Isaac is much more accurate. At first glance, the operational HWRF outer domain western boundary is situated over the Northeast Pacific Ocean for this forecast cycle (Fig. 7b) and flow over the Rocky Mountains is now well-captured within the H215 domain. At 48h, 200 hPa geopotential height errors are less than half for this case than they were for the 12Z, 24 August 2015 cycle (Fig. 7b). As a result, Isaac correctly tracks to the west-northwest instead of being misdirected to the north, as was the case in prior forecast cycles. In addition, the forward speed of Isaac is more accurate in this case for H215, which allows Isaac to move under the steering of the central U.S. ridge rather than being steered by the trough near the U.S. East Coast. Noteworthy, H3HW produces even smaller 200hPa geopotential height errors across the continental U.S., yet exhibits a curious westward bias at landfall, which suggests that upper-tropospheric heights are not the only influence in TC steering. The reason for this westward bias in H3HW is not well understood at this time and may be investigated in a future study.

6. SENSITIVITY TO LAND SURFACE MODELS

One of the primary upgrades in H215 is the inclusion of the Noah LSM, which replaces the simple GFDL slab scheme. However, it is unclear how big of an improvement, if any, this LSM upgrade will make to track errors. Upper-tropospheric geopotential height errors in the Southeast U.S. may be associated with latent heating errors in association with deep convection, which would amplify the trough-ridge pattern. Due to the difference in how the Noah and GFDL schemes handle surface temperature and moisture, latent heating might be represented differently by the two schemes. We reran the 12Z, 24 August 2015 cycle with the GFDL slab scheme to test the sensitivity of TC track to the LSM. If the Noah LSM is in fact adding value to track skill for this particular case, then degrading to the GFDL slab scheme should result in an even worse track.

The tracks for H215 and the GFDL sensitivity test (H15G) are compared to the NHC best track in Fig. 8. The sensitivity of TC track to the LSM is very weak in this particular case. In both versions, the trough is still too strong and Isaac continues to track East of Florida, which results in only minor differences to the track between H215 and H15G. This result suggests that the geopotential height errors observed in Section 5a are not sensitive to land-atmosphere interactions. We also reran the 12Z, 26 August 2015 forecast cycle, for which the H215 produces a realistic track forecast. The tracks were very similar between H215 and H15G in that case, as well (not shown). Of course, in order to completely understand the sensitivity of HWRF tracks to LSMs, we plan to test several seasons of H5HW with both the GFDL slab scheme and the Noah LSM to assess the value added to track and intensity forecasts for dozens of TCs. However, for these Isaac cases, our immediate conclusion is that TC track does not appear to be sensitive to LSM.

7. CONCLUSIONS

H3HW is a parallel version of the operational HWRF aimed at reducing track errors for TC forecasts. One of the main differences between the H3HW and operational HWRF versions (e.g., H213, H214, and H215) is the inclusion of a basin-scale outer domain that spans from the central Pacific Ocean to East of the Greenwich Meridian. By improving the simulation of multi-scale interactions, H3HW provides a more realistic large-scale environment that leads to smaller TC track errors. Therefore, the primary focus of this study was to assess the value added by an outer domain that covers close to a quarter of the globe.

Our conclusions about the value of the basin-scale domain in H3HW may be summarized as follows:

- For all TCs from 2011-2013, H3HW track skill scores are better than H213 track skill scores and are at least competitive with H214 and H215 track skill scores. Overall, H3HW is more skillful for TC tracks in the Atlantic basin than in the East Pacific basin.
- Track skill scores for the operational HWRF versions (H213, H214, H215) are sensitive to the outer domain location. For 120h forecasts from 2011-2013, all operational HWRF versions have lower track skill than H3HW in the West Atlantic and Caribbean Sea. This is a critical region for TC track forecasts given the proximity to land, including the U.S. Gulf Coast and U.S. East Coast.
- When TCs are initialized in the West Atlantic and Caribbean Sea, the northern and western boundaries of the operational HWRF outer domain are located over the Rocky Mountains, which may introduce small-scale errors during the interpolation from the GFS vertical coordinate and resolution to the HWRF vertical coordinate and resolution.
- These boundary-induced errors can grow to the synoptic scale and impact the trough-ridge pattern over the United States by 48h into the forecast. Even small errors to the amplitude and location of mid-latitude troughs and ridges appear to have large consequences on the steering flow and, ultimately, TC tracks.
- TC propagation speed also appears to be an important factor in how a TC interacts with the large-scale environment. For example, in the 12Z, 24 August 2012 forecast cycle for Isaac, H215 simulated Isaac with a slower forward speed, which increased the interaction of this TC with a U.S. East Coast trough and factored into an erroneous turn to the North. It is unclear why Isaac moves noticeably slower in H215 than in the NHC best track.
- If the Rocky Mountains are included within the operational HWRF outer domain, such as when a TC is initialized in the Gulf of Mexico, tracks seem to improve, as in the 12Z, 26 August 2012 forecast cycle for Isaac. However, more cases are needed to solidify this finding.
- The weak sensitivity of H215 to LSMs (e.g., GFDL slab and Noah) supports the notion that land-atmosphere interactions are not vital to the large-scale environment simulated by the model outer domain. However, the basin-scale HWRF may exhibit more sensitivity to LSM given the multi-scale interactions captured within the large outer domain, which is an area of future research.

We have demonstrated that the basin-scale domain improves track forecasts, especially in the West Atlantic and Caribbean Sea, where TC forecasts are critical given the proximity of these regions to land. With the 2015 basin-scale HWRF on the horizon, future research will continue to focus on value of the basin-scale domain and if this model configuration can keep pace with the advances made in subsequent operational versions of HWRF.

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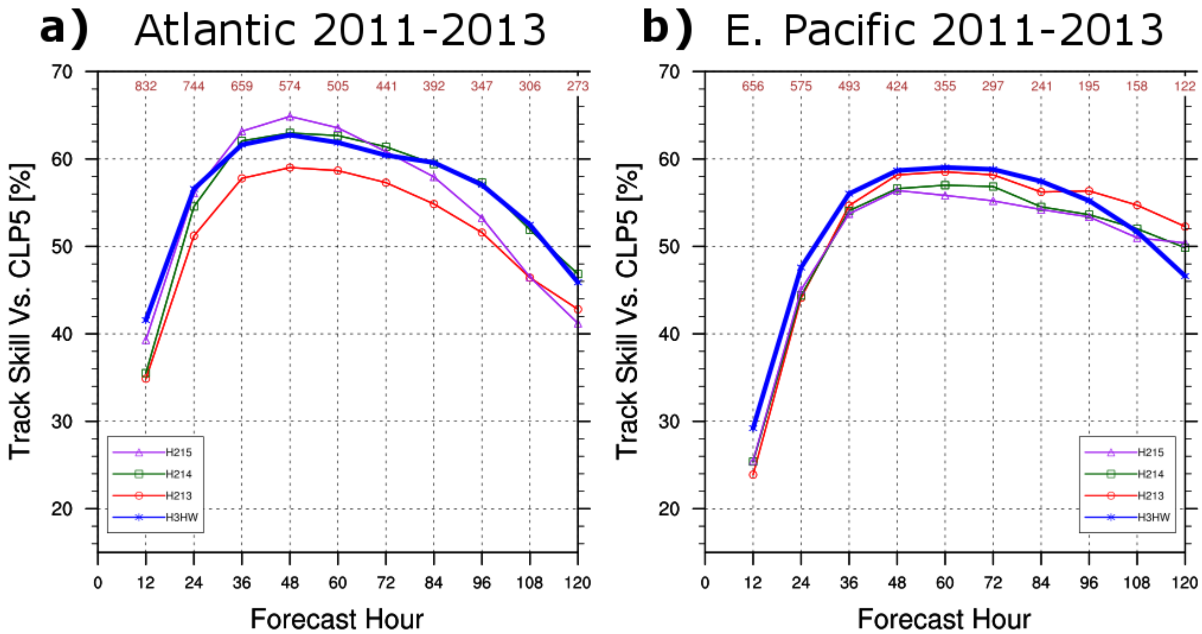

Fig. 1. Track skill scores for various HWRF models versus the CLIPER5 (CLP5) model for a) the Atlantic basin and b) the East Pacific basin. Data includes all tropical cyclones from 2011-2013 in each basin. HWRF models include: 2015 Operational HWRF (H215; purple-triangle), 2014 Operational HWRF (H214; green-square), 2013 Operational HWRF (H213; red-circle), and the 2013 Basin-Scale HWRF (H3HW; blue-asterisk).

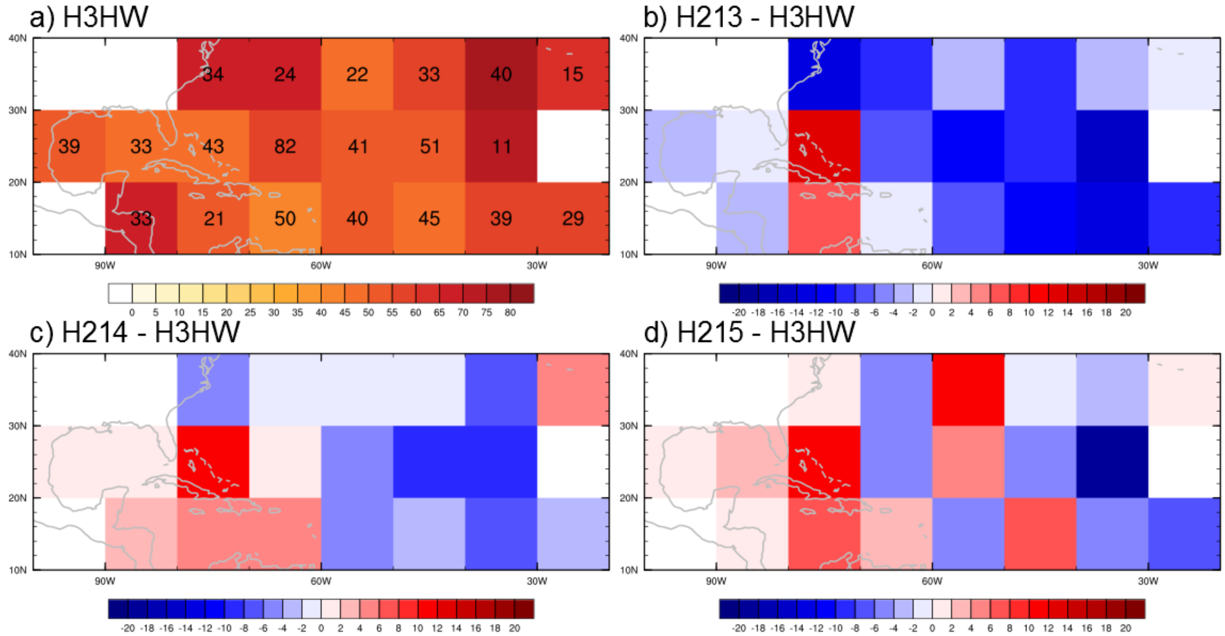

Fig. 2. a) 24-hour track skill scores for the 2013 basin-scale HWRF (H3HW). 24h track skill score differences between b) H213, c) H214, and d) H215 and H3HW. The number of cases used to calculate skill scores in each box are given in a). All track skill scores are percentages calculated by comparison to the CLIPER5 model.

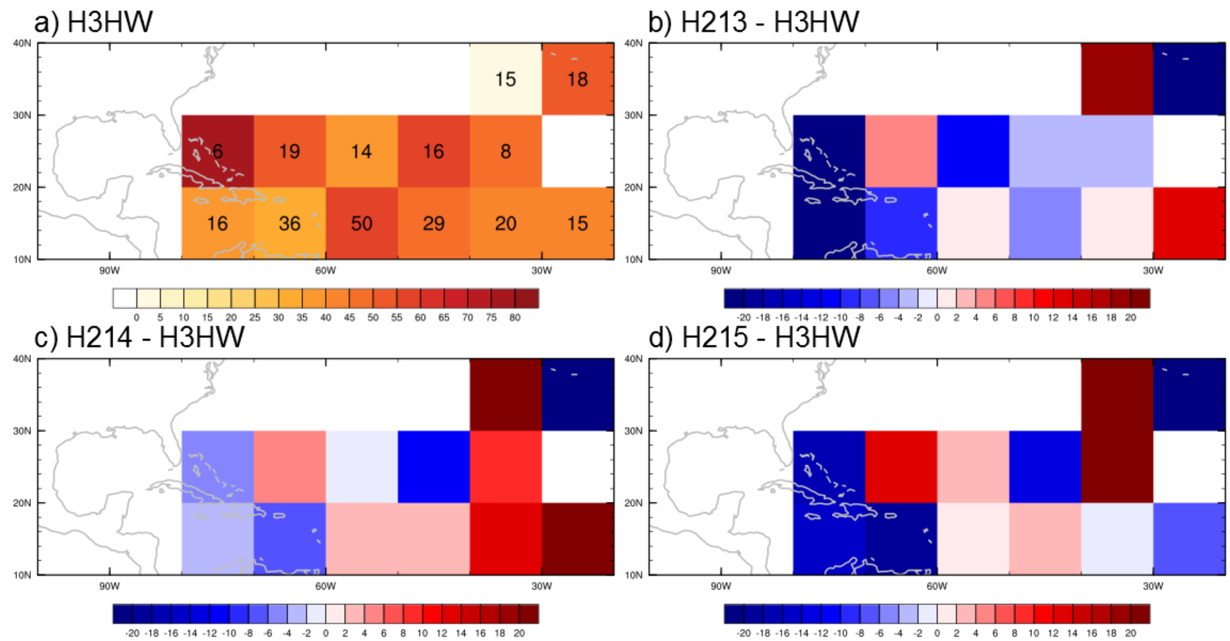

Fig. 3. As in Fig. 2, except for 120h forecasts.

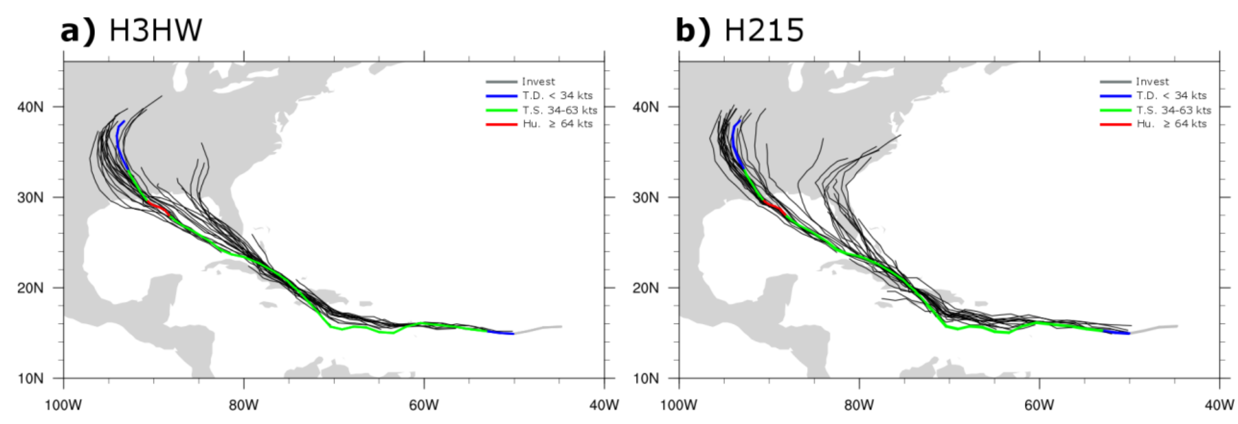

Fig. 4. The best track (multi-colored line) and all forecast tracks (black lines) of Isaac (AL092012) from a) the 2013 basin-scale HWRF and b) the 2015 operational HWRF. The best track is color-coded based in NHC status: gray for invest, blue for tropical depression, green for tropical storm, and red for hurricane.

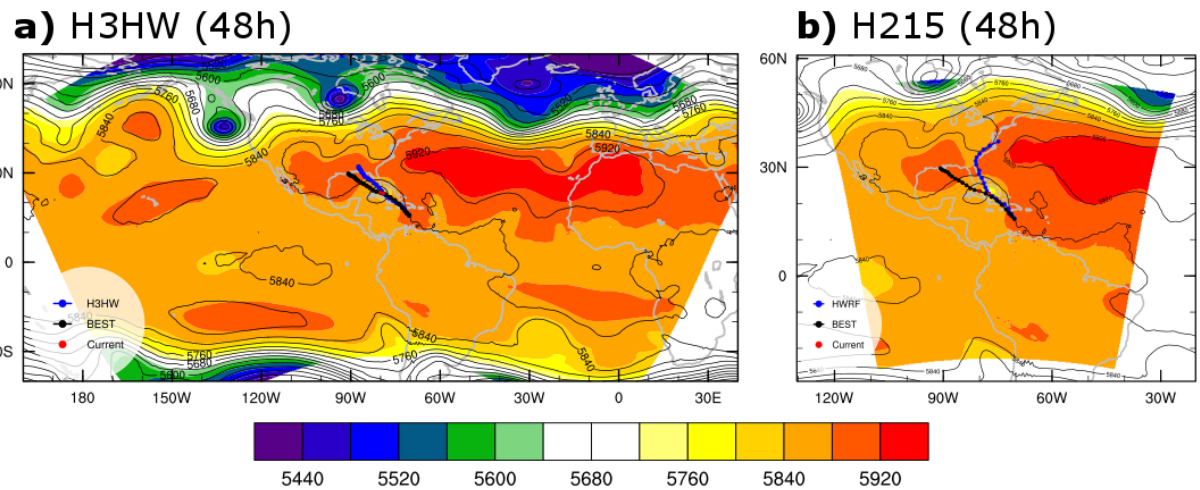

Fig. 5. Shaded fields represent 48h model forecasted 500 hPa geopotential height, shown for a) the 2013 basin-scale HWRF and b) the 2015 operational HWRF. Contoured fields represent the GFS Analysis 500 hPa geopotential heights at the valid time (18Z, 26 August 2012). Both shaded and contoured fields range from 5440-5920 m, with an interval of 40 m. The black dotted-line represents the Best Track for Isaac, while the blue dotted-line represents the corresponding model track. The red dot represents the current location for all tracks.

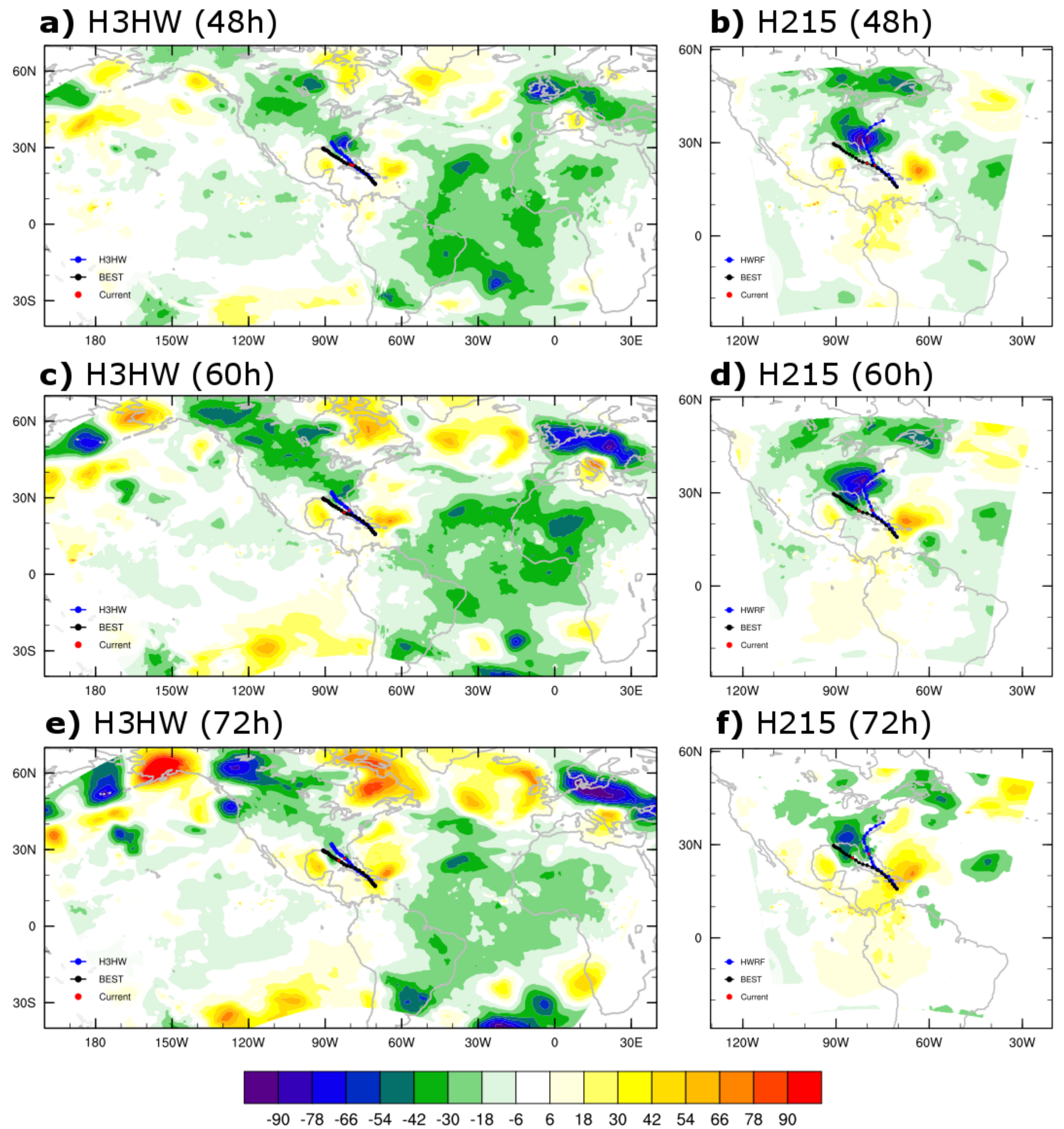

Fig. 6. The difference between model forecasted 200 hPa geopotential height and GFS Analysis 200 hPa geopotential heights at the corresponding valid time. The models are initialized at 12Z, 24 August 2012. Model fields shown are as follows: a), c), e) the 2013 basin-scale HWRF and b), d), f) the 2015 operational HWRF. Model forecast fields are shown for: a-b) 48h, c-d) 60h, e-f) 72h. Height differences range from -90 to 90 m, with an interval of 12 m. The black dotted-line represents the Best Track for Isaac, while the blue dotted-line represents the corresponding model track. The red dot represents the current location for all tracks.

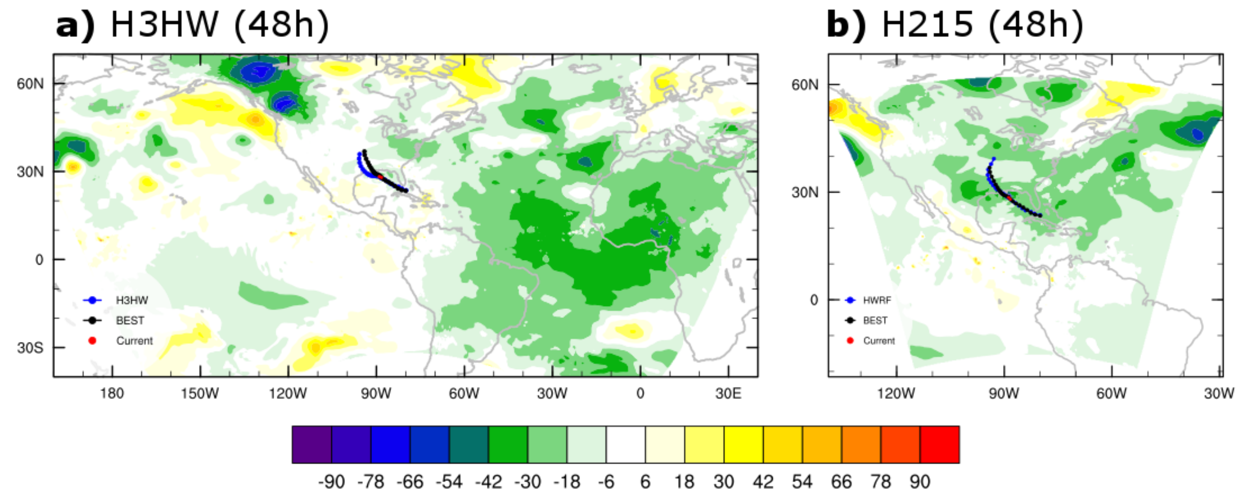

Fig. 7. The difference between 48h model forecasted 200 hPa geopotential height and GFS Analysis 200 hPa geopotential heights at the corresponding valid time. The models are initialized at 12Z, 26 August 2012. Model fields shown are as follows: a) the 2013 basin-scale HWRF and b) the 2015 operational HWRF. Height differences range from -90 to 90 m, with an interval of 12 m. The black dotted-line represents the Best Track for Isaac, while the blue dotted-line represents the corresponding model track. The red dot represents the current location for all tracks.

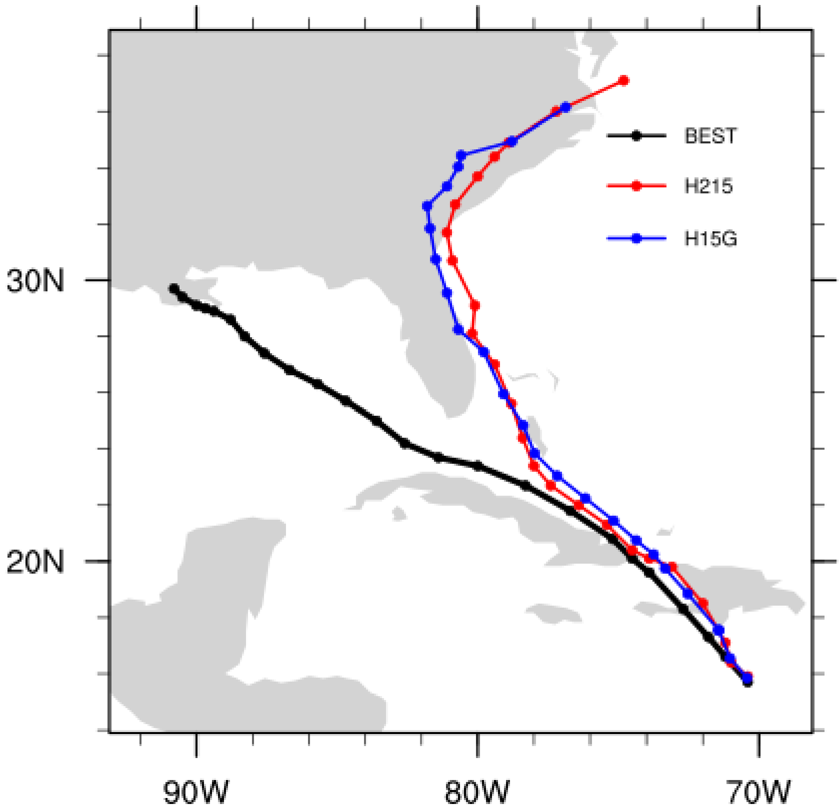

Fig. 8. Isaac track for the Best Track (black), H215 (red), and H15G (blue). The two model tracks are from a forecast cycle initiated at 12Z, 24 August 2012.

	2013 Basin-Scale HWRF	2013 Operational HWRF	2014 Operational HWRF	2015 Operational HWRF
Domain	27 KM: 178.2° × 77.6° 9 KM: 10.6° × 10.2° 3 KM: 6.1° × 5.4°	27 KM: 77.6° × 77.6° 9 KM: 11.0° × 10.0° 3 KM: 7.2° × 6.5°	27 KM: 77.6° × 77.6° 9 KM: 12.0° × 12.0° 3 KM: 7.1° × 7.1°	18 KM: 77.6° × 77.6° 6 KM: 12.7° × 12.2° 2 KM: 7.9° × 7.1°
Model top	2 hPa	50 hPa	2 hPa	2 hPa
Vertical levels	61	42	61	61
Vortex initialization	at 3 km	at 3 km	at 3 km	at 2 km
Data assimilation	No GSI DA	GSI DA	Hybrid DA	Hybrid DA HWRF ensemble DA (TDR)
Ocean coupling	No coupling	27-9 KM: Yes 3 KM: Downscaled	27-9 KM: Yes 3 KM: Downscaled	18-6 KM: Yes 2 KM: Downscaled
Multi-Storm	Yes	No	No	No
Physics Scheme				
Microphysics	Modified Ferrier (High Resolution)	Modified Ferrier (High Resolution)	Modified Ferrier (High Resolution)	Modified Ferrier-Aligo (High Resolution)
Radiation	GFDL	GFDL	GFDL	RRTMG
Surface	GFDL	GFDL	GFDL	Modified GFDL
PBL	Modified GFS	Modified GFS	Modified GFS	Modified GFS
Convection	SAS, No CP (3 KM), Shallow Convection	SAS, No CP (3 KM), Shallow Convection	SAS, No CP (3 KM), Shallow Convection	SAS, No CP (2 KM), Shallow Convection
Land surface	GFDL Slab	GFDL Slab	GFDL Slab	NOAH LSM

Table 1. Configuration and physics schemes for the four HWRF versions analyzed in this study. In general, newer versions are to the right. Red text signifies an upgrade from the previous version.