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Advances in Tropical Cyclone Intensity Forecasts

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Abstract

NOAA established the 10 year Hurricane Forecast Improvement Project (HFIP) to accelerate the improvement of forecasts and warnings of tropical cyclones and to enhance mitigation and preparedness by increased confidence in those forecasts. Specific goals include reducing track and intensity errors by 20% in 5 years and 50% in ten years and extending the useful range of hurricane forecasts to 7 days. Under HFIP, there have been significant improvements to NOAA's operational hurricane prediction model resulting in increased accuracy in the numerical guidance for tropical cyclone intensity predictions. This paper documents many of the improvements that have been accomplished over the last 5 years, as well as some future research directions that are being pursued.

Keywords: Hurricane, Hurricane Forecast Improvement Program (HFIP), Hurricane Weather Research and Forecasting Model (HWRF).

1. Introduction

Each year hurricanes, typhoons, and other tropical cyclones (TC) cause extensive damage and loss of life throughout the world. Severe examples include the TC that killed more than 300,000 people in Bangladesh in 1970; the Galveston, Texas hurricane of 1900, which destroyed the city and killed between 6000-8000 people; Hurricane Andrew (1992), which caused monetary losses of 26.5 billion dollars; and Hurricane Katrina (2005), which killed more than 1300 people and resulted in losses in excess of 100 billion dollars. Even storms of much lesser intensity can produce significant loss of life and property, presenting a daunting challenge for hurricane forecasters and the communities they serve.

The reduction of losses related to hurricanes involves many complex aspects, ranging from purely theoretical, observational, computational, and numerical, to operational and decision-making. A correct warning can lead to an appropriately scaled and timed evacuation and damage mitigation, producing immense benefits. However, over-warning can lead to substantial unnecessary costs, a reduction of confidence in warnings, and a lack of appropriate response. Therefore, accurate forecasts of hurricane track and intensity are of great importance.

TC forecasting methods have evolved considerably. The earliest methods were primarily subjective and were limited to forecasting the motion of TCs. Initially, these methods were based on local observations of high level cloud and ocean swell movements, and later were based on the application of steering patterns on synoptic charts. The past decades have been marked by significant advances in dynamical models such as the National Oceanic and Atmospheric Administration's (NOAA) Global Forecast System (GFS), the US Navy Operational Global

Atmospheric Prediction System (NOGAPS), the European Centre for Medium-Range Weather Forecasts (ECMWF) model, and the Met Office model (UKMET). Such advances have contributed greatly to a steady improvement in the official TC track forecasts issued by the NOAA/National Weather Service's (NWS) National Hurricane Center (NHC), resulting in a substantial reduction in track forecast errors (Gopalakrishnan et al., 2012). This, in turn, has reduced warning and evacuation areas, thereby saving lives and resources (Rappaport et al., 2009).

Forecasting intensity changes is also extremely important, especially in the case of storms that rapidly intensify or weaken just prior to landfall (e.g., TCs Charley, 2004; Katrina and Wilma, 2005; Humberto, 2007; Karl, 2010). However, forecasting intensity changes in TCs is a complex and challenging multiscale problem. Since the 1950s, both statistical and dynamical methods have been adopted to tackle this problem (Anthes, 1982). For instance, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) is a sophisticated statistical model that predicts storm intensity using multiple regression relationships with climatological, persistence, and GFS model predictors (DeMaria and Kaplan, 1999; DeMaria et al., 2005). DSHIPS (Decay-SHIPS) is SHIPS adjusted for the decay of storms when they move inland, according to DeMaria et al. (2006), and is regarded by the forecasters as one of the most reliable intensity forecast models (Franklin, 2010).

During the past three years, significant progress has been made in TC track, intensity, and structure forecasts with support from NOAA's Hurricane Forecast Improvement Project (HFIP, Gall et al., 2013). In particular, for the first time, a very high-resolution (3 km) deterministic numerical weather prediction (NWP) model, known as the Hurricane Weather Research and

Forecast (HWRF) modeling system, has shown comparable and, at times, superior TC intensity forecast skill compared to the best performing statistical models.

HWRF was jointly developed by NOAA's Environmental Modeling Center (EMC) and Hurricane Research Division (HRD) and implemented at the National Centers for Environmental Prediction (NCEP). The HWRF model is now paving the way to improve operational TC intensity forecasts, which have had virtually no improvement in skill for the last two decades. This paper summarizes recent advances in hurricane modeling at NOAA, in collaboration with academic and international partners, which has provided improved operational numerical forecast guidance on TC track, intensity, and structure to the forecasters at NHC, the Central Pacific Hurricane Center (CPHC), and the US Navy and Air Force Joint Typhoon Warning Center (JTWC). Future development activities are also discussed.

2. NOAA Hurricane Forecast Improvement Project

Since its official start in 2010, HFIP has been providing a unified organizational infrastructure and funding for NOAA and other agencies to coordinate the hurricane research needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts. HFIP's 5-year (for 2014) and 10-year (for 2019) goals are to:

- Reduce average track errors by 20% in 5 years; 50% in 10 years for days 1 through 5.
- Reduce average intensity errors by 20% in 5 years; 50% in 10 years for days 1 through 5.
- Increase the probability of detection for rapid intensification (RI) to 90% at day 1, decreasing linearly to 60% at day 5, and decrease the false alarm ratio for RI change to 10% for day 1, increasing linearly to 30% at day 5.

- Extend the lead time for hurricane forecasts out to day 7 (with an accuracy equivalent to that of the day 5 forecasts when they were introduced in 2003).

It is hypothesized that the HFIP goals could be met with high-resolution (~10-15 km) global atmospheric numerical forecast models run as an ensemble in combination with, and as a background for, regional models at even higher resolution (~1-5 km). HFIP expects that its intensity goals will be achieved through the use of regional models with a horizontal resolution near the core finer than about 3 km. This paper focuses on the intensity forecast improvements obtained from the NCEP HWRF modeling system during the first phase (i.e., first 5 years) of HFIP.

3. NCEP HWRF Modeling System

Specialized regional TC models used at NCEP, the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model (Bender et al., 2007) and the HWRF model (Tallapragada et al., 2014b), are designed to provide real-time TC forecasts to NHC for the North Atlantic (NATL) and eastern North Pacific (EPAC) basins, to the CPHC for the Central Pacific (CPAC) basin, and to the JTWC for all tropical ocean basins including the northwestern Pacific (WPAC), North Indian Ocean (NIO), South Indian Ocean (SIO), and Southern Pacific (SP). The GFDL model was one of the primary track and intensity prediction tools used by NHC forecasters after it became operational in 1994. In addition, the US Navy version of the GFDL model (GFDN) has been used by the JTWC since 2002. With an aim to replace the hydrostatic GFDL model with a more advanced atmosphere-ocean coupled non-hydrostatic model with storm following nests capable of producing high-resolution TC forecasts, the HWRF modeling system was developed and implemented at NCEP in 2007. Figure 1 shows the regions where the HWRF and GFDL/GFDN models are currently operational in real time.

4. HWRF Forecast Improvements in the North Atlantic Basin

In the early 2000s, the development of an operational TC forecast system with a non-hydrostatic dynamic core was started at the NCEP-EMC to better forecast TC intensity, structure, and rapid intensity changes. In fulfillment of this goal, the HWRF modeling system was established in 2007 to provide NHC with improved operational track and intensity forecast guidance. The original HWRF model operated at a resolution of 27 km for the static domain and 9 km for the single movable nest. Meanwhile, HRD scientists developed an experimental research version of HWRF called HWRFx (Zhang et al., 2011) to target the intensity change problem at a higher resolution (about 3 km, Gopalakrishnan et al., 2011, 2012). Central to the development of the high resolution HWRF model is the improvement of the surface and boundary layer parameterization schemes. Inner-core data collected by NOAA's WP-3D research aircraft were used as the basis to redesign the parametrization schemes for high-resolution hurricane applications (Gopalakrishnan et al., 2013). Significant improvements to the model forecasted boundary layer structure, as well as size predictions, were demonstrated with those advances. Supported by HFIP, a triply-nested, high-resolution HWRF system (27:9:3 km) with improved physics that were calibrated to match observations was run in real-time demonstration mode in 2011.

Based on HIFP demonstration experiments that illustrated significant impacts of high resolution for TC predictions (Gopalakrishnan et al., 2012), scientists at EMC worked with NOAA research partners, in particular at HRD and academic institutions, and implemented major changes to the original operational version of HWRF, resulting in a new operational

HWRF model at NCEP for the 2012 hurricane season (Tallapragada et al., 2013; Goldenberg et al., 2015). The central improvement was the triple-nest capability (27:9:3 km) that included a cloud-resolving innermost grid operating at 3 km horizontal resolution, along with several improvements to the physics schemes based on observational findings and advanced vortex initialization data assimilation techniques for better representation of the inner core structure of storms. Apart from obtaining significant improvements in track forecast skill compared to previous versions, the 2012 version of the operational HWRF model conclusively demonstrated the positive impact of resolution on storm size and structure forecasts (Tallapragada et al., 2013).

The 2013 version of the operational HWRF model made significant additional improvements in track, intensity, and structural prediction of TCs by taking better advantage of the high-resolution capability built into the 2012 HWRF model (Bernardet et al., 2015). For the first time, the HWRF Data Assimilation System (HDAS), a Gridpoint Statistical Interpolation (GSI) based one-way hybrid ensemble-variational data assimilation scheme, was implemented to assimilate inner-core observations from the NOAA WP-3D aircraft Tail Doppler Radar (TDR) data in real-time, when available. One of the highlights of the 2013 HWRF configuration retrospective tests and evaluations performed on a sample of named TCs, comprised of 835 cases from three North Atlantic hurricane seasons (2010-2012), was the remarkable reduction of intensity forecast errors. Results shown in Figure 2 indicate that the 2013 HWRF model (denoted by H3FI) outperformed the statistical models (DSHP: Decay SHIPS and LGEM: Linear Growth Equation Model), operational HWRF (HWFI), operational GFDL (GHMI), and 2012 version of HWRF (H2FI), as well as the NHC Official (OFCL) forecasts for intensity prediction in the 2-3 day forecast period. Historically, statistical models have been more skillful than dynamical models for hurricane intensity prediction.

Upgrades to the HWRF system continue on an annual basis. Each new configuration of the HWRF model is implemented for operations at the start of hurricane season for NHC forecasters to have access to improved hurricane guidance. Systematic evaluation of each individual upgrade (and combinations thereof) for multiple hurricane seasons is the key element of model development activities at NCEP supported by HFIP, and this process ensures appropriate testing of model stability, reliability, and expected performance levels in real-time operations. Important upgrades to the 2014 version of the operational HWRF model (H214) include increased vertical resolution (61 levels), a higher model top (2 hPa), assimilation of aircraft reconnaissance dropsonde data in the inner core, and implementation of a new, high-resolution version of the POM-TC (MPIPOM-TC) ocean model. An evaluation of the 2014 HWRF upgrades has shown further improvements in track and intensity forecasts, with the average track errors now comparable to the GFS model and average absolute intensity errors better than NHC's official forecasts at all forecast times. Figure 3 shows the cumulative improvements obtained from the operational HWRF model during the last 4 years (2011-2014), highlighting the role of HWRF in providing more accurate track and intensity forecast guidance for NHC.

4.1 *Experimental Real-Time HWRF Forecasts for the WPAC Basin in Support of JTWC*

The progress in the NATL basin prompted the HWRF team at EMC to provide experimental real-time guidance to JTWC for typhoon forecasts in the WPAC basin starting in 2012, using the same operational HWRF model implemented at NCEP, except for the ocean coupling (i.e., sea surface temperatures did not evolve during the forecasts over the WPAC basin). An evaluation of model performance in 2012 showed lower forecast track and intensity errors for the HWRF model compared to other operational regional models then used by JTWC

(Evans and Falvey, 2013; Tallapragada et al., 2015a). Intensity forecasts also showed improved performance as compared to other regional models with much reduced forecast errors during the first 24 h owing to better vortex initialization. These experimental forecasts were performed with computational resources and support provided by HFIP and delivered to JTWC with about 85% real-time reliability achieved through specially-established procedures. Given the positive performance of the HWRF model in the WPAC basin during the 2012 season, the HWRF team at EMC continued its efforts to provide real-time forecasts in 2013 and 2014 using the 2013 upgrade of the HWRF model.

Performance of the HWRF model during the real-time experiments in the 2012-2013 typhoon seasons is shown in Figure 4. Non-homogeneous seasonal statistics of the absolute TC track forecast errors and the absolute intensity errors in the WPAC basin between the 2012-2013 seasons are provided in this figure (Tallapragada et al., 2015a, 2015b). One notices a very significant improvement of the 2013 HWRF model compared to the 2012 version of HWRF with both the track and intensity forecast errors reduced at all forecast lead times.

Given the fact that the WPAC basin was very active in 2013 with 34 storms, of which five were super typhoons (STY) including the extremely powerful landfalling STY Haiyan, the improvement seen in the intensity and track forecast errors at the 3-5 day lead times is strong evidence that HWRF improves the forecasts of structure and development of TCs in the WPAC basin. The performance and reliability of the HWRF forecasts allowed JTWC to officially include HWRF as one of their track and intensity consensus models. Figure 5 shows the homogeneous verification of HWRF relative to the suite of other operational models used by JTWC, namely COAMPS-TC (Naval Research Laboratory Coupled Ocean-Atmosphere Prediction System for TCs, referred to as COTC), GFDL, GFDN, NCEP GFS, and the official

JTWC forecasts for WPAC typhoons in 2013. HWRF outperformed all other regional models in terms of track and intensity forecasts, with HWRF's track errors comparable to the global GFS forecasts except at day 4, and HWRF's absolute intensity errors demonstrated consistently better forecasts than all other models during the entire 5-day forecast times.

4.2 *Evolution of HWRF as a Unique, High Resolution Regional Hurricane Model with Extended Coverage over Indian Seas*

The successful demonstration of the HWRF model's performance for the WPAC basin led to expanding the scope of the real-time experimental forecasts from HWRF to all world tropical oceanic basins. HWRF forecast guidance for track, intensity, structure, and rainfall for all six tropical cyclones that formed in the NIO basin during 2013 were provided to the India Meteorological Department (IMD) Cyclone Warning Division (CWD), including the very severe cyclone Phailin. IMD has been routinely using the operational forecast guidance from the NCEP models and acknowledged the superior quality of the products they received from NCEP (Mohapatra, personal communication). An example illustrating the HWRF model's forecasts for the life cycle, from genesis to landfall, of TC Phailin is shown in Figure 6. The improved numerical model forecast guidance for the track, intensity, structure, and storm surge 4-5 days prior to the landfall of TC Phailin, and the enhanced warning products that were disseminated collectively, helped disaster management personnel evacuate more than a million people in India from potentially affected areas to cyclone shelters, safe houses, and inland locations (Mohanty et al., 2015).

Track and intensity forecast error statistics (Figure 7) for all six tropical cyclones that formed in the NIO basin during 2013 indicated the superior performance of the HWRF model at almost all forecast times compared to other model guidance received by JTWC.

4.3 *Rapid Intensification and Intensity Change Forecasts from HWRF: A Major Accomplishment*

Improving RI[1] forecasts is one of the highest priorities for TC forecasters at NHC and JTWC and has been recognized as the most challenging aspect of TC research. Much of the lack of improvement in the RI forecast skill is rooted in our lack of understanding on when and how RI occurs in different environmental conditions and the historic inability of dynamical models to adequately predict the multi-scale processes that produce an RI event. The impressive intensity forecast performance from the new operational HWRF model has demonstrated its improved ability in representing and forecasting RI, as shown through extensive numerical experiments and observations for Hurricane Earl (2010), a hurricane that intensified even when the environmental vertical wind shear was very large (Chen and Gopalakrishnan, 2015).

In that study, Chen and Gopalakrishnan performed a simulation of Hurricane Earl (2010) using the operational 2013 HWRF system, verified the predictions against available inner-core observations, and used the simulation to understand the asymmetric RI of a TC in a sheared environment. The forecast verification illustrated that the HWRF model realistically simulated Hurricane Earl's observed evolution of intensity, as well as several aspects of its inner-core structure, including convective and wind asymmetries and vortex tilt[2] prior to and during RI. An examination of the high-resolution forecast data revealed that Hurricane Earl's tilt was large at the RI onset and decreased quickly once RI commenced, suggesting vertical alignment is the result instead of the trigger for RI.

Furthermore, this study found that the RI onset is associated with the development of upper-level warming in the eye region. A thermodynamic budget calculation showed that warming over the low-level center results primarily from radially inward storm-relative

[1]An increase in maximum sustained winds of a TC by at least 30 knots in a 24-h period.

[2]As measured by the circulation centers at 2- and 8-km altitude (Figure 5 in Chen and Gopalakrishnan, 2015).

advection of subsidence-induced warm air in the upshear-left region. This advection does not occur until persistent convective bursts (CBs) are concentrated in the downshear-left quadrant. It is the favorable juxtaposition of convective-scale subsidence and the broader-scale, shear-induced subsidence which is most conducive for intensification. When CBs are concentrated in the downshear-left and upshear-left quadrants, the net subsidence warming is maximized upshear, and the resulting warm air is advected over the low-level storm center by the upper-level, storm-relative flow. Subsequently, the surface pressure falls and RI occurs. This HWRF simulation of Earl provides a promising baseline for understanding the RI problem in three dimensions during a time period when the resolution of observations was not high enough to study the evolution of RI and vortex tilt.

RI events appear more frequently in WPAC compared to other basins, thus allowing for extensive examination of the capability of the HWRF model in forecasting these events. Using an idealized configuration, Bao et al. (2012), Gopalakrishnan et al. (2011, 2013), and Kieu et al. (2014) demonstrated that the onset of RI in the HWRF model only occurred when a specific set of conditions were present in the modeled storm's dynamic and thermodynamic structure (i.e., phase-lock condition). Specifically, the HWRF model vortex must possess three basic ingredients for RI onset to occur, namely: (1) a warm anomaly of 1-3 K around 400-300 hPa; (2) a moist column with relative humidity >95% within the storm central region; and (3) low-level tangential flow ≥15 m s^{-1} (Figure 8a). Examples of the vertical structure of modeled storms right at the onset of RI about 24 h into the forecast of STY Usagi initialized at 1800 UTC 16 September (Figure 8b) and for a forecast of STY Soulik that was initialized at 0600 UTC 7 July (Figure 8c) show strikingly similar and coherent structure with all three components of the phase-lock condition present at the RI onset (Tallapragada and Kieu, 2014a).

Verification of the probability of detection (POD) and the false alarm rate (FAR) of RI forecasts for the WPAC basin during 2013, shown in Figure 9, indicates further improvements in the POD for the 2013 HWRF model compared to the 2012 version. Specifically, the POD index for RI forecasts (at >30 kt intensity change in 24 h) in the 2013 HWRF model is 0.22 compared to 0.09 in 2012. While the POD index is still quite low, it is far better than other models used by JTWC and their official forecasts (Tallapragada and Kieu, 2014a). A significant reduction in the FAR index (from 0.81 in 2012 to 0.45 in 2013) also indicates improved reliability of RI forecasts from the HWRF model in 2013.

5. Future Directions for HWRF

This work demonstrates the advances and steep-step performance improvements in the operational the HWRF system. These significant improvements obtained with the new HWRF implementation are attributed to a number of major changes since 2012, including a new, higher resolution nest that is capable of better resolving eyewall convection and scale interactions, improved vortex initialization, improved planetary boundary layer and turbulence physics, an improved nest motion algorithm and, above all, systematic testing and evaluation (T&E) that are not only based on single simulations and idealized case studies, but on several seasons of testing. This kind of development and T&E would not be possible without the support of the HFIP high performance computing capability.

Although the operational HWRF system is showing exceptional skill in intensity forecasting, experience with TCs such as Irene (2011), Isaac (2012), and Sandy (2012) have illustrated the importance of providing more accurate structure (e.g., size) and rainfall predictions. The current operational HWRF configuration is storm centric and single nested, not ideal for representing multi-scale interactions or for TC genesis forecast applications; it is greatly limited in extending forecast lead times beyond 5 days. A key for improving TC forecasts of genesis, size near landfall, rainfall post-landfall, and for extending forecast lead times beyond 5 days lies in the creation of a basin-scale model (eventually covering the entire globe) with multiple moving nests at 1-3 km resolution covering all the storms in the basin. Based on the 2013 HWRF system that includes the operational initialization scheme and recent upgrades to physics, HRD and NCEP-EMC researchers have created a basin scale HWRF system that can operate with multiple moving nests at resolutions as high as 3 km now (Figure 10) and potentially at higher resolution in the near future.

An additional area where significant improvement is needed is the initial conditions for HWRF. To this end, improvements to data assimilation methodology and use of all available hurricane observations are being pursued. This includes the development and deployment of new observing systems (such as Doppler wind lidar) on NOAA’s hurricane hunter aircraft and conducting Observing System Simulation Experiments (OSSEs) to evaluate sampling strategies for both reconnaissance aircraft and unmanned aerial systems, as well as to evaluate the potential impact of new space-based observing systems (Atlas et al., 2015).

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Figure Captions

Figure 1. HWRF/GFDL model domains for providing real-time TC forecasts in different ocean basins. Solid lines represent operational HWRF domains coupled to the MPIPOM ocean model. Dashed lines show uncoupled model forecasts provided by HWRF in real time.

Figure 2. Average intensity forecast errors in knots for the Atlantic Basin during the 2010-2012 hurricane seasons based on the 2013 version of the HWRF model (H3FI; 27:9:3 km) compared to the 2012 version (H2FI; 27:9:3 km), the original operational HWRF model (HWFI; 27:9 km), the GFDL model (GHMI), and statistical models LGEM (Linear Growth Equation Model) and DSHP (Decay Statistical Hurricane Intensity Prediction System). Black line represents NHC's official forecast errors as a function of time, and the number of cases verified at each forecast period is shown along the x-axis.

Figure 3. Forecast improvments in the NATL basin from the operational HWRF model since 2011. Each configuration of HWRF was evaluated for multiple hurricane seasons. The dashed lines shows the HFIP baseline (BASE) and 5-year goal for track and intensity errors. The samples are non-homogeneous, and the number of cases verified at the initial time for each configuration is provided in parentheses. HWRF (in purple) represents operational forecasts during 2007-2011 prior to the implementation of the high-resolution version in 2012. H212, H213, H214, and H215 represent, respectively, the 2012, 2013, 2014, and 2015 HWRF versions.

Figure 4. Top: Non-homogenous comparison of the absolute track forecast errors between the 2012 HWRF version during 2012 (blue columns) and the 2013 HWRF version

during 2013 (red columns). Bottom: similar to (a) but for the absolute intensity forecast errors.

Figure 5. Verification of the absolute track errors (top) and absolute intensity errors (bottom) during 2013 for typhoons in the WPAC basin for HWRF (red), COAMPS-TC (blue), AVNO (GFS) (black), GFDN (cyan), and JTWC's official forecast (purple). The numbers below the x-axis denote the number of cases verified for each forecast time.

Figure 6. HWRF forecast of the life cycle of TC Phailin starting from (a) genesis at 06 UTC 6 Oct 2013, (b) formation of depression on 8 Oct 2013, (c) intensification, and (d) dissipation. Shading depicts the microwave satellite imagery (37 GHz) equivalent from the model, and contours represent minimum sea level pressure (hPa). The black line represents the best track from JTWC, and the white line is the HWRF predicted track from 00 UTC 10 October 2013.

Figure 7. Verification of the average absolute track errors (top) and average absolute intensity errors (bottom) during 2013 for tropical cyclones in the NIO for HWRF (red), COAMPS-TC (COTC, blue), AVNO (GFS, black), GFDN (cyan), and JTWC's official forecast (purple). The numbers below the x-axis denote the number of cases verified for each forecast time.

Figure 8. (a) Radius-height, azimuthally-averaged cross section of the relative humidity (shaded, unit percent), tangential wind (black contours at intervals of 3 m s^{-1}), and potential temperature anomalies with respect to the far-field environment (red contours at intervals of 10 K, solid/dotted contours for positive/negative values) in an idealized experiment with the HWRF model compared to an analysis of storm

vertical structure at the time of RI onset for (b) 6-h forecast of STY Soulik and (c) 18-h forecast of STY Usagi.

Figure 9. Scatter plots of the 24-h change of the maximum 10-m winds (in m s^{-1}) from observations (BEST, x-axis) and real-time model forecasts (HWRF, y-axis) for 2013 (left panel) and 2012 (right panel). Black boxes denote the points that both HWRF and the observations capture RI, whereas gray boxes denote the points that HWRF forecasts RI events that were not observed in reality.

Figure 10. Basin scale HWRF model with multiple moving nests covering the Atlantic and East Pacific basins valid at 18 UTC 26 Aug 2010. Shading represents sea level pressure, and the steering flow is represented by wind vectors over the static domain set at 27-km resolution. In this case, the nest at 3-km resolution covers TCs Danielle and Earl in the Atlantic and Frank in the East Pacific. Brightness temperatures are shown in the high resolution nest. Inset: Basin scale HWRF (green) and observed (blue) evolution of 10-m-wind speeds for Earl (top left), Danielle (top right), and Frank (bottom). Please refer to http://hwrf.aoml.noaa.gov/pix/website/HWRF-Basinscale_06L-07L-09E.gif for the animation.

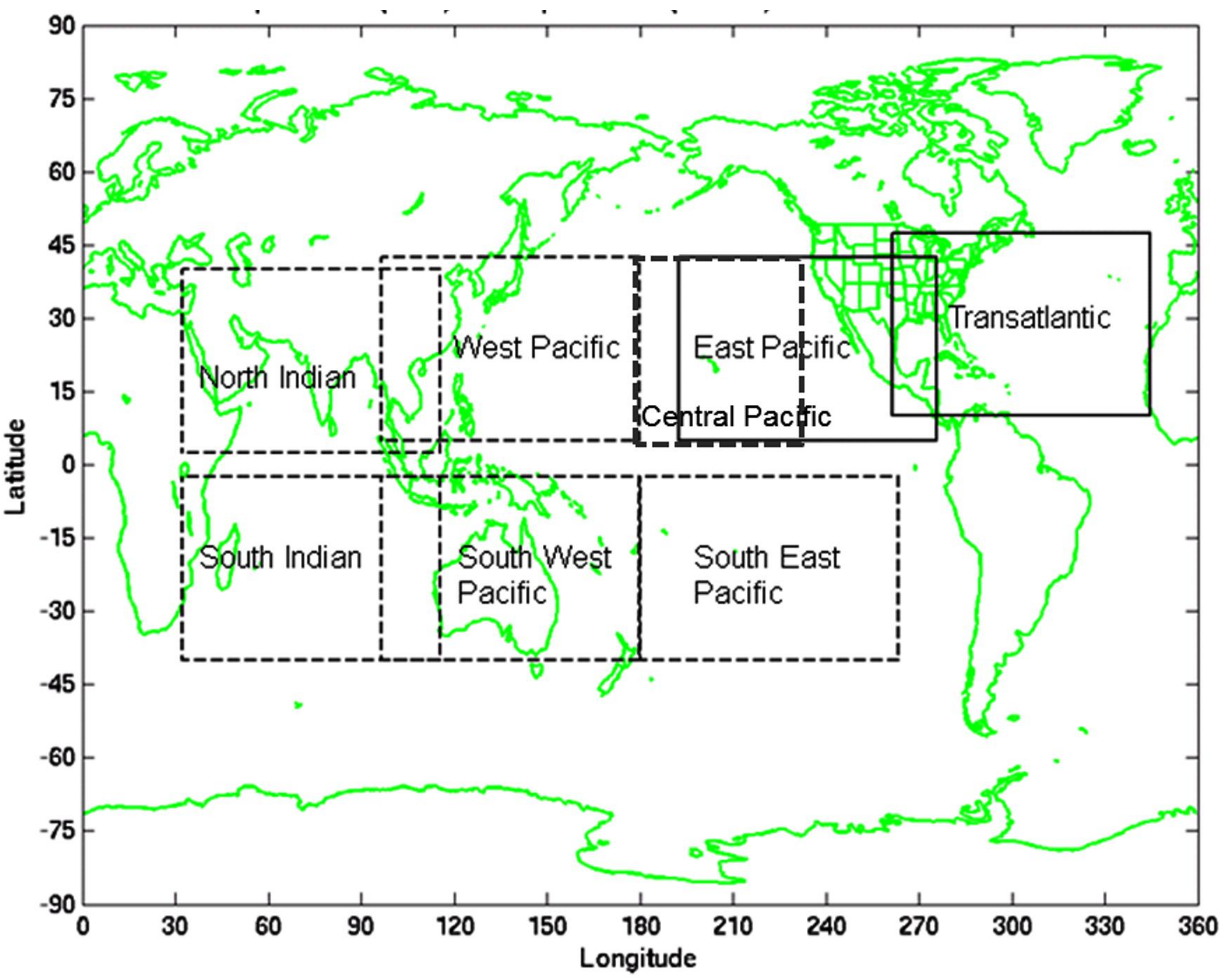

North Indian
West Pacific
East Pacific
Central Pacific
Transatlantic
South Indian
South West
Pacific
South East
Pacific
Latitude
Longitude

Figure 1

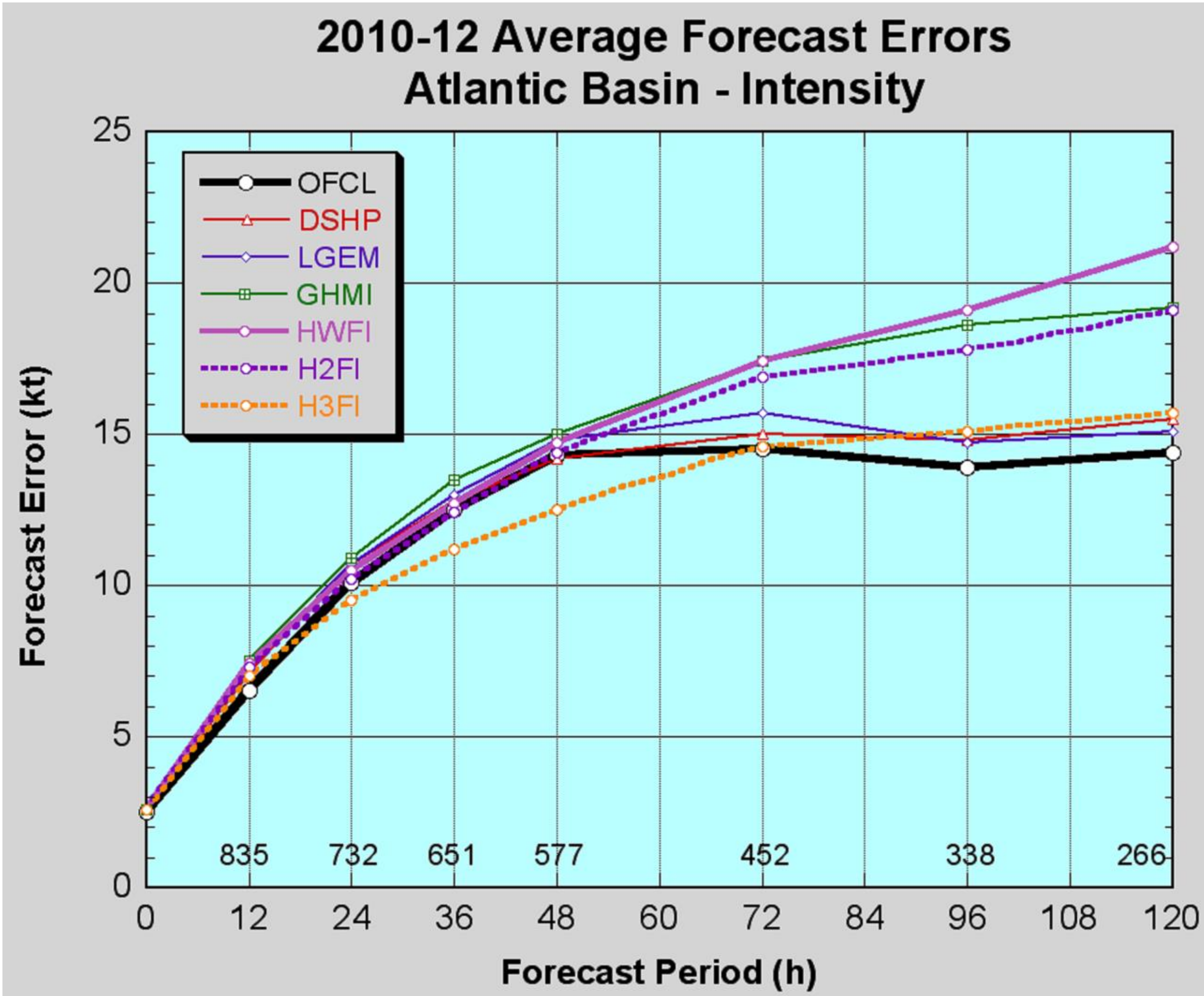

2010-12 Average Forecast Errors
Atlantic Basin - Intensity
OFCL
DSHP
LGEM
GHMI
HWFI
H2FI
H3FI
Forecast Error (kt)
Forecast Period (h)
0
5
10
15
20
25
0
12
24
36
48
60
72
84
96
108
120
835
732
651
577
452
338
266

Figure 2

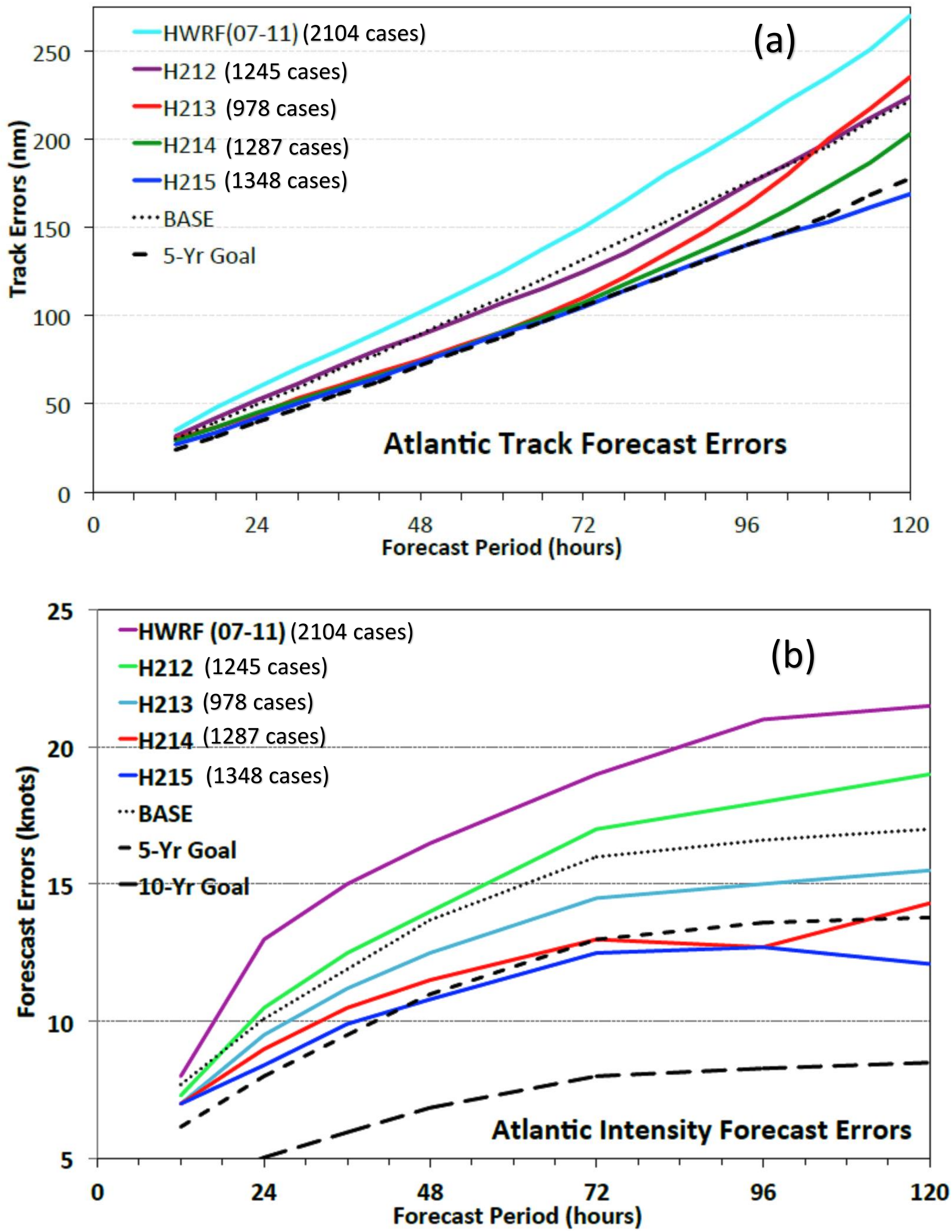

HWRF(07-11) (2104 cases)
H212 (1245 cases)
H213 (978 cases)
H214 (1287 cases)
H215 (1348 cases)
BASE
5-Yr Goal
(a)
Atlantic Track Forecast Errors
Track Errors (nm)
0
50
100
150
200
250
0
24
48
72
96
120
Forecast Period (hours)
HWRF (07-11) (2104 cases)
H212 (1245 cases)
H213 (978 cases)
H214 (1287 cases)
H215 (1348 cases)
BASE
5-Yr Goal
10-Yr Goal
(b)
Atlantic Intensity Forecast Errors
Forecast Errors (knots)
5
10
15
20
25
0
24
48
72
96
120
Forecast Period (hours)

Figure 3

Code:49.6004d

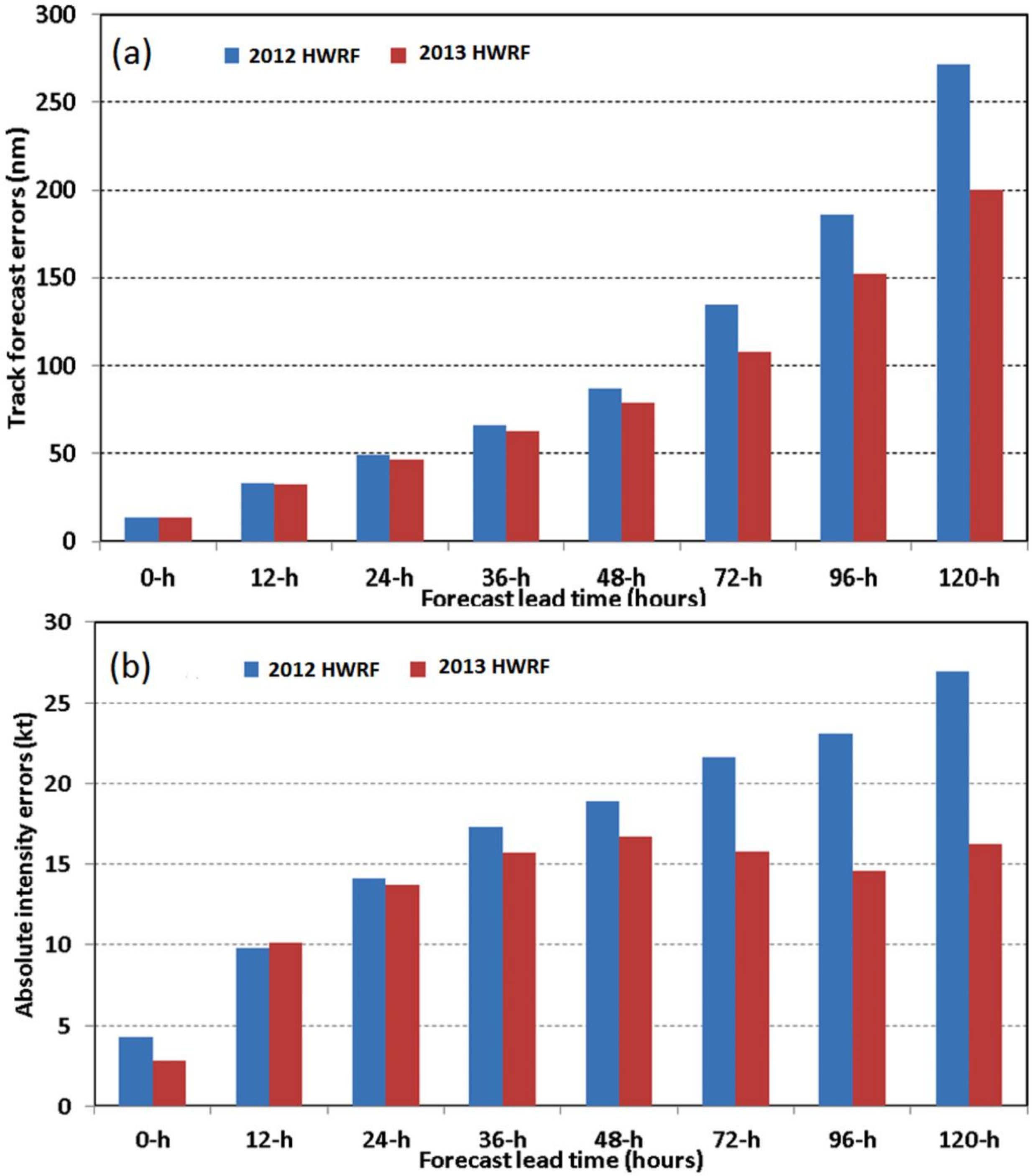
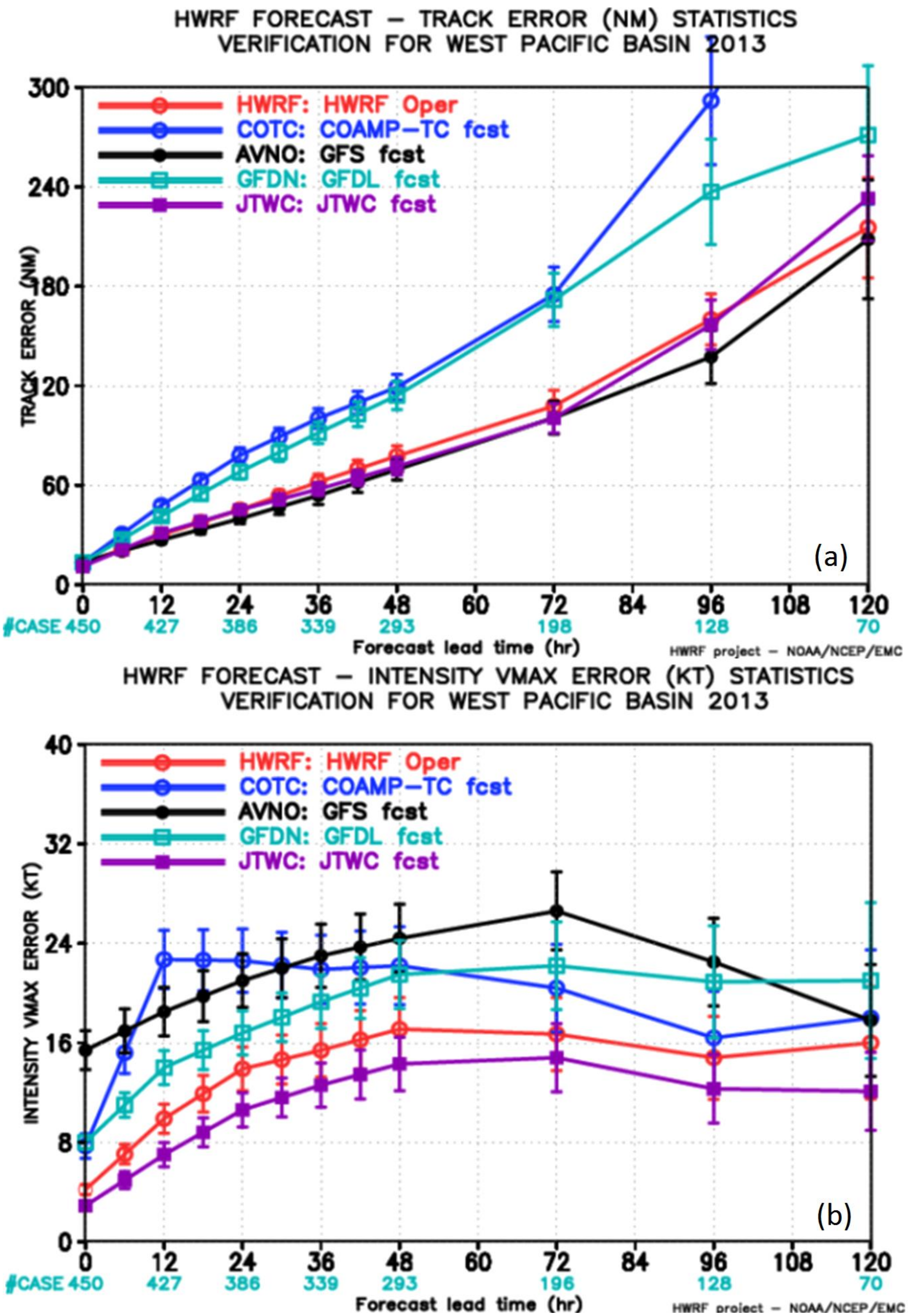


Figure 4



HWRF FORECAST – TRACK ERROR (NM) STATISTICS
VERIFICATION FOR WEST PACIFIC BASIN 2013
HWRF: HWRF Oper
COTC: COAMP–TC fcst
AVNO: GFS fcst
GFDN: GFDL fcst
JTWC: JTWC fcst
TRACK ERROR (NM)
0
60
120
180
240
300
(a)
0
12
24
36
48
60
72
84
96
108
120
#CASE 450
427
386
339
293
198
128
70
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC
HWRF FORECAST – INTENSITY VMAX ERROR (KT) STATISTICS
VERIFICATION FOR WEST PACIFIC BASIN 2013
HWRF: HWRF Oper
COTC: COAMP–TC fcst
AVNO: GFS fcst
GFDN: GFDL fcst
JTWC: JTWC fcst
INTENSITY VMAX ERROR (KT)
0
8
16
24
32
40
(b)
0
12
24
36
48
60
72
84
96
108
120
#CASE 450
427
386
339
293
196
128
70
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC

Figure 5

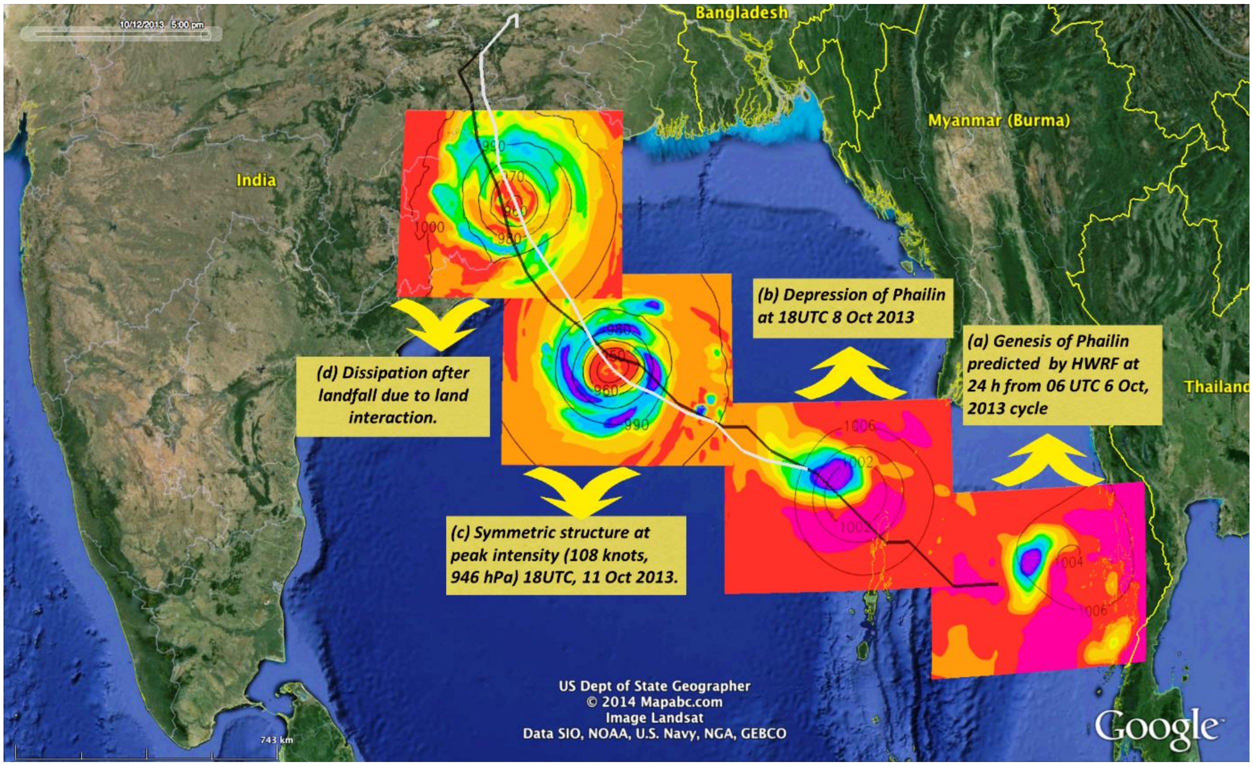

Bangladesh
Myanmar (Burma)
India
Thailand
(b) Depression of Phailin at 18UTC 8 Oct 2013
(a) Genesis of Phailin predicted by HWRF at 24 h from 06 UTC 6 Oct, 2013 cycle
(d) Dissipation after landfall due to land interaction.
(c) Symmetric structure at peak intensity (108 knots, 946 hPa) 18UTC, 11 Oct 2013.
US Dept of State Geographer
© 2014 Mapabc.com
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google

Figure 6

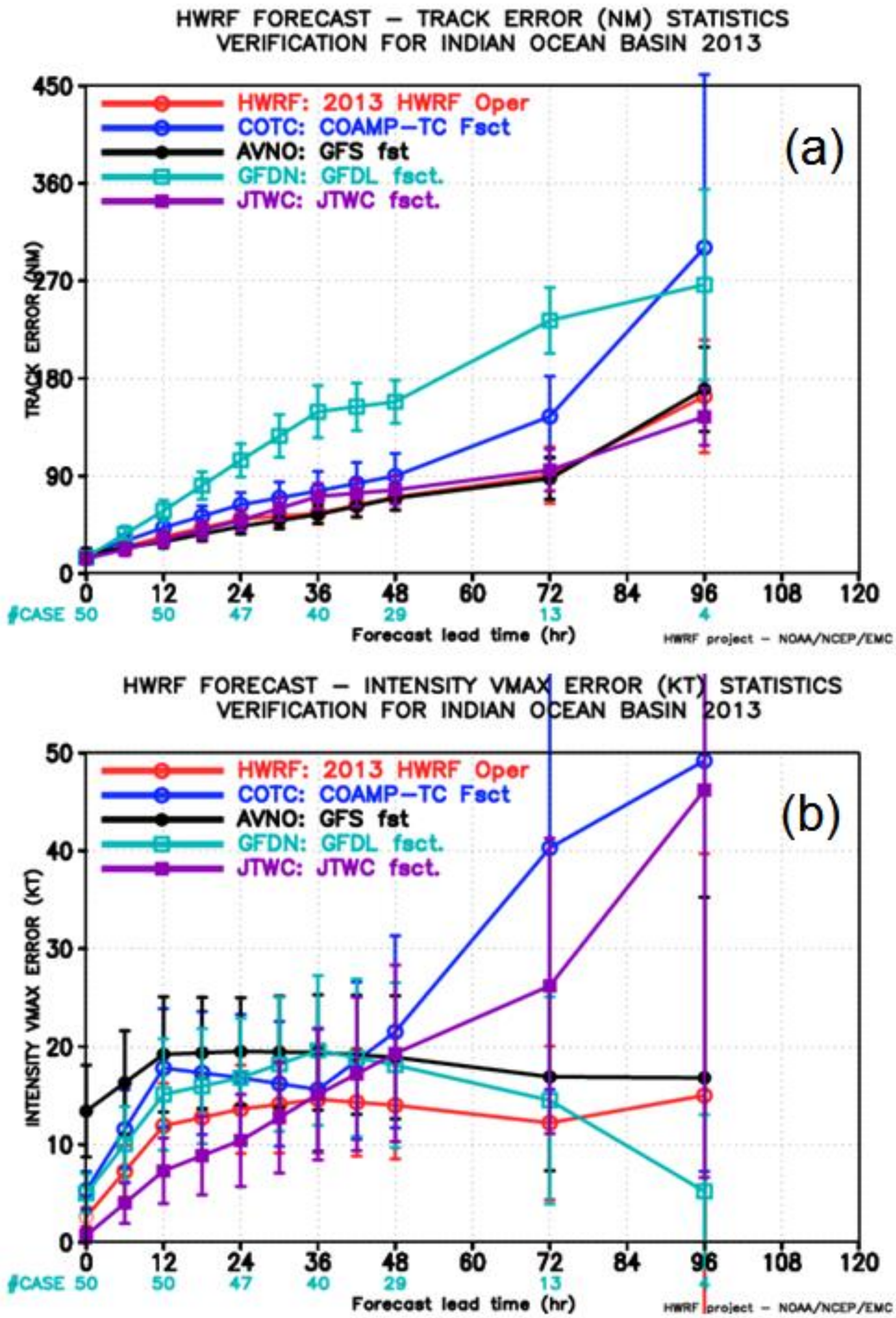

HWRF FORECAST – TRACK ERROR (NM) STATISTICS
VERIFICATION FOR INDIAN OCEAN BASIN 2013
HWRF: 2013 HWRF Oper
COTC: COAMP–TC Fsct
AVNO: GFS fst
GFDN: GFDL fsct.
JTWC: JTWC fsct.
(a)
TRACK ERROR (NM)
#CASE 50 50 47 40 29 13 4
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC
HWRF FORECAST – INTENSITY VMAX ERROR (KT) STATISTICS
VERIFICATION FOR INDIAN OCEAN BASIN 2013
HWRF: 2013 HWRF Oper
COTC: COAMP–TC Fsct
AVNO: GFS fst
GFDN: GFDL fsct.
JTWC: JTWC fsct.
(b)
INTENSITY VMAX ERROR (KT)
#CASE 50 50 47 40 29 13 4
Forecast lead time (hr)
HWRF project – NOAA/NCEP/EMC

Figure 7

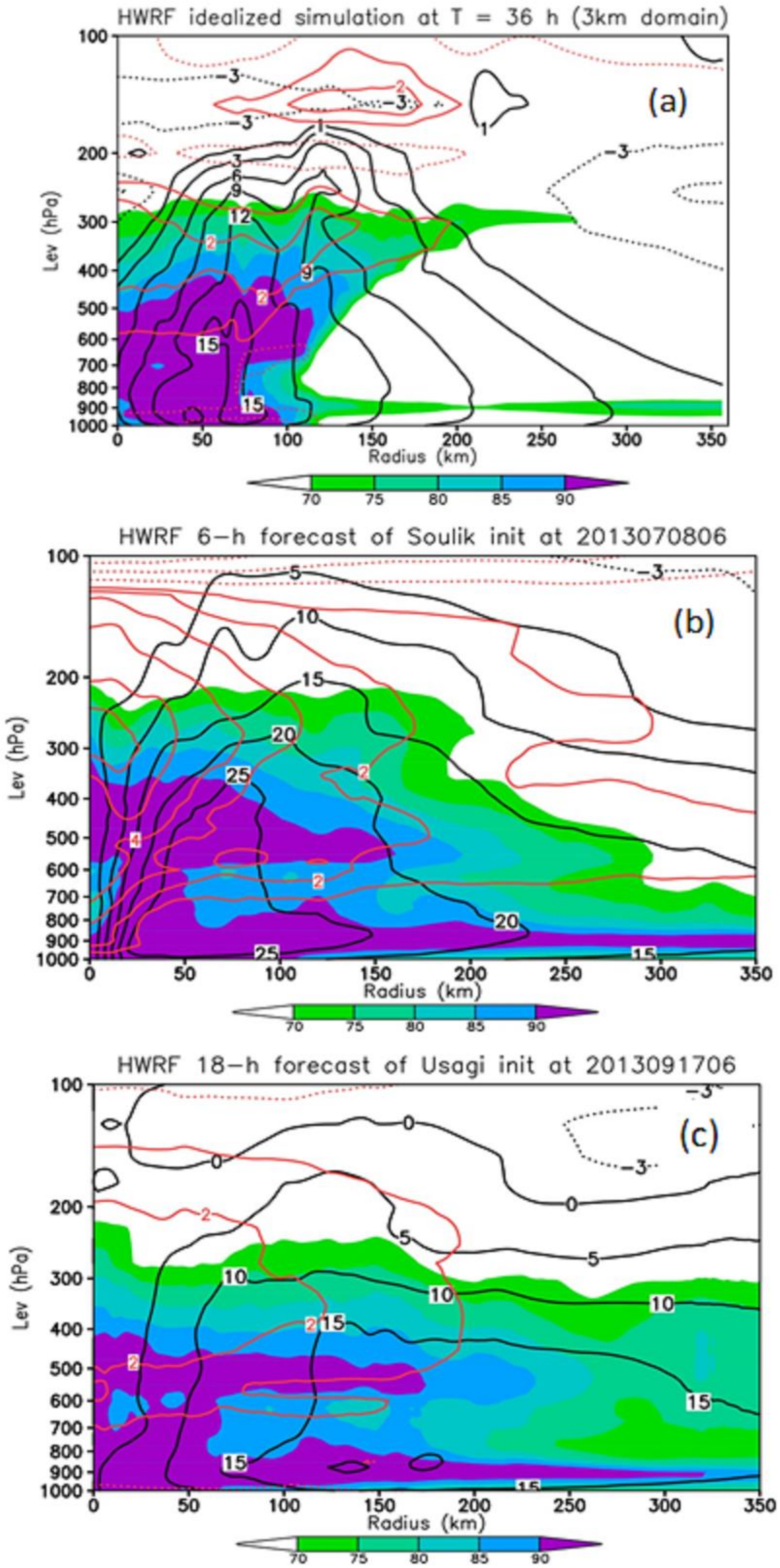

HWRF idealized simulation at T = 36 h (3km domain)
(a)
Lev (hPa)
Radius (km)
HWRF 6–h forecast of Soulik init at 2013070806
(b)
Lev (hPa)
Radius (km)
HWRF 18–h forecast of Usagi init at 2013091706
(c)
Lev (hPa)
Radius (km)
70
75
80
85
90

Figure 8

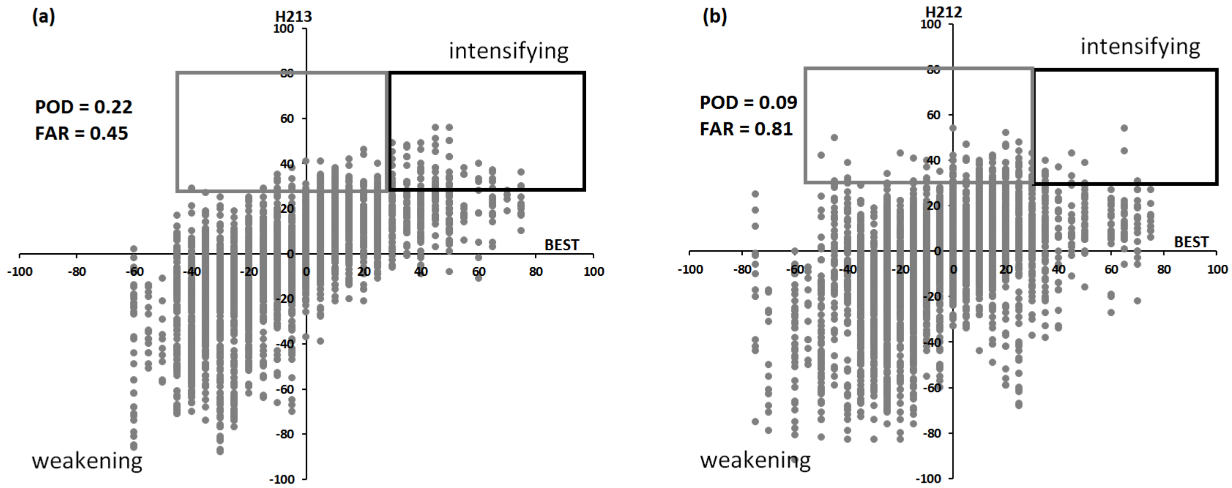

(a)
H213
intensifying
POD = 0.22
FAR = 0.45
BEST
weakening
(b)
H212
intensifying
POD = 0.09
FAR = 0.81
BEST
weakening

Figure 9

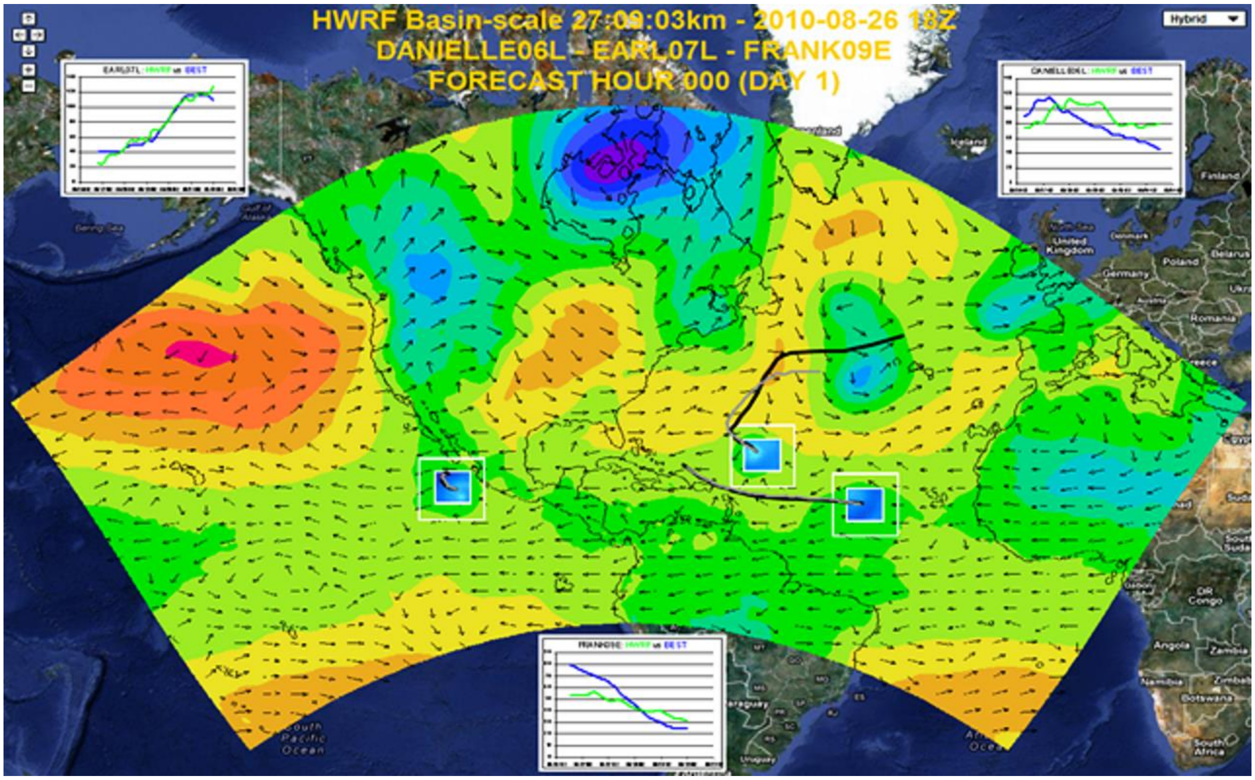

HWRF Basin-scale 27:09:03km - 2010-08-26 18Z
DANIELLE06L - EARL07L - FRANK09E
FORECAST HOUR 000 (DAY 1)
Hybrid

Figure 10