ADVANCING THE STATE OF THE ART IN OPERATIONAL TROPICAL CYCLONE FORECASTING AT NCEP

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ABSTRACT

Regional Hurricane modeling systems developed and implemented into operations at National Centers for Environmental Prediction (NCEP) of National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) are now used for tropical cyclone forecast guidance in all ocean basins of the world. Lately, HWRF (Hurricane Weather Research and Forecast) modeling system has made significant improvements to the state of the art in numerical guidance for tropical cyclone track, intensity, size, structure and rainfall forecasts. These improvements come from advances in various components of the modeling system that are incorporated into the model in yearly upgrade cycles.

NWS/NCEP/Environmental Modeling Center's hurricane team has also developed another non-hydrostatic hurricane model in NOAA Environmental Modeling System (NEMS) framework known as HMON (Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic) model which was implemented at NCEP operations this past year. Development of HMON is consistent with, and a step closer to developing Next Generation Global Prediction System (NGGPS) chosen Finite Volume Cubed-Sphere (FV3) dynamic core based global to local scale coupled models in a unified modeling framework. In this paper, operational configuration details of this new HMON model are discussed along with operational HWRF model upgrades, and their forecast performance is compared to other models. We also discuss plans for hurricane model improvements in the next two to five years.

Keywords: operational models, forecasting, tropical cyclones

1. Introduction

The Hurricane Weather Research and Forecast modeling System (HWRF) was designed and developed by scientists at the Environmental Modeling Center (EMC) of National Centers for Environmental Prediction (NCEP) utilizing the community WRF software infrastructure to rapidly advance hurricane forecast skills for operational needs. HWRF became operational in the year 2007 preceded by extensive testing and evaluation for three hurricane seasons (2004-2006), and has been constantly improved since then using annual updates to increase the forecast skill for track, intensity and structure of tropical cyclones for all global basins.

A history of all the annual upgrade changes since 2010 are captured in HWRF documentation available at the Development Testbed Center's web page (https://dtcenter.org/HurrWRF/users/docs/index.php). Details on more recent science changes can be found in the 2017 version of documentation (Biswas et al., 2017) along with the HWRF's most recent users guide (available at https://dtcenter.org/HurrWRF/users/docs/users_guide/HWRF_v3.9a_UG.pdf). With the support of NOAA's Hurricane Forecast Improvement Project (HFIP) HWRF has rapidly advanced and evolved as a unique and one of the best tropical cyclone models, catering to both operations and research for all oceanic basins of the world.

HMON, which stands for Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic model is a new hurricane forecast system running operationally in the NCEP production suite on the NOAA's Weather and Climate Operational Supercomputing System (WCOSS) since 2017 North Atlantic hurricane season. Development of HMON is an important step towards implementing a long-term strategy at NCEP/EMC for multiple static and moving nests globally, with one- and two-way interaction and coupled to other models (ocean, wave, land, surge, inundation, etc.) using NEMS (NOAA's Environmental Modeling System) infra-

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structure. Use of NEMS also paves the way for the future use of CCPP (Common Community Physics Package) style physics packages. Developed initially as a collaborative effort between NOAA's EMC and Hurricane Research Division (HRD) as a component of High Impact Weather Prediction Project (HIWPP), HMON's development has also been supported by the Next Generation Global Prediction System (NGGPS) program.

The next section highlights some of the main features of these two (HWRF and HMON) modern state-of-the-art tropical cyclone forecast systems. Section 3 provides details on their 2017 upgrades while sections 4 and 5 discuss their performance in North Atlantic, East Pacific and Western Pacific basins. We close in section 6 with details on planned enhancements of these operational systems for the next 2-5 years.

2. State of the art in NCEP tropical cyclone models

a. HWRF

The atmosphere-ocean-wave coupled HWRF modeling system runs in the NCEP production suite on the NOAA's WCOSS. This system is developed and supported by EMC and operated by NCEP Central Operations (NCO) since 2007. In 2017, HWRF Model was designed to run in operations on demand for a maximum of eight storms throughout their life cycle from genesis to dissipation four cycles a day in all global tropical cyclone basins as determined by the National Hurricane Center (NHC) for North Atlantic, North Eastern Pacific and Central Pacific basins, and with Joint Typhoon Warning Center (JTWC) providing inputs for storms in the Western Pacific, North Indian Ocean and Southern Hemisphere Ocean basins. Each HWRF run provides 126-hr forecast guidance for hurricane track, intensity and structure at every 6-hr interval with eight simultaneous storm forecast capability in operations to run all year long.

HWRF model consists of multiple movable two-way interactive nested grids that follow the projected path of the storm. Atmospheric component of the HWRF model has been coupled to the Message Passing Interface-Princeton Ocean Model (MPI-POM) and WaveWatch III (WW3) in the North Atlantic, Eastern Pacific and Central Pacific basins, and Hybrid Coordinate Ocean Model (HYCOM) in the Western Pacific and North Indian Ocean basins. HWRF uses a sophisticated coupler developed at NCEP for providing accurate representation of air-sea-wave interactions. WW3 is one-way coupled to the atmospheric component to provide accurate significant wave-heights and wave periods under and near the storm. An advanced vortex initialization scheme and NCEP's Grid-Point Statistical Interpolation (GSI) based HWRF Data Assimilation System (HDAS) provide means to represent the initial location, intensity, size and structure of the inner core of a hurricane and its large-scale environment. The NCEP Global Forecast System (GFS) analysis and forecasts provide initial and boundary conditions for the HWRF model. MPI-POM uses either a feature based initialization procedure in the Atlantic basin or fields from Real Time Ocean Forecast System (RTOFS) in the East Pacific and Central Pacific basins, while HYCOM is always initialized from RTOFS for the Western Pacific and North Indian Ocean basins.

HWRF has been configured with triple-nest capability that includes a cloud-resolving inner most grid operating at 2 km horizontal resolution, encompassed by an intermediate grid at 6 km resolution and the parent domain at 18 km resolution. The FY17 configuration of HWRF model uses 75 vertical levels in the North Atlantic, East Pacific and Central Pacific basins and 61 vertical levels in other basins. Model physics in HWRF has been upgraded over the years to accommodate high storm-scale model resolutions including scale-aware convection, micro-physics process, radiation, surface physics and PBL. The land surface model is the NOAH Land Surface Model (LSM) and all system scripts are in Python for a unified system. The data assimilation system uses hybrid HWRF-based EnKF and GSI systems and self-cycled HWRF ensembles based warm starts are used for storms when NOAA P3 Tail Doppler radar data is made available for the inner core. More details on this state-of-the-art Tropical Cyclone forecast system can be found in Tallapragada (2016).

b. HMON

The 2017 version of HMON is the first version for the system and it uses the Non-hydrostatic Multi-scale Model on a B grid (NMMB) (Janjic and Gall, 2012) as its dynamical core. This dynamic core is also currently being used in other NCEP's operational NAM (North American Mesoscale Model) and SREF (Short Range Ensemble Forecast) systems. The NMMB dynamic core is much faster and more scalable than other contemporary dynamic cores deployed for modeling hurricanes at NCEP. In 2017, HMON was designed to run in operations on demand for a maximum of five storms four cycles a day as determined by NHC and the Central Pacific Hurricane Center (CPHC) for the North Atlantic, North Eastern Pacific and Central Pacific basins. Each HMON run provides 126-hr forecast guidance for hurricane track, intensity and structure at every 6-hr intervals.

3. Recent 2017 operational upgrades

a. HWRF

In 2017, several infrastructure enhancements were made to HWRF as part of its annual operational upgrade. The NMM core of the operational HWRF model was upgraded to latest community version referred to as version 3.8.1. The model vertical resolution was increased from 61 (with a model top at 2mb) to 75 levels (model top at 10mb) for the North Atlantic, Eastern Pacific, and Central Pacific basins, and from 43 levels (with a model top at 50mb) to 61 levels (with a model top of 10mb) for Western Pacific and North Indian Ocean basins. An adjustment was made to the domain configurations to allow for storm's meridional movement when determining parent domain center. Besides, a new version of Geophysical Fluid Dynamics Laboratory (GFDL) vortex tracker (Marchok, 2002) was also implemented.

A number of physics improvements were implemented which include updates to the scale-aware SAS convection scheme (Han et al., 2017) and the Ferrier-Aligo microphysics scheme (Aligo et al., 2017). The partial cloudiness algorithm was modified for the RRTMG radiation scheme (Iacono et al., 2008) and the air-sea momentum and enthalpy exchange coefficients were updated. Vortex initialization was improved with a new design of the composite storm vortex. Data assimilation upgrades included addition of new data sets to be used with Grid Statistical Interpolation algorithm (e.g., hourly shortwave, clear air water vapor and visible AMV's from GOES; HDOBS flight level data). For the first time in 2017, a fully cycled HWRF ensemble hybrid Data Assimilation System (Lu et al., 2017) was implemented for storms with Tail Doppler Radar (TDR) reconnaissance data and for other land-falling priority storms.

Multiple changes were also made to ocean and wave coupling for 2017. One-way coupling to the wave model (WW3) was enabled for the North Atlantic, East Pacific and Central pacific basins. Also, for the first time, HYCOM was coupled to HWRF in the Western Pacific and North Indian Ocean basins. The coupling time step for waves and oceans was further reduced to 6 min (from 9 min) for ease of generating hourly products and the vertical resolution of MPIPOM ocean model was increased to 40 levels (from 24 levels). New hurricane surface wave products were included for the first time which allowed for decommissioning of the NCEP operational Hurricane Wave model. Besides, maximum number of storms that can be run in operations was increased from 7 to 8 storms.

b. HMON

The first version of HMON was implemented at NWS/NCEP operations in 2017. The HMON system runs on-demand with input provided by NHC and CPHC. The atmospheric component of HMON is a triple-nested regional model, with two movable, two-way interactive nested grids following the path of a tropical system. It is coupled to HYCOM through a sophisticated coupler developed at NCEP to provid accurate representation of air-sea interactions. The NCEP operational Global Forecast System (GFS) analysis and forecasts and operational Real Time Ocean Forecast System (RTOFS) provide initial and boundary conditions for the HMON system. This release was fully tested and compared with the GFDL hurricane model (decommissioned in 2017) and it showed significant skill improvements in term of storm track and intensity forecasts in Northern Atlantic, Eastern Pacific and the Central Pacific basins. HMON also provides a first step for EMC's efforts towards unification of operational models within the NEMS framework.

For 2017, HMON had 43 vertical levels with the model top fixed at 50 hPa. It included vortex relocation, but no data assimilation. It was coupled to HYCOM ocean model in the North East Pacific (EPAC) and Central Pacific basins but ran uncoupled for the North Atlantic basin. Just like HWRF, HMON has been configured with triple-nest capability that includes a cloud-resolving inner most grid operating at 2 km horizontal resolution, encompassed by an intermediate grid at 6 km resolution and the outer domain at 18 km resolution. Model physics in HMON is mostly inherited from HWRF model including SAS convection, Ferrier-Aligo micro-physics processes, RRTMG radiation, GFDL surface physics, GFS PBL and NOAH LSM as the land surface model.

4. Performance in the North Atlantic & North East Pacific basins

In the 2017 season, over the North Atlantic basin (Figure 1) NHC's official track forecasts were very skillful, near the best performing models (consensus aids). HWRF results were similar to the other global models (not shown). In fact, HWRF upgrades in vertical resolution increased the skill of track forecasts significantly for 2017, especially out to days 4-5 (Figure 1) with HWRF having better track skill than GFS (AVNO) at Day 5. HMON and COAMPS TC had much larger track errors from hrs 48-96 with HMON showing the lowest track errors of all regional models by Day 5. For maximum wind speed, HWRF matched official skill from hrs 36-96 with official results doing best for early lead times (< 36 hrs) and COAMPS TC giving the least errors at Day 4. HMON showed the lowest bias errors amongst all models till hr 84 and both HWRF and HMON showing minimum bias for Days 4 and 5 ahead of the official results. For the East Pacific basin (Figure 2), once again the NHC official track and intensity forecasts were most skillful. HWRF tracks and intensities had the least error amongst all dynamical and statistical models. HMON tracks had less skill for Days 4 and 5 but intensities were comparable to those from COAMPS TC at all lead times.

Overall, HWRF track forecast skill was substantially improved comparing to FY 2015-2016 HWRF performance for the North Atlantic and East Pacific basins, and HWRF continues to provide very good intensity model guidance (close to OFCL intensity forecast guidance), with improved performance for storms undergoing rapid intensity change. There was also significant improvement of simulations of storm size and structure, with substantially reduced storm size errors and good evidence of modeling concentric eyewalls and eyewall replacement cycles (not shown). For HMON, given that 2017 was the first year into operations (as a replacement for the legacy GFDL hurricane model), overall results are comparable (with slightly reduced skills) for track and intensity forecasts to HWRF forecasts, using much less computation resources compared to HWRF (26

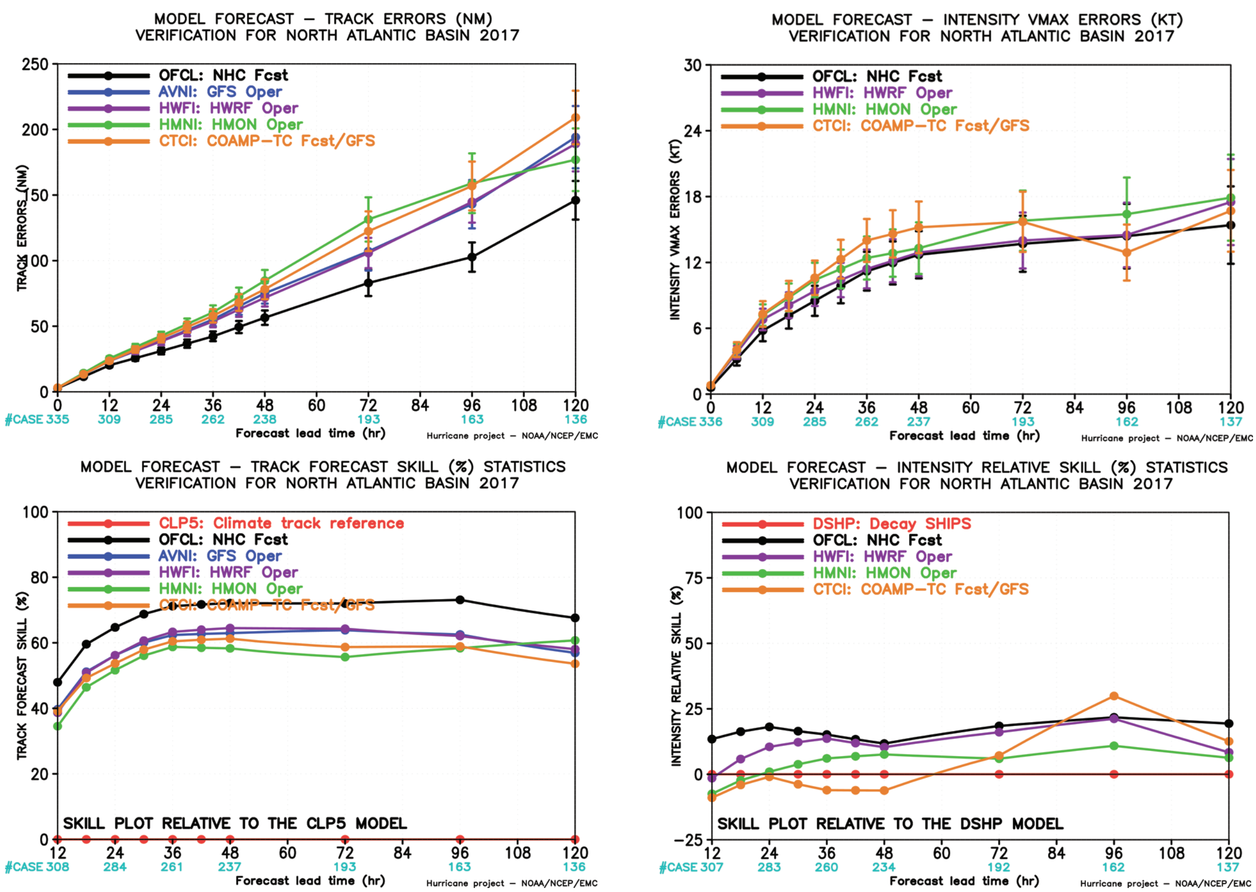

FIG. 1. Model and official (NHC) track (top left panel) and maximum intensity (top right panel) errors for the 2017 North Atlantic basin. Bottom panels show track (left) and intensity (right) forecast skill for the 2017 North Atlantic basin as compared to statistical models CLP5 and DSHP respectively.

nodes vs 63 nodes per storm in operations). For individual storms/forecast cycles, HMON and HWRF provided the desired diversity in track and intensity forecast skill numerical guidance to the operational forecasters at NHC, CPHC and JTWC.

5. Performance in the Western Pacific basin

For the Western Pacific basin (Figure 3), GFS global model had the best track forecasts which were comparable or slightly better than the official track forecasts from JTWC. HWRF was a close second with larger track errors for longer lead-times at Days 4 and 5. COAMPS TC had the lowest intensity errors amongst all dynamical models.

2017 was an unusual year for the Western Pacific basin with very few strong storms (super typhoons) which led to larger intensity errors for HWRF which has done well with stronger storms in the Western Pacific basin in the previous years (2015 and 2016). Efforts are ongoing to increase the number of vertical levels and introduce data assimilation capability in HWRF for 2018 in the Western Pacific basin to improve track and intensity performance.

6. Future plans

Based on real-time experiments during the active North Atlantic season for the last three years, multi-model ensembles based on members from HWRF (Zhang et al., 2014), HMON and COAMPS TC are being considered for operational use for a better estimate of uncertainty in numerical guidance and related products. Other configurations with active three-way coupling (Atmosphere-Ocean-Waves) are also being considered for improved track and intensity skill.

The annual upgrade cycle for both HWRF and HMON will continue for the next two to three years. After that, current plans are to switch all tropical cyclone model development to the NGGPS FV3 dynamical core for operational regional modelling at NCEP including forecasts for tropical cyclones. As part of the recently adopted strategic implementation plan for NCEP/EMC, a number of research efforts are underway to build such capability. These include,

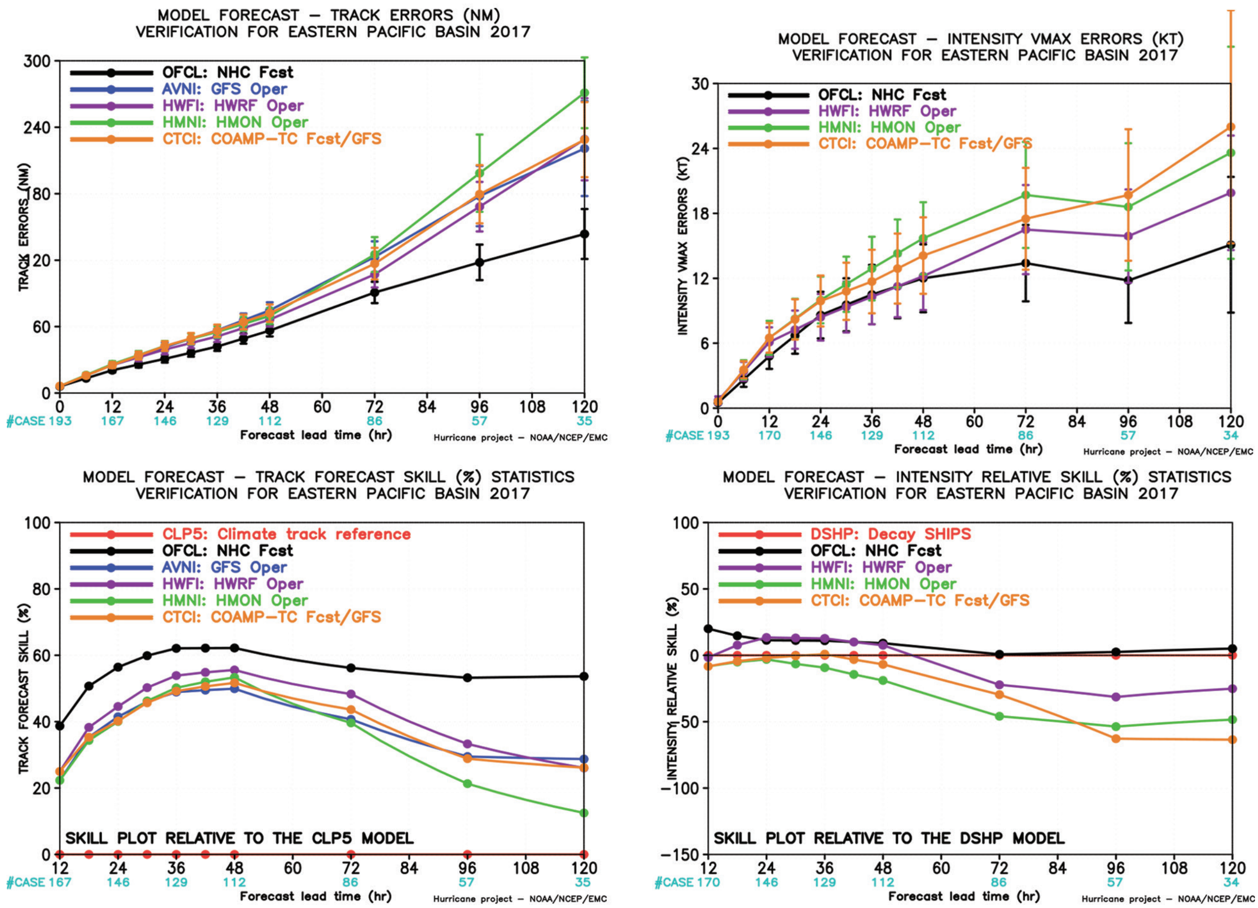

FIG. 2. Model and official (NHC) track (top left panel) and maximum intensity (top right panel) errors for the 2017 North East Pacific basin. Bottom panels show track (left) and intensity (right) forecast skill for the 2017 North East Pacific basin as compared to statistical models CLP5 and DSHP respectively.

amongst others: (a) stand-alone regional FV3 and static high-resolution nests for global FV3; (b) generalized moving nest for FV3 hurricane applications; and (c) FV3 based hurricane model developments for parent grid oriented moving nests and coupling to other earth system components.

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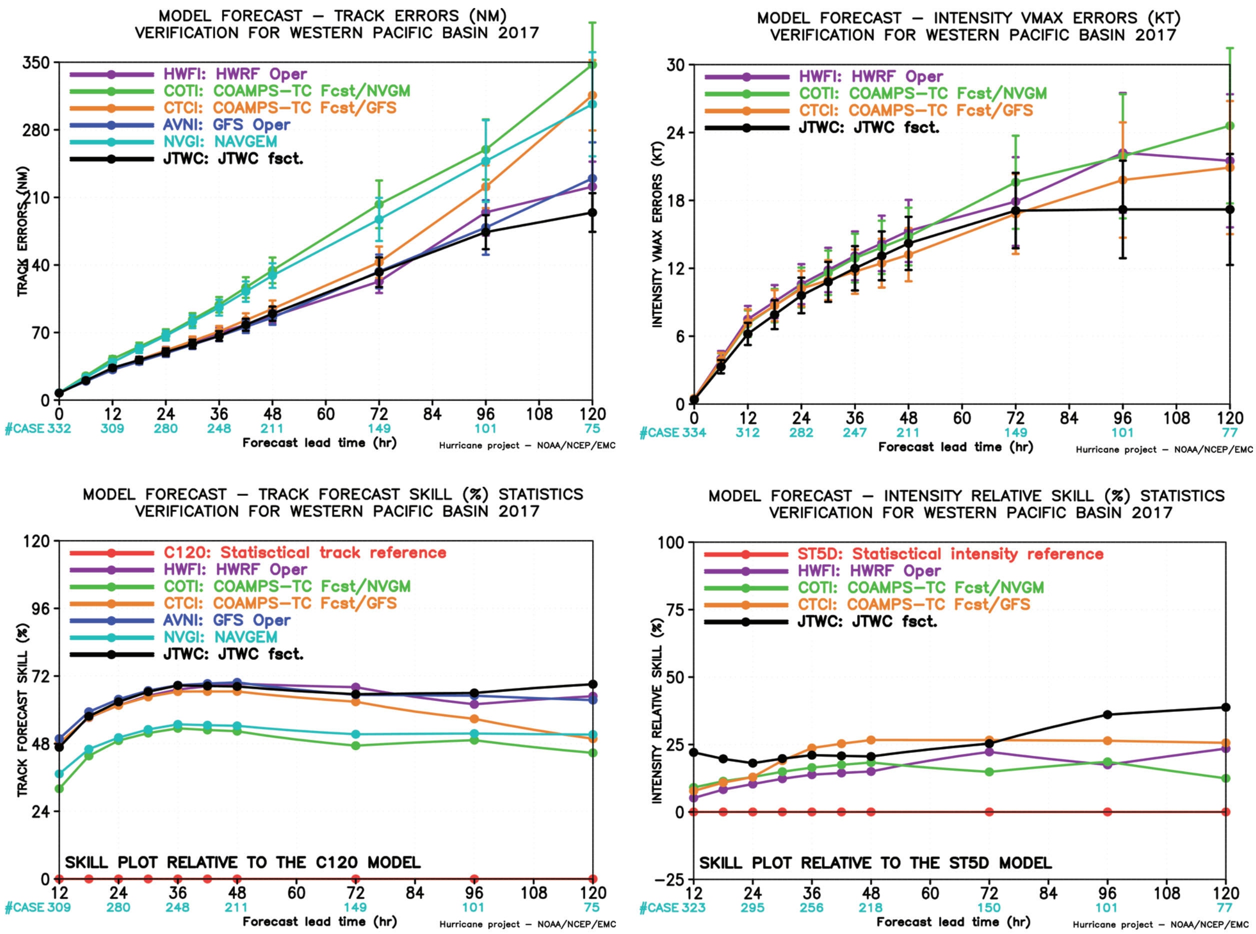

FIG. 3. Model and official (JTWC) track (top left panel) and maximum intensity (top right panel) errors for the 2017 Western Pacific basin. Bottom panels show track (left) and intensity (right) forecast skill for the 2017 Western Pacific basin as compared to statistical models C120 and ST5D, respectively.

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