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ScienceDirect

Tropical Cyclone Research and Review 12 (2023) 30–49

Tropical Cyclone Research and Review

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A review of recent advances (2018–2021) on tropical cyclone intensity change from operational perspectives, part 1: Dynamical model guidance

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Available online 12 May 2023

Abstract

This review summarizes the rapporteur report on tropical cyclone (TC) intensity change from the operational perspective, as presented to the 10th International Workshop on TCs (IWTC-10) held in Bali, Indonesia, from Dec. 5–9, 2022. The accuracy of TC intensity forecasts issued by operational forecast centers depends on three aspects: real-time observations, TC dynamical model forecast guidance, and techniques and methods used by forecasters. The rapporteur report covers the progress made over the past four years (2018–2021) in all three aspects. This review focuses on the progress of dynamical model forecast guidance. The companion paper (Part II) summarizes the advance from operational centers. The dynamical model forecast guidance continues to be the main factor leading to the improvement of operational TC intensity forecasts. Here, we describe recent advances and developments of major operational regional dynamical TC models and their intensity forecast performance, including HWRF, HMON, COAMPS-TC, Met Office Regional Model, CMA-TYM, and newly developed HAFS. The performance of global dynamical models, including NOAA's GFS, Met Office Global Model (MOGM), JMA's GSM, and IFS (ECMWF), has also been improved in

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Peer review under responsibility of Shanghai Typhoon Institute of China Meteorological Administration.

ELSEVIER Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.tcrr.2023.05.004

recent years due to their increased horizontal and vertical resolution as well as improved data assimilation systems. Recent challenging cases of rapid intensification are presented and discussed.

Keywords: Dynamical models; Intensity forecast; Operational forecasts; Tropical cyclone

1. Introduction

Despite steady improvements of tropical cyclone (TC) track forecasts during the past several decades (Landsea and Cangialosi 2018; McAdie and Lawrence 2000), TC intensity forecasting remains a major challenge. As a result of continuous improvements in TC model forecast guidance, the official TC intensity forecast errors from operational centers have shown signs of gradual reductions over the past four years (2018–2021), especially at longer forecast lead times. Fig. 1 shows the official intensity forecast errors (RMSEs) at different lead times as a function of year for Atlantic storms from the National Hurricane Center (NHC) since 1990, and for Western North Pacific storms from the Joint Typhoon Warning Center (JTWC) since 2001, indicating a clear trend of decreasing errors and larger improvement for longer lead times. The improvement is attributed to improved observations, numerical weather prediction (NWP) model guidance, and techniques, as discussed in a series of WMO International Workshops on TCs (IWTC) (https://community.wmo.int/en/meetings). As part of the rapporteur report presented to the 10th IWTC held in Bali, Indonesia, from Dec 5–9, 2022, this review discusses the progress made in the intensity forecasts over the past 4 years (2018–2021), with focus on dynamical model guidance improvements. Recent progress of intensity forecasting by selected operational agencies along with current practices and guidance employed is discussed in the companion paper (Part II) (Wang et al., 2023b). Previous reviews before 2018 on the same subject can be found in the literature (e.g., Courtney et al., 2019a; Courtney et al., 2019b; Leroux et al., 2018).

Recent advancement and development of TC intensity forecast guidance are reviewed from regional models in Section 2, and from global models in Section 3. Both sections will also include models that are under development and will become operational in the near future. Section 4 presents some challenging cases for which models performed poorly in intensity prediction. Summaries and recommendations for the future research and operational communities for the next four years are provided in Section 5. For convenience, a list of acronyms used in the paper is provided at the end of the paper.

2. Intensity forecast guidance from regional models

Despite the aforementioned challenges, there have been steady improvements in TC intensity forecasts over the last four years. One of the main advancements has been in the use of NWP models, especially regional models, which have become more accurate and sophisticated. This section discusses the progress and performance of major operational regional dynamical models: HWRF, HMON, HAFS, COAMPS-TC, Met Office regional model, and CMA-TYM during the last four years (2018–2021).

2.1. HWRF system

The Hurricane Weather and Research Forecasting (HWRF) model is the flagship TC intensity prediction tool at NWS/NOAA (Tallapragada 2016). It is based on the Non-Hydrostatic Mesoscale Model on an E-grid (NMM) dynamical core and can be coupled to Princeton Ocean Model (POM) or HYbrid Coordinate Ocean Model (HYCOM) (Bleck, 2002).

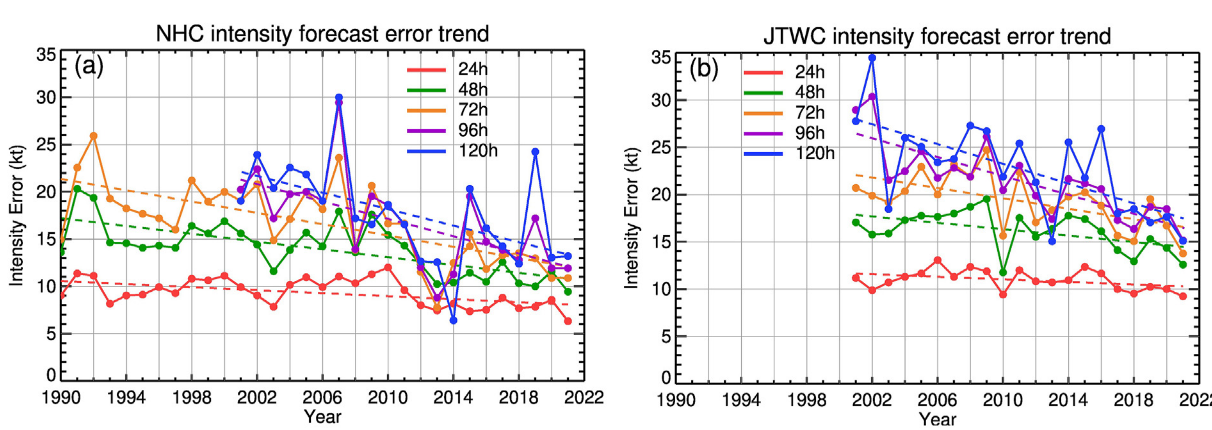

Fig. 1. Trends (dashed lines) of TC intensity forecast errors (RMSEs) at different forecast lead times (a) for Atlantic storms from NHC since 1990 and (b) for Western North Pacific storms from JTWC since 2001 (based on preliminary best-track data as of 1 Nov 2021).

Table 1
HWRF/HMON model physics.

	Schemes	Reference
Land/ocean Surface	Noah Land surface model	Ek et al. (2003)
Surface Layer	GFDL surface layer with TC-specific ocean surface roughness length	Bender et al. (2007) Biswas et al. (2017)
Boundary Layer	GFS Hybrid K-based EDMF PBL with TC-specific tuning	Han et al. (2016) Wang et al. (2018)
Microphysics	Ferrier-Aligo MP	Aligo et al. (2018) Ferrier et al. (2002)
Radiation	RRTMG	Iacono et al. (2008)
Cumulus convection (deep & shallow)	Scale-aware-SAS	Han et al. (2017) Han and Pan (2011)
Gravity wave drag	Unified GWD	Alpert et al. (1988)

The operational HWRF model is configured with triply telescopic storm-following, two-way interactive grids. The atmospheric model physics schemes are summarized in Table 1. The atmospheric component of the HWRF system is coupled to POM and WaveWatch III (WW3) in the North Atlantic, Eastern North Pacific and Central North Pacific basins, and HYCOM in the Western North Pacific Ocean, North Indian Ocean, and Southern Hemisphere basins. The system includes a vortex initialization (VI) procedure (Liu et al., 2020) and an inner-core data assimilation (DA) system (Zhang et al., 2020) to adjust the initial vortex state (intensity and location) based on observations. The boundary and initial conditions of the atmospheric model are provided by the NCEP operational Global Forecast System (GFS).

In the past four years (2018–2021), the HWRF system was annually upgraded, with most upgrades occurring in 2018 and 2020. In 2018, the HWRF implementation incorporated a further decrease in horizontal grid spacings of parent and two moving nest domains, from 18/6/2 km to 13.5/4.5/1.5 km, as well as continued improvement of VI and DA techniques. Stochastic physics were used for self-cycled DA ensemble members (Zhang et al., 2020), with the inclusion of new data sets (GOES-16 AMVs, NOAA-20, SFMR, P-3 TDR), and by accounting for dropsonde drift. The vertical level configuration for the JTWC basins (WPAC, NIO, and SH) was unified to be the same as the NHC and CPHC basins (NATL, EPAC, and CPAC), such that they all have 75 vertical levels with a model top of 10 hPa. With the 2018 upgrade in model resolution, the HWRF model is now the highest-resolution hurricane model ever implemented for operations in the NWS. In the 2020 HWRF upgrade, high-resolution land-sea masks were applied for the moving nests (Ma et al., 2020). The Global Real-Time Ocean Forecast System (RTOFS) was used to initialize the ocean model. The regridding of initial data from RTOFS to the POM grid was improved over shallow layers to fix cold spots of sea surface temperature. The wind speed thresholds in VI were further adjusted to improve the intensity forecast for weak storms, as well as the first several cycles of a storm. DA continued to be improved by including additional satellite and Next Generation Weather Radar datasets. A twenty-member HWRF-based hurricane ensemble prediction system (Zhang et al. 2014; 2019) was run in parallel in real-time from 2018 to 2020 to support multi-model based hurricane forecast guidance. The system was driven by NCEP Global Ensemble Forecast System (GEFS), with stochastic perturbations of model physics parameters such as surface drag coefficients, PBL height, and convection trigger functions.

HWRF has been a reliable model for providing intensity guidance to the TC operational forecasting centers. Its skills have been constantly improving over the years due to annual model upgrades. Fig. 2 shows the reductions of HWRF intensity forecast errors (RMSE) since it became operational in 2007, and the HWRF intensity forecast verification for rapid intensification (RI) cycles only in the past five years

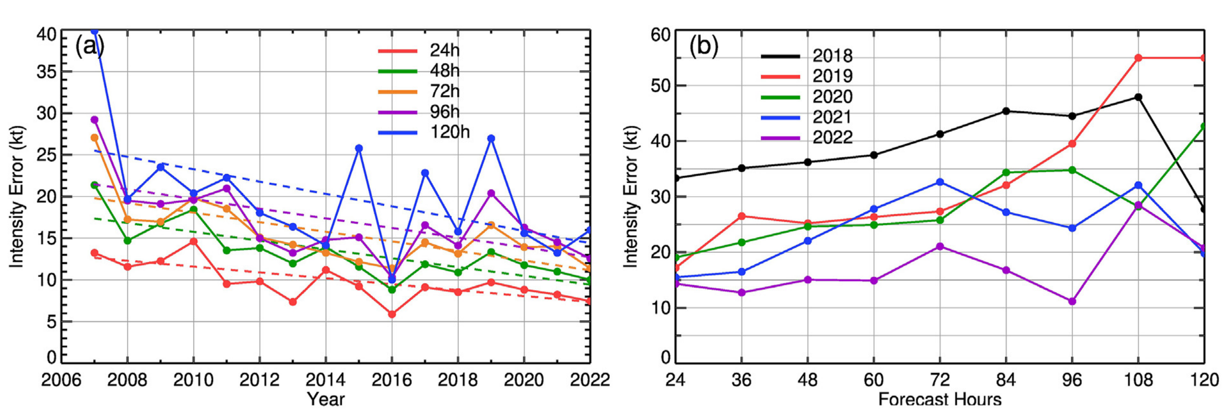

Fig. 2. (a) Trends (dashed lines) of TC intensity forecast errors (RMSEs) at different forecast lead times for Atlantic storms from HWRF since 2007. (b) HWRF intensity forecast verification against best track for RI cycles only in 2018 (black), 2019 (red), 2020 (green), 2021 (blue), and 2022 (purple).

(2018–2022). It can be clearly seen from Fig. 2a that the HWRF intensity forecast errors exhibit a similar decreasing trend as NHC and JTWC official forecast errors shown in Fig. 1, and the downward trend continued since IWTC-9 was held in 2018. Fig. 2b demonstrates that HWRF has made significant progress on improving model capability of predicting RI events. The intensity forecast errors in 2022 have been reduced more than about 50% for RI events compared to that in 2018.

In order to assess the performance of RI prediction of each forecast cycle, Fig. 3 shows the percentage of the RI-observed cycles that were successfully predicted by the HWRF model in each year from 2009 to 2021 in the NATL basin (Wang et al., 2023a). The RI forecast of a cycle is considered as a success if the probability of detection (POD) of RI events is equal to or greater than 0.5 and the false alarm rate (FAR) is equal to or smaller than 0.5 in the 5-day integration period. There is a clear trend that the improvement of the successful prediction rate has accelerated in the past 4 years, compared with earlier years before 2017. The false prediction rate is also reduced, but the improvement is less notable than the successful prediction rate. Nevertheless, the overall performance of HWRF intensity and RI forecast have kept improving.

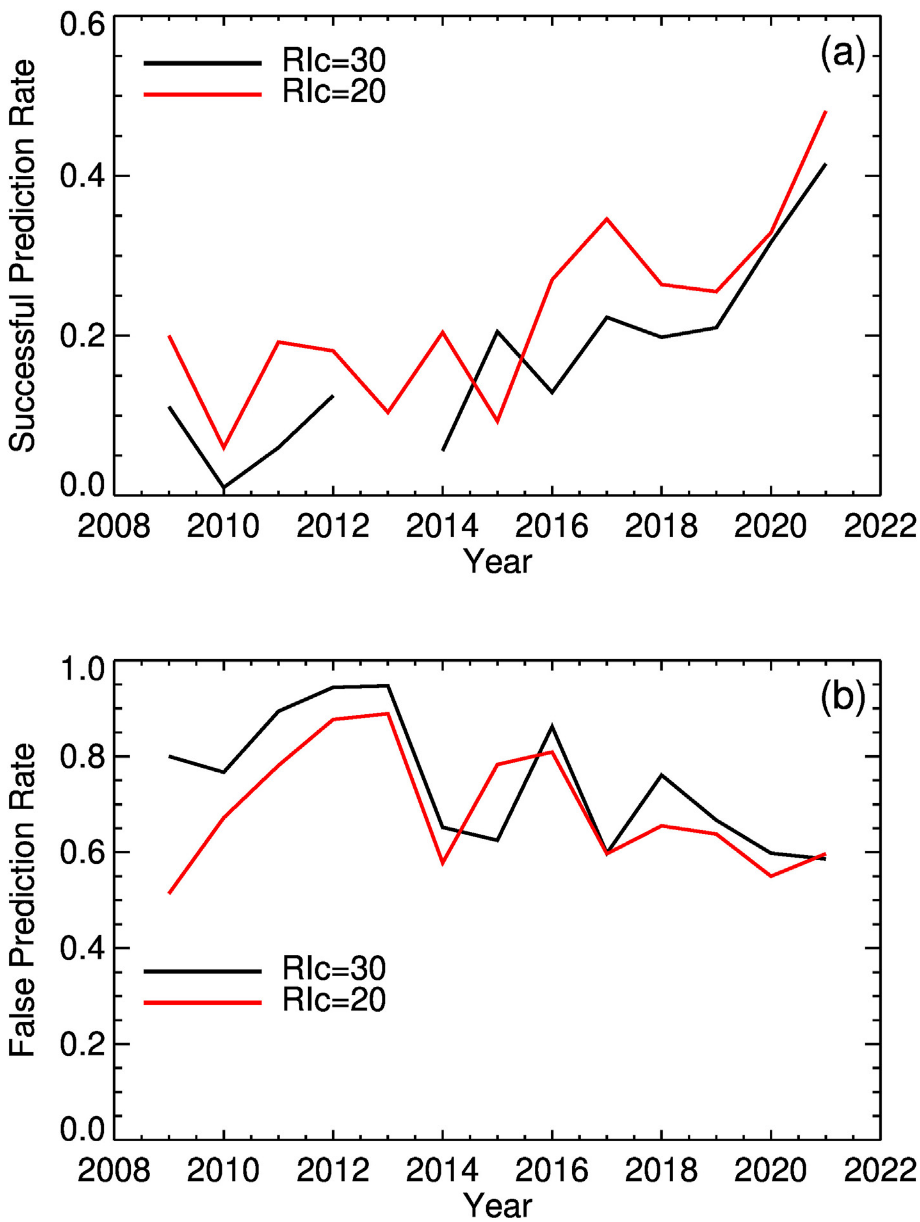

Fig. 3. (a) Successful prediction rate of the RI-observed cycles over the NATL basin, with critical RI values of 30 kt per day (black) and 20 kt per day (red). A RI cycle forecast is successful if FAR ≤0.5 and POD ≥0.5 during the 5-day integration period. Intensity changes are calculated over the preceding 24-h period for each forecast time. Forecasts are compared with NHC's best-track data. (b) False RI prediction rate of the RI-forecast cycles. A forecast cycle is a false alarm cycle if FAR >0.5 during the 5-day integration period. Note that POD cannot be calculated in 2013 with a critical RI value of 30 kt per day because no RI events can be identified in the best-track with the critical RI value in that year.

The TC intensity forecast reported from an NWP model is normally defined as the maximum instantaneous 10-m wind at a single model grid point at a given synoptic hour (Tallapragada et al., 2014). Zhang et al. (2021c) showed that the maximum 10-m wind speed (Vmax) fluctuations from high-frequency ($3^{1}/_{3}$ second) HWRF output could be as high as 20 kt in less than 1 h (Fig. 4a). On the other hand, the NHC best track defines Vmax as the 1-min average based on available observational data. To reduce high-frequency Vmax fluctuations, they tested running-mean with different time windows (3–9 h) at synoptic times and found that the smoothed high-frequency HWRF output improved Vmax forecast skill in general as well as RI cycles by up to 8% and produced a more realistic distribution of 6-h intensity change when compared with low-frequency, instantaneous output (Fig. 4b). The 6-hourly running mean Vmax forecast has been delivered to NHC as an operational product since 2020.

2.2. HMON system

Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic model (HMON) (Mehra et al., 2018; Wang et al., 2019) is another operational system at NCEP designed to provide high-resolution intensity and track forecast guidance to NHC, along with HWRF. The atmospheric component of the HMON model is based on the Non-Hydrostatic Mesoscale Model on a B-grid (NMMB) dynamic core, which is 2-way coupled to HYCOM (Bleck 2002). The operational deterministic HMON system is configured as triple-nested regional domains, with one parent domain and two movable nests. The atmospheric model of HMON uses the same physics schemes as that of HWRF (Table 1). Currently, the model has 71 vertical levels, with the horizontal grid spacing of three domains of 18, 6, and 2 km, respectively. Large scale data are provided by the NCEP operational GFS and RTOFS. A VI procedure was used to adjust the initial location and intensity of the TCs based on observations (Liu et al., 2020). The initialization process of HMON does not include a DA system. HMON has been in operations since 2017 and has demonstrated continuous improvements in intensity prediction.

Several upgrades were made to the model infrastructure and physics during the past four years. In 2018, the number of the vertical levels of the atmospheric model was increased from 42 to 51. The scale-aware simplified Arakawa-Schubert (SAS) convection scheme was used to replace the old version of the SAS scheme, and the NCEP GFS EDMF-based PBL scheme was used to replace the old GFS PBL scheme with the counter-gradient for nonlocal fluxes. The composite vortex library was updated for the initialization. The momentum and enthalpy exchange coefficients (i.e., Cd and Ch) were updated based on the latest observational estimates. In 2020, the number of vertical levels of the atmospheric model was further increased from 51 to 71. The original IGBP roughness length was used in the model to address an issue where wind speed is reduced too quickly once a TC moves to land. The Gravity Wave Drag (GWD) scheme was turned on in the outer nest domain. The upgrades also include the use of the latest HYCOM model and coupler. An eleven-member HMON-based ensemble system (Wang et al., 2019) was run in parallel from 2018 to 2019 to provide track and intensity forecast guidance based on the multi-model (HMON, HWRF, and CTCX) ensemble system. The HMON ensemble system is driven by the large-scale fields from NCEP GEFS, with different PBL and convection schemes as well as random perturbations to physics parameters and initial vortex intensity and position.

Fig. 5 shows the annual RMSEs of the track and intensity in the NATL and EPAC basins at all lead times forecasted by the HMON model from 2017 to 2021. It is clear that both track and intensity forecast errors are reduced over the years. The performance of the HMON model in 2021 is close to the HWRF model, with the intensity outperforming many other models. Similar to the HWRF model, the HMON model shows some ability to forecast RI events. DeMaria et al. (2021) found that HWRF and HMON are the dynamical models providing the best RI forecast guidance for the Atlantic basin. As of this writing, the HMON model continued to perform very well for the storms in 2022 over both basins, even better than the HWRF model. In general, the HMON model performs better in forecasting the track and intensity for EPAC storms than for NATL storms (Zhu et al., 2021). HMON performed well for

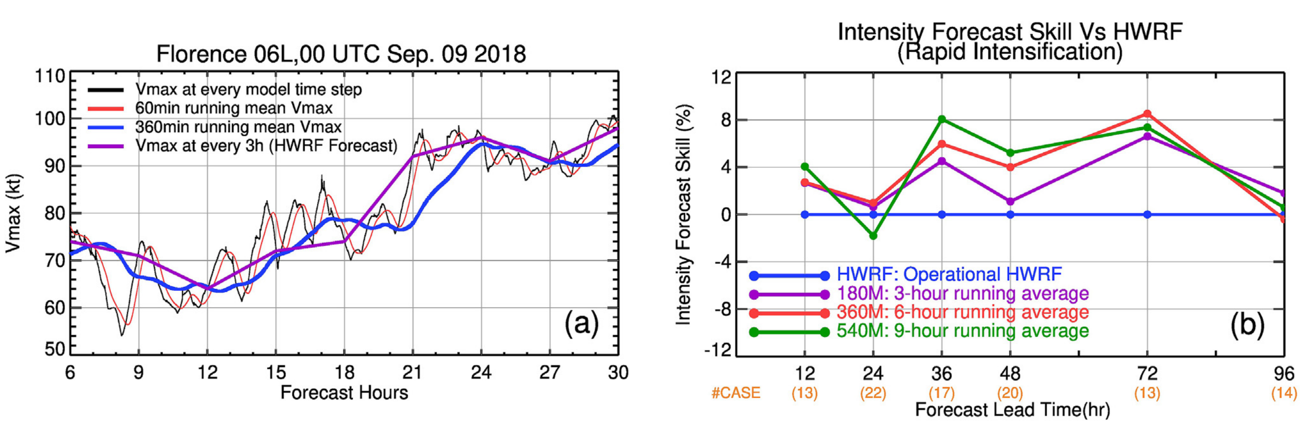

Fig. 4. (a) The Vmax from HWRF forecasts of Hurricane Florence initialized at 0000 UTC 9 Sep 2018 during the forecast period of 6–30 h. (b) Intensity forecast skill scores for forecast cycles in which RI occurred are compared for the operational HWRF (HWRF; blue), the running mean of the high-frequency output over a ±1.5-h time window (180M; purple), over a ±3-h time window (360M; red), and over a ±4.5-h time window (540M; green).

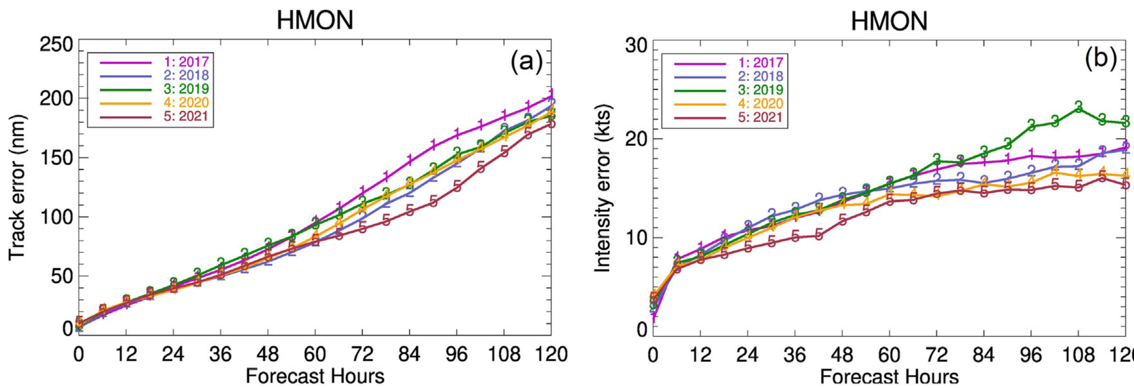

Fig. 5. The RMSEs of (a) track and (b) intensity of HMON forecasts in the NATL and EPAC basins from 2017 to 2021.

several land falling storms in the NATL basin. For example, Fig. 6 compares the performance of several operational models in forecasting the track and intensity for Hurricane Laura (13 L) in 2020. Hurricane Laura was a deadly and destructive Category 4 hurricane that made landfall in Louisiana. For this major hurricane, the HMON model had remarkable performance on both track and intensity, with the smallest track and intensity errors after 72 h among the three regional hurricane models (i.e., HWRF, HMON, and CTCX). The HMON model forecasted the track very close to the best track, even better than NCEP GFS before 72 h (Fig. 6a). Also, the HMON model captured RI events very well for this storm (figures not shown).

2.3. HAFS system - a new hurricane model at NCEP

The Hurricane Analysis and Forecast System (HAFS) is a Unified Forecast System (UFS) application for TC prediction that is expected to become operational in 2023. HAFS is an atmosphere-ocean-wave coupled TC forecast system, featuring a cloud-permitting, high-resolution, and storm-following nest, vortex initialization, and inner-core data assimilation. HAFS has been under active development and running experimentally in real-time since 2019. The Initial Operational Capability (IOC) of HAFS is scheduled for the 2023 hurricane season. HAFS will replace HWRF and HMON to become NCEP's operational TC forecast system.

HAFS is designed as a coupled atmosphere-ocean-land multi-scale model and data assimilation system. The atmospheric model dynamics is based on the fully compressible Finite-Volume Cubed-Sphere (FV3) dynamical core (Harris et al., 2020; Lin 1997; 2004; Lin and Rood 1996; 1997) with a Lagrangian vertical coordinate (Chen et al., 2013). The ocean model implemented in HAFS is HYCOM (Bleck 2002; Bleck et al., 2002). HAFS can be configured as either a stand-alone regional system or global system, both of which can include nested domains with higher resolutions. Before 2021, all developmental experiments were based on a fixed basin scale domain with high resolution (3 km) and without a vortex initialization process (Dong et al., 2020; Hazelton et al., 2021). Similar to HMON and HWRF, HAFS has a basin-scale ensemble system driven by large scale fields from NCEP GEFS with lower spatial resolution (6 km) and stochastic perturbations in model physics schemes (Zhang et al., 2021b).

The moving nest capability and a combined VI and DA system had been developed and added to the HAFS system since late 2021. To maintain the current operational capability of dynamical model diversity, the operational HAFS is required to provide two sets of TC track and intensity forecasts (HFSA and HFSB), with the former replacing HWRF and the latter replacing HMON. Like the HWRF and HMON models, both HFSA and HFSB will be configured with one movable and two-way interactive nested grid that follows the projected path of the storm. Table 2 lists the main features of the two proposed HAFS configurations. The parent domain of HFSB (75° × 75°) is slightly smaller than that of HFSA (78° × 75°), while the nest domain coverages are the same. Both configurations have the same resolutions for the parent and nest domains using an Extended Schmidt Gnomonic (ESG) grid system (Purser et al., 2020). Different model physics schemes are used in the two configurations, as shown in Table 3. Currently the single-moment GFDL microphysics scheme (Chen and Lin 2013; Krueger et al., 1995; Lin et al., 1983; Lord et al., 1984) is used in HFSA, while the double-moment Thompson microphysics scheme (Thompson and Eidhammer 2014) is used in HFSB. This is the major difference between the HFSA and HFSB configurations. Because the use of the double-moment Thompson scheme in HFSB is more computationally costly than that of the single-moment GFDL scheme in HFSA, the calling frequency of the radiation scheme in HFSB is lower than that in HFSA in addition to smaller parent domain (Tables 2 and 3). More model differences will be needed in the future for the two configurations to provide diverse model guidance.

Three-year retrospective experiments have been conducted for HFSA and HFSB for NATL and EPAC TCs during 2020–2022. Fig. 7 shows the early model intensity forecast skill relative to the corresponding operational HWRF from both HAFS configurations, referred to as HFAI and HFBI, respectively. It can be seen that in general, the intensity forecast skills for NATL TCs are improved over HWRF after 36 h with the maximum improvements of about 10% at later forecast lead times from HFBI. For EPAC TCs, both HAFS experiments outperformed HWRF (H221, 2021 version) at all

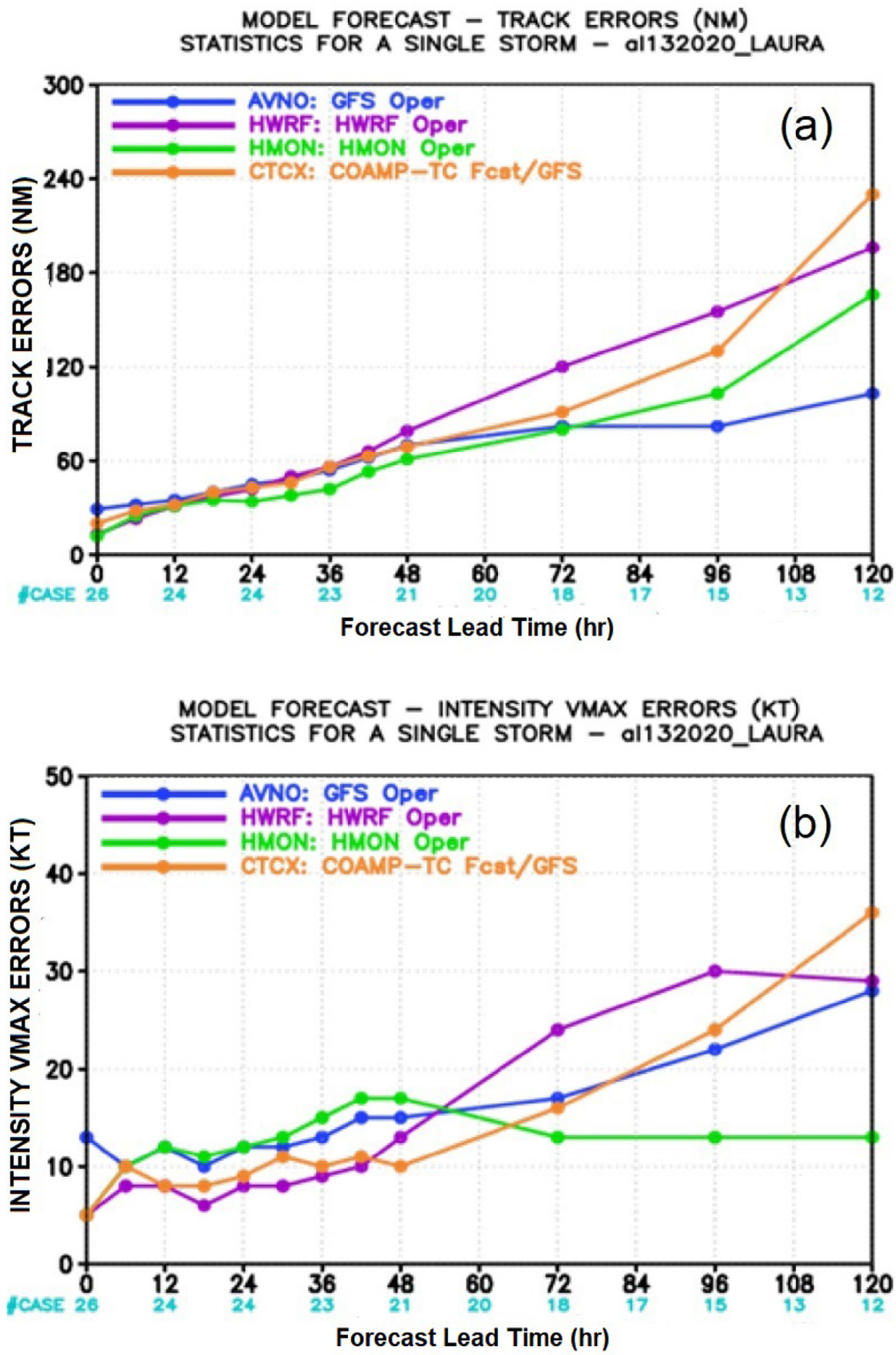

Fig. 6. The RMSEs of (a) track and (b) intensity forecasts for Hurricane Laura (13 L) in 2020 by AVNO, HWRF, HMON, and CTCX. The number of forecast cases used in the verification are shown at the bottom of each panel.

forecast lead times except for 48 h lead time from HFAI, which is ~6% degradation compared to HWRF. These comparisons demonstrated that HAFS is now capable of producing comparable or slightly better TC track (not shown) and intensity forecast guidance than HWRF. One noticeable feature in Fig. 7 is that HFBI provides better intensity forecast skills than HFAI, especially at later forecast hours. This is possibly due to the fact that the HAFS model using the Thompson microphysics scheme is better at predicting RI events than that using the GFDL microphysics scheme.

The future HAFS development includes, (1) increasing the diversity of the two HAFS configurations, especially model physics, (2) improving model physics schemes in TC environments, and (3) improving HAFS vortex initialization procedure to ensure it is consistent with inner-core DA procedure. Also, the current HAFS VI procedure uses the same composite vortex library as HWRF. Given the sensitivity of VI to the composite vortex in different models (Liu et al., 2020), the composite vortex may need updating and testing for the HAFS framework in the next upgrade.

Table 2
Main features of the two HAFS configurations.

HAFSv1.0	Domain	Resolution	DA/VI	Ocean/Wave Coupling	Physics	Basins
HFSA	Storm-centric with one moving nest, parent: ~78 × 75°, nest: ~12 × 12°	Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top	Vmax >50 kt warm-cycling VI and 4DEnVar DA	Two-way HYCOM, one-way WW3 coupling for NHC AOR	Physics suite-1 (Table 3)	All global Basins Max 7 Storms Replace HWRF
HFSB	Storm-centric with one moving nest, parent: ~75 × 75°, nest: ~12 × 12°	Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top	Vmax >40 kt warm-cycling VI and 4DEnVar DA	Two-way HYCOM No Wave	Physics suite-2 (Table 3)	NHC/CPHC Max 5 Storms Replace HMON

Table 3
Two suites of HAFS model physics.

	HFSA	HFSB	Reference
Land/ocean Surface	NOAH LSM VIIRS veg type, HYCOM	NOAH LSM VIIRS veg type HYCOM	Ek et al. (2003)
Surface Layer	GFS, HWRF TC-specific sea surface roughnesses	GFS, HWRF TC-specific sea surface roughnesses	Miyakoda and Sirutis (1986); Long (1984, 1986) Zheng et al. (2017)
Boundary Layer	Sa-TKE-EDMF, TC-related calibration, mixing length tuning#	Sa-TKE-EDMF, TC-related calibration, tc_pbl = 1*, mixing length tuning	Han et al. (2019) #Wang et al. (2022) *Chen et al. (2022)
Microphysics	GFDL single-moment	Thompson double-moment	Lin et al. (1983) Chen and Lin (2013) Thompson and Eidhammer (2014)
Radiation	RRTMG Calling frequency 720 s	RRTMG Calling frequency 1800 s	Iacono et al. (2008)
Cumulus convection (deep & shallow)	Scale-aware-SAS calibrated deep convection entrainment	Scale-aware-SAS	Han et al. (2017)
Gravity wave drag	Unified GWD (orographic on/convective off)	Unified GWD (orographic on/convective off)	Alpert et al. (1988)

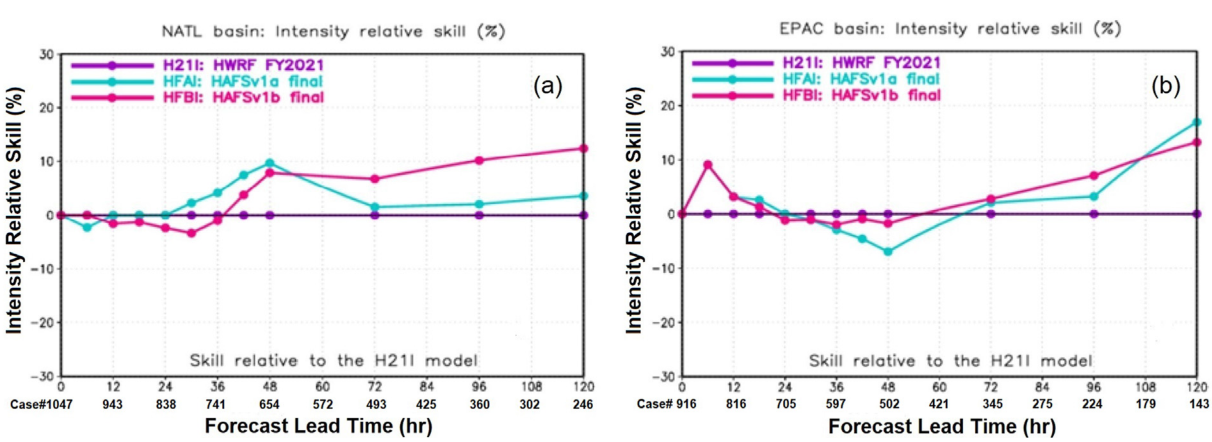

Fig. 7. Early model HFAI (cyan) and HFBI (red) intensity forecast skill relative to the operational HWRF (H221, purple) from retrospective experiments for (a) NATL and (b) EPAC TCs during 2020–2022.

2.4. COAMPS-TC

The operational deterministic COAMPS-TC model (Doyle et al., 2014), developed by the U.S. Naval Research Laboratory, has been upgraded on an annual basis over the last 4 years, with significant advances in forecast performance for track, intensity, and storm structure. The 2018 COAMPS-TC deterministic model consists of a fixed outer grid mesh at 36-km horizontal resolution and two storm-following inner grid meshes at 12- and 4-km resolution. The atmospheric model uses 40 vertical levels, with a top near 10 hPa. COAMPS-TC includes a balanced vortex for initialization of tropical

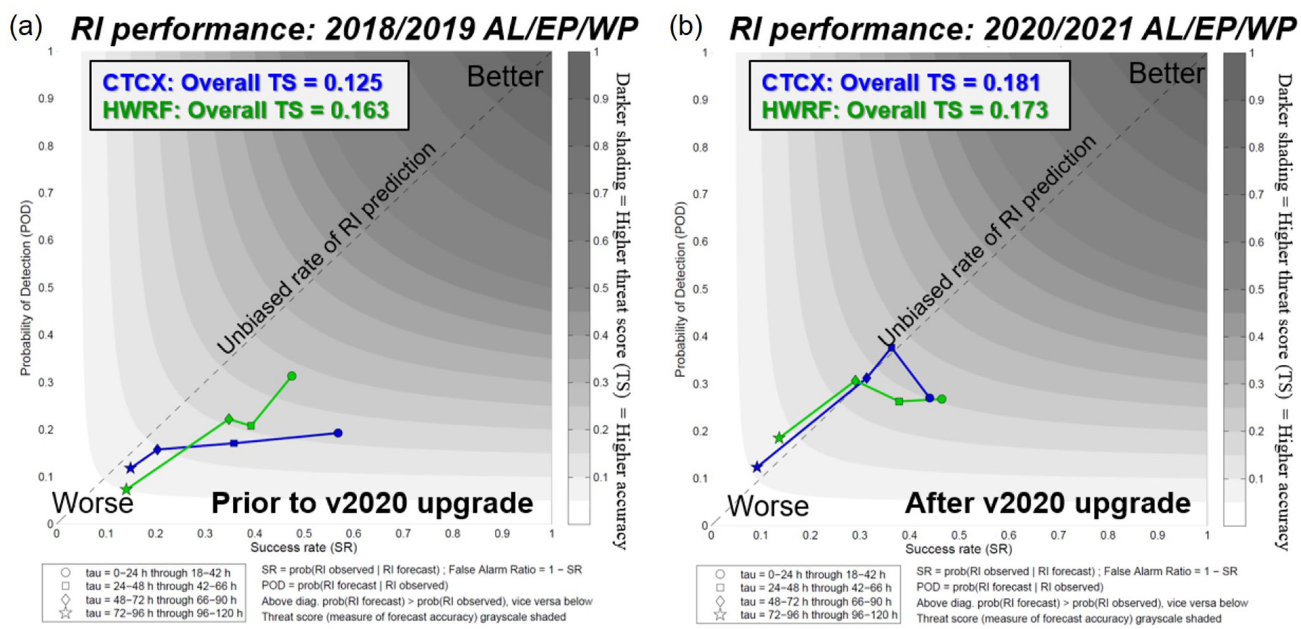

Fig. 8. Performance diagrams comparing real-time rapid intensification forecasts from the HWRF (green) and CTCX (blue) models for 2018–2019 (a) and 2020–2021 (b), for the Western Atlantic, Eastern North Pacific, and Western North Pacific basins. The threat score is shaded in gray with darker shading corresponding to higher threat scores. The four symbols in the legend correspond to the various forecast time bins.

cyclones, a full suite of physical parameterizations including bulk microphysics, 1.5-order turbulent kinetic energy closure PBL, surface layer with a drag coefficient relationship appropriate for the high-wind regime, dissipative heating, shallow and deep convection, and radiative processes. The atmospheric model is coupled with the NRL Coastal Ocean Model (NCOM) and utilizes the Navy Coupled Ocean Data Assimilation (NCODA) system. A major recent milestone was the introduction of the GFS-based deterministic COAMPS-TC (CTCX) into operational production at the Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) in 2019, joining the Navy Global Environmental Model (NAVGEM) based deterministic COAMPS-TC (COTC) which has been in operations since 2013. CTCX performance in predicting RI, in terms of accuracy and relative frequency, has been drastically improved over the past four years due to upgrades in model initialization (downscaling the initial state from GFS for weak TCs rather than utilizing balanced vortex initialization) and surface drag coefficient formulation (reducing values at high wind speeds). CTCX RI prediction performance has improved substantially from 2018 to 2019 (Fig. 8a) to 2020–2021 (Fig. 8b) with improvement relative to HWRF as well.

Another major advance was the implementation of the 11-member COAMPS-TC ensemble (Komaromi et al., 2021) into operations in 2020. The COAMPS-TC ensemble runs at the same atmospheric model resolution as the deterministic model, and it has synoptic-scale and TC vortex initial condition perturbations, lateral boundary condition perturbations, and model formulation perturbations for representation of forecast uncertainty. The operational ensemble runs for up to three storms per watch (00 UTC, 06 UTC, 12 UTC, and 18 UTC), prioritizing storms in the Western North Pacific and other JTWC basins. The COAMPS-TC ensemble system includes a graphics package to generate plots representing the ensemble forecast distributions for TC position, intensity, intensity change, minimum MSLP, and wind radii.

2.5. Met Office Regional Model

The Met Office regional model capability is primarily focused on the UK area (Bush et al., 2020). The deterministic regional model uses a variable resolution which has a high resolution inner domain (1.5 km grid boxes) over the area of forecast interest, separated from a coarser grid (4 km) near the boundaries by a variable resolution transition zone. The atmospheric model uses 70 levels in the vertical, with a fixed model lid of 40 km above the sea level. Regional "downscaler" models (starting from downscaled MOGM analyses) are also run for various other parts of the world for use in Met Office forecast operations and as part of international collaborations. One such model is the Southeast (SE) Asia Model developed for the WCSSP (Weather and Climate Science for Service Partnership) Southeast Asia project. Details can be found in the website.[1]

Two recent cases indicate how the SE Asia Model can provide better TC intensity guidance than the Met Office Global Model (MOGM). The left panel of Fig. 9 compares the central pressure predictions for Typhoon Goni between the MOGM and SE Asia Model. The former was not able to

[1] https://www.metoffice.gov.uk/research/approach/collaboration/newton/weather-and-climate-science-for-service-partnership-southeast-asia.

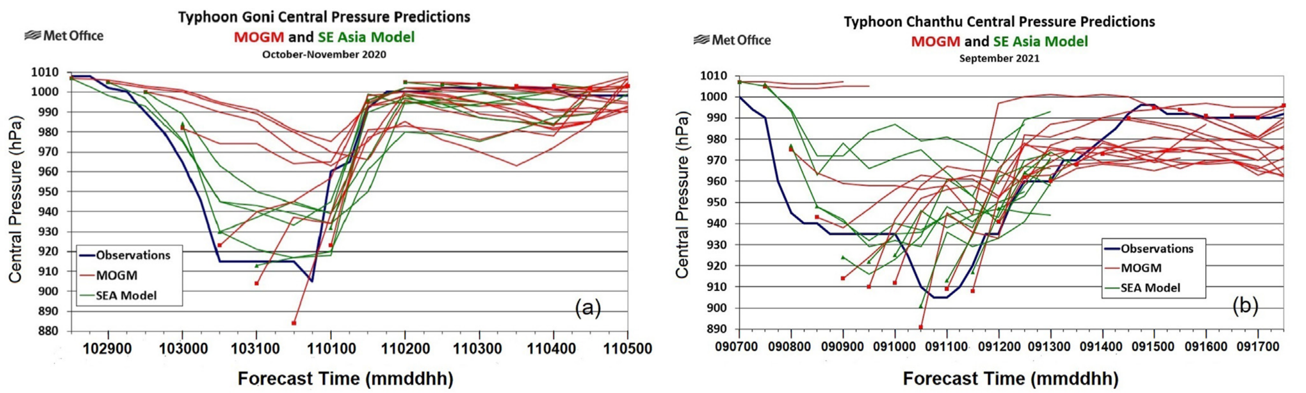

Fig. 9. MOGM and SE Asia Model central pressure predictions at different forecast times (UTC in format of mmddhh) for (a) Typhoon Goni, October–November 2020 and (b) Typhoon Chanthu, September 2021.

predict the initial rapid intensification of the storm into an intense typhoon. In contrast the SE Asia Model predicted much faster rates of intensification including one run which predicted a deepening of 54 hPa in the first 12 h of the forecast. On the other hand, most global models, including the MOGM, were extremely poor at predicting the rapid intensification of Typhoon Chanthu. Some runs of the models showed no intensification at all and quick dissipation. The right panel of Fig. 9 shows that the first few runs of the SE Asia Model were far superior to the MOGM in that they predicted intensification by as much as 43 hPa in 24 h, whereas the MOGM shows no intensification and dissipation within 48 h.

2.6. CMA-TYM model

The operational version of the China Meteorological Administration Typhoon Model (CMA-TYM) is formerly known as GRAPES_TYM (before 2021). CMA-TYM (Ma et al., 2021) underwent two upgrades in 2019 and 2021, respectively, during the period of 2018–2021. The upgrade of CMA-TYM in 2019 includes the expansion of the model integration area from 90 to 171 °E, 0–50 °N to 40–180 °E, 15S-60 °N, an increase in model horizontal resolution from 0.12° to 0.09°, and an increase in the number of vertical levels from 50 to 68. With the upgrade, CMA-TYM has been able to provide TC forecasts in the Bay of Bengal and the Arabian Sea. The upgrade in 2021 mainly includes the implementation of a scale-aware convection parameterization scheme and the optimization of roughness calculation in the surface layer scheme. The increased number of vertical levels likely lead to the reduction of the 48–120 h mean track errors by 4%, 5%, 8% and 7% (not shown) and 24–120 h mean intensity errors by 14%, 17%, 29%, 31%, and 9% (Fig. 10). Configuration information regarding CMA-TYM in 2022 is described in Table 4.

The evolution of mean track and intensity absolute errors from 2018 to 2021 are shown in Fig. 11. Thus, in the recent 4 years (2018–2021), the mean track errors of the lead times longer than 84 h have decreased significantly, while the mean track errors of the lead times within 48 h have not changed

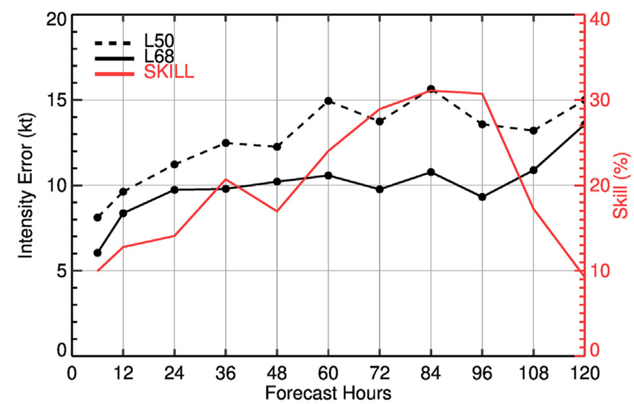

Fig. 10. Comparison of the CMA-TYM's mean intensity forecast errors from vertical L68 (black solid line) and L50 (black short dash), and intensity forecast skill improvements by increasing vertical levels from 50 to 68 (red solid line).

much (Fig. 11a). The intensity forecasts are improved for the lead times within 72 h, but they are degraded for the lead times longer than 84 h (Fig. 11b).

3. TC intensity forecast guidance from global models

With the increased model resolution, TC intensity forecasts provided by global models are much improved. The upgrades and performance of four global models from the Met Office, ECMWF, US NCEP, and JMA, during the past four years (2018–2021) are discussed here.

3.1. MOGM

The deterministic Met Office global atmospheric model is fully coupled to a ¼ degree ocean model. The horizontal grid

Table 4
CMA-TYM configuration in 2022.

Integration domain	Model resolution	Vortex initialization	Forecast time
40-180°E;-15-60°N	0.09°/L68	Intensity correction	120 h

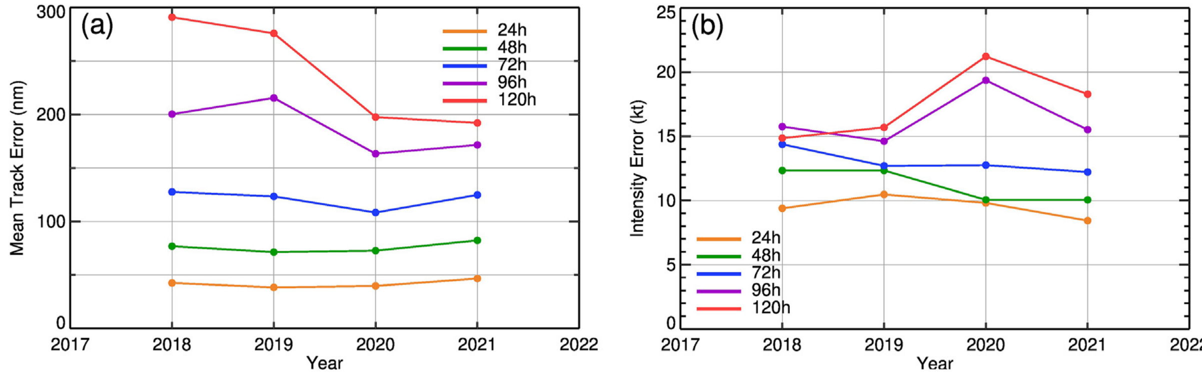

Fig. 11. (a) Mean CMA-TYM track absolute errors at different lead times varying from 2018 to 2021. (b) Mean CMA-TYM intensity absolute errors.

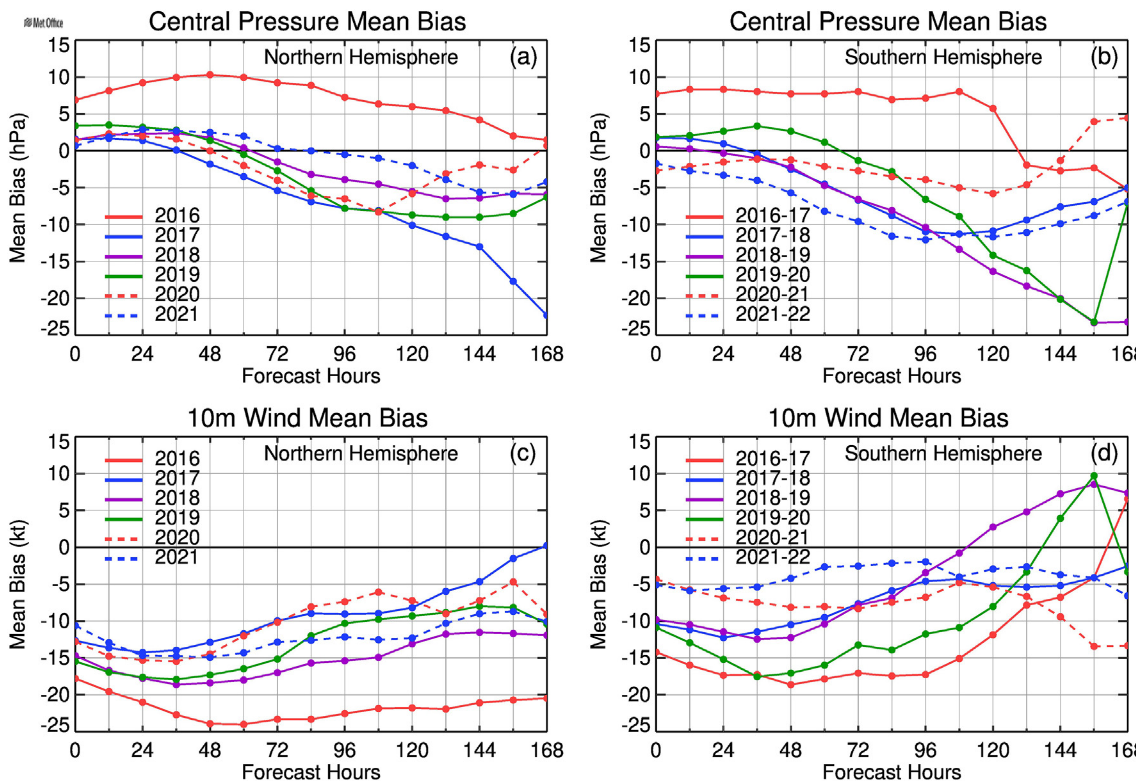

Fig. 12. Met Office Global Model TC intensity biases for recent seasons in the northern hemisphere (left) and southern hemisphere (right). Top row central pressure, bottom row 10-m wind. Results from individual seasons are shown by different colors.

length of the atmospheric model is about 10 km (in mid-latitudes), with 2560 × 1920 grid points. In the vertical, the model uses 70 levels, with the top of 80 km above the sea level. This section describes the performance of the deterministic MOGM in the prediction of TC intensity and intensity change – both central pressure and 10-m winds. Note, in all cases, model 10-m winds are compared to warning center estimates of 1-min sustained winds.

Fig. 12 shows the intensity biases for the last six TC seasons (2016–2021). Longer lead time values are more volatile than values at shorter lead times due to the smaller number of cases (particularly in the southern hemisphere). The top row of Fig. 12 shows that in recent years the central pressure bias is small and slightly positive (storms too weak) at short lead times, but becomes increasingly negative (storms too strong) at longer lead times. This demonstrates a propensity for the model to strengthen TCs too slowly and reach peak intensity too late. Examination of extreme cases also shows that the large negative bias at long lead times is partly due to the over-deepening of intense TCs which move poleward into the subtropics. The lack of ocean feedback due to operating an atmosphere-only model at the time was primarily responsible for this. The MOGM was coupled to the ocean from May 2022.

The maximum 10-m wind bias (bottom row of Fig. 12) was mostly negative at all lead times, reflecting the long-standing low bias in model winds. This has also resulted in a bias in the wind-pressure relationship which is discussed further below.

Mean absolute errors for central pressure and 10-m wind (Fig. 13) shows a gradual increase with forecast lead time until around 72 h, with errors then level off at longer lead times. Errors for the last two seasons (dotted lines) are amongst the lowest for shorter lead times.

In common with some other modeling centers, the Met Office has modified its numerical weather prediction models to cap the near surface drag over the ocean for high wind speeds. This is based on theoretical research and experimental simulations (Donelan et al., 2004; Soloviev et al., 2014). The main effect of this change to the model configuration is to increase model wind speeds with little or no change in the surface pressure, thus improving the wind-pressure relationship for TC forecasts. The change was implemented in the MOGM late in 2020. Fig. 14 shows the wind-pressure relationship for all MOGM forecasts for all TCs in 2020 (left) and 2021 (right) and illustrates how the change to the near surface drag over the ocean in the model improved the wind-pressure relationship for TCs in 2021.

3.2. IFS ECMWF

It is known that the IFS ECMWF coupled atmospheric and ocean modeling system performs well in TC track forecasting.

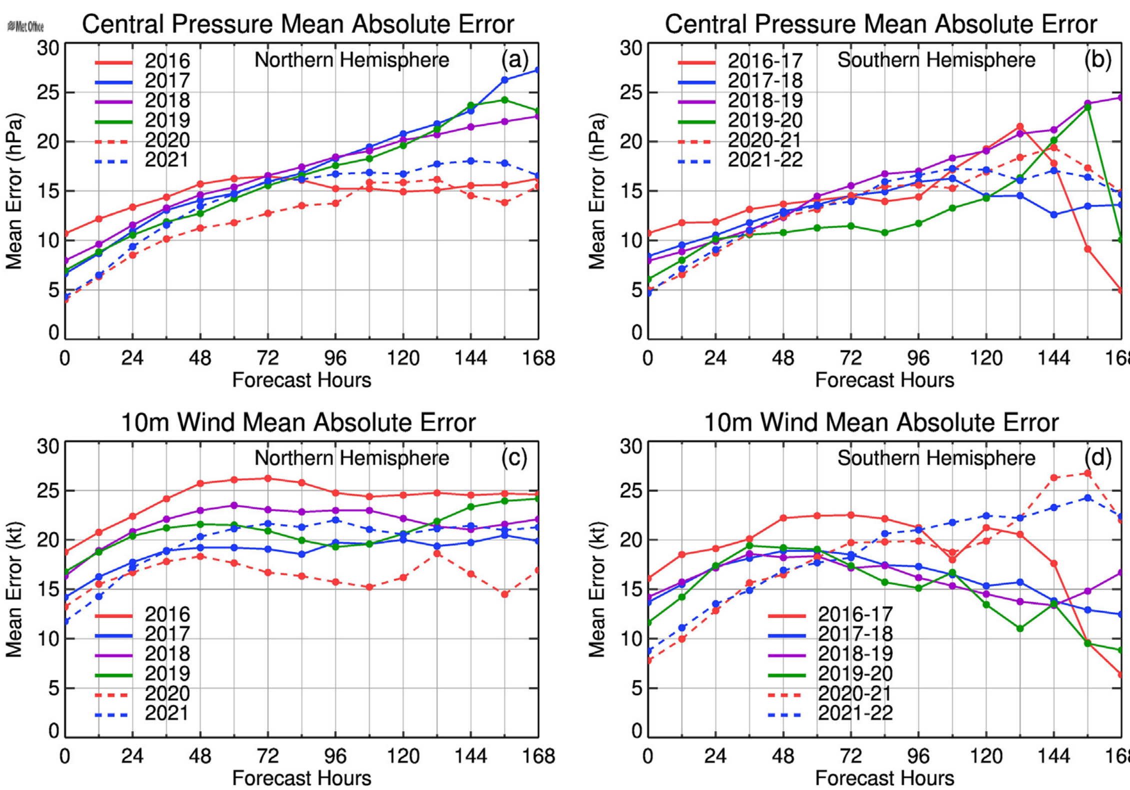

Fig. 13. Met Office Global Model TC intensity mean absolute errors for recent seasons in the northern hemisphere (left) and southern hemisphere (right). Top row central pressure, bottom row 10-m wind. Results from individual seasons are shown by different colors.

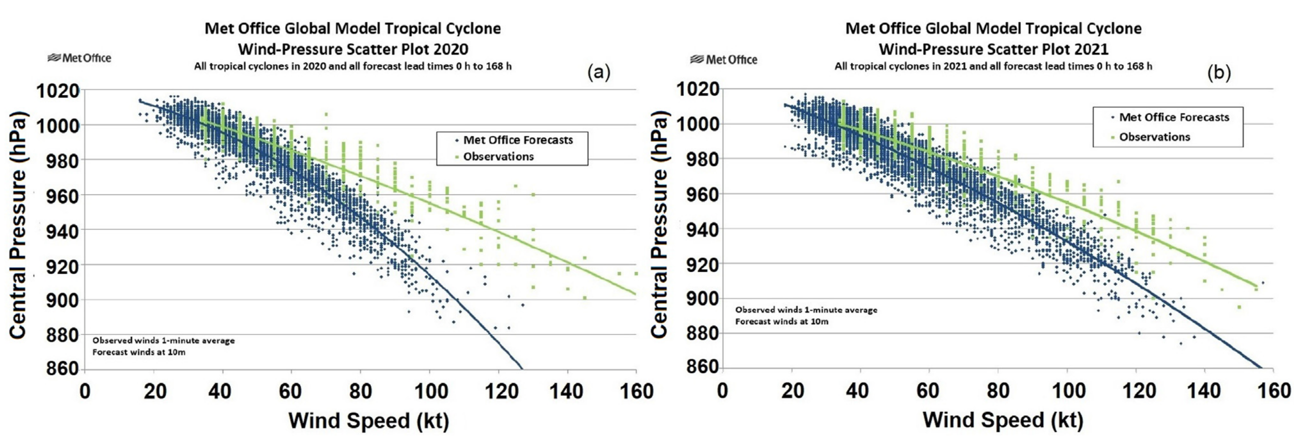

Fig. 14. Met Office Global Model wind-pressure scatter plot for all tropical cyclones in 2020 (a) and 2021 (b), as compared to the observations.

This section presents recent and ongoing development activities in the ECMWF to improve TC intensity forecasting (Magnusson et al., 2021). During the 2020 Atlantic hurricane season, model Cy47r1 was operational. Model Cy47r2 was implemented with an increase of vertical levels for the ensemble from 91 to 137 in 2021. At the same time model Cy47r3 was under development with a new moist physics package (Bechtold et al., 2020). One main driver of the new moist package development is the effects of a possible future 4 km resolution and how convection is handled on this scale.

Five sets of experiments were conducted to study the impacts of model resolutions and physics on IFS TC intensity forecasts. The experiments include 9-km and 4-km resolutions with current and new moist physics package (i.e., named as 9 km, 9 km-newMP, 4 km, 4 km-newMP, respectively), and an experiment that turns off the deep convective parameterization to let the model explicitly resolve the convection ("4 km-ExplConv"). Fig. 15 shows the mean biases and mean absolute errors of Vmax (i.e., intensity) from the experimental runs. Given that Vmax is the key intensity metric used by most operational TC forecasting centers, and it is generally recognized that models of resolution 4 km or less are required for meaningful predictions of this metric, the 4 km experiments here are of particular interest. The results are impressive. Not only does the increase in resolution to 4 km substantially reduce the magnitude of the negative bias in Vmax, but the mean absolute error in Vmax for two-to four-day forecasts is reduced by ~7 kt. For the Atlantic TCs in the experiment

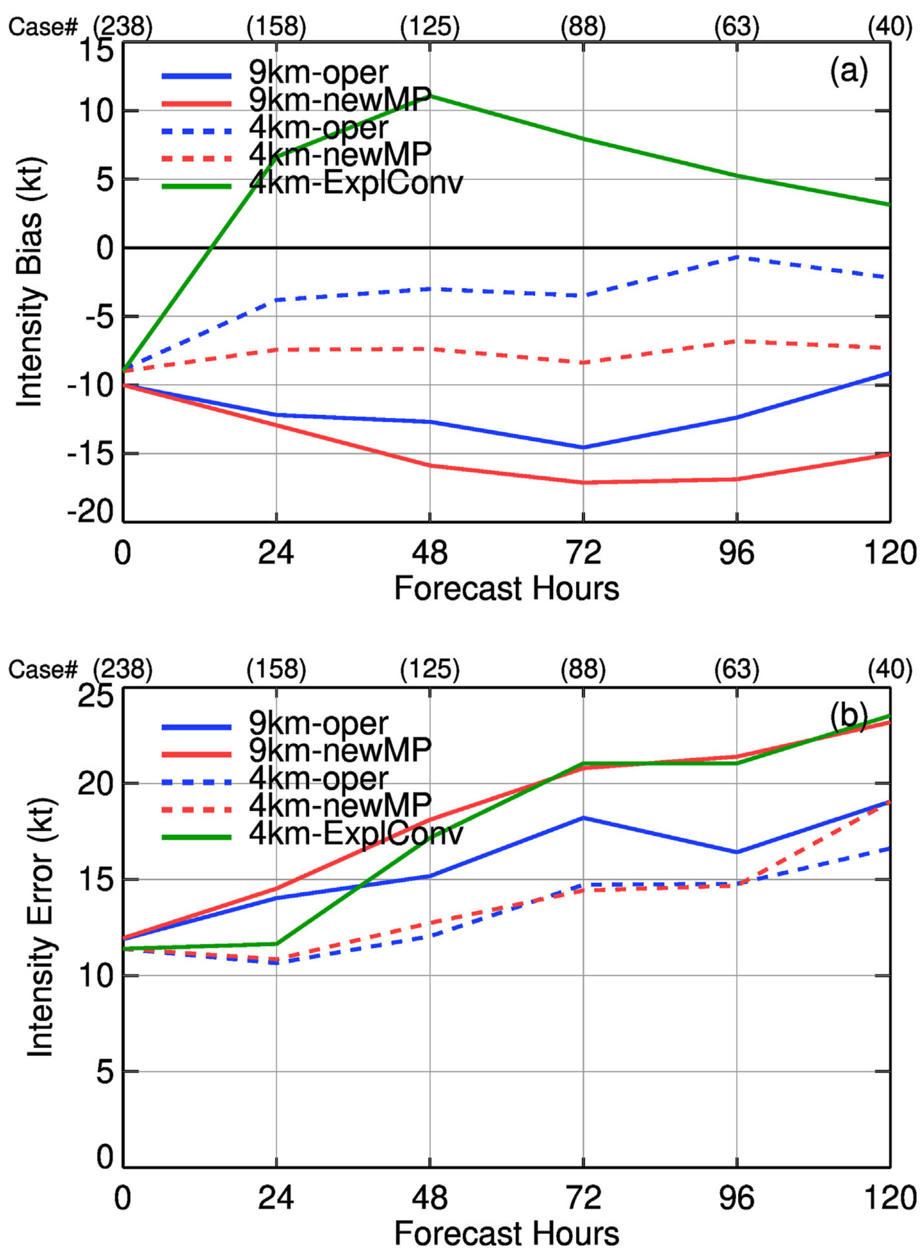

Fig. 15. TC intensity bias (a) and mean absolute error (b) from various experiments: 9 km/4 km (blue, solid/dash), 9 km/4 km with the new moist physics package (red, solid/dash), and 4 km-newMP with deep convective parameterization turned off (green). The numbers of samples at different times are shown in parentheses.

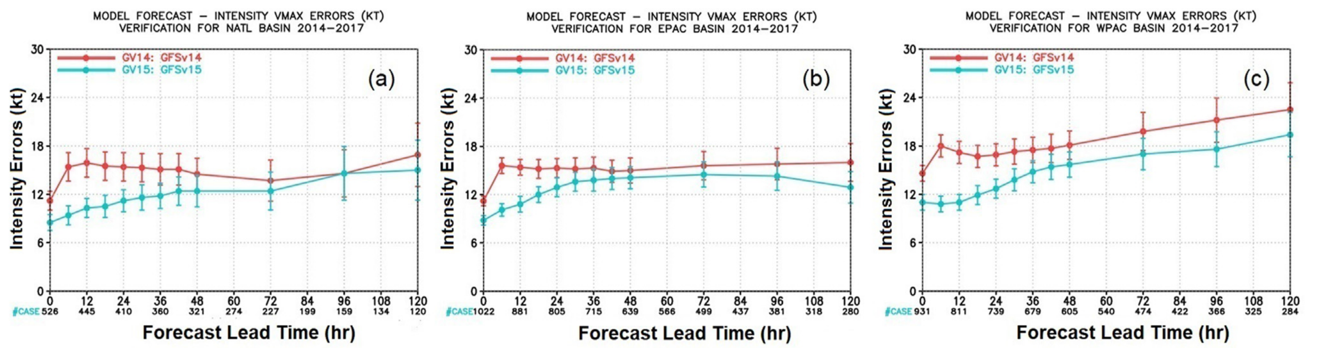

Fig. 16. Comparisons of TC intensity Vmax forecast error verification between GFSV14 (red) and GFSV15 (cyan) for North Atlantic (a), East Pacific (b), and West Pacific (c), homogeneous samples from 2014 to 2017 retrospective experiments.

sample, these improvements are statistically significant (compared with "9 km-oper", using a one-tailed *t*-test) at the 85% level for all forecast times, and usually significant at the 90% or 95% levels. The improvements are most evident and significant for the cases in the sample that were initially weak TCs (Vmax <50 kt), for all forecast times out to five days (not shown). Overall, the level and consistency of improvement in both Pmin and Vmax when the resolution was increased to 4 km with newMP was not evident in any of the other modeling or data assimilation experiments.

3.3. US NOAA NCEP's GFS – transition to FV3 based dynamical core

To unify NOAA's operational forecast system with a few applications, US NCEP's GFS adopted GFDL's fully compressible FV3 dynamical core (Harris et al., 2020; 2021; Lin 1997; 2004; Lin and Rood 1996; 1997) with a Lagrangian vertical coordinate (Chen et al., 2013) to replace its global spectral model (GSM). The first version of FV3 based GFS (GFSv15.1) became operational on June 12, 2019. Compared with GFSv14 (GSM), the salient features of the GFSv15.1 system include:

a) Resolution: C768L64 with ~13 km/64 Layers, 54 km top at 0.2 hPa;
b) Data Assimilation: C384 with ~25 km, 80 member ensemble, advanced stochastic physics;
c) Dynamical core: FV3, non-hydrostatic, single precision;
d) Physics: GFDL Cloud Microphysics, double precision;
e) Uniform resolution for all 16 days of forecast.

The upgrade of GFSv15 greatly improved TC intensity forecasts in all major global oceanic basins from the GFS system (Fig. 16). The FV3-based GFS also shows a much better wind-pressure (W-P) relation than the then-operational GFSv14 (GSM) for strong storms. During the course of upgrade, two horizontal advection schemes (called hord = 5 and hord = 6 in the model namelist) were tested, where the hord = 5 scheme is less diffusive than the hord = 6 scheme (Harris et al., 2021). Fig. 17 indicates that GFS with the hord = 5 scheme (G19A) produced a better W-P relationship than that with the hord = 6 scheme (G19B).

The NCEP's GFS system was further upgraded to GFSv16.0 on March 22, 2021, in which the number of the vertical levels was increased from 64 to 127 and the model top was raised from 54 to 80 km. Model physics and DA were improved with more satellite and in-situ observations assimilated. The NOAA's GFS has gradually improved its TC intensity forecasts in the past few years. Fig. 18 shows the annual TC intensity forecast error statistics of the NCEP's operational GFS from 2017 to 2021 for NATL and EPAC TCs, which indicates a general trend of intensity error reductions. Such an improvement is due to the improvements of model vertical resolution, DA algorithm and injection of more observations, and model physics.

3.4. JMA's GSM

JMA runs several NWP models for various purposes, including GSM, the Meso-Scale Model (MSM), the Local Forecast Model (LFM), the Global Ensemble Prediction System (GEPS) based on a low-resolution version of GSM, an

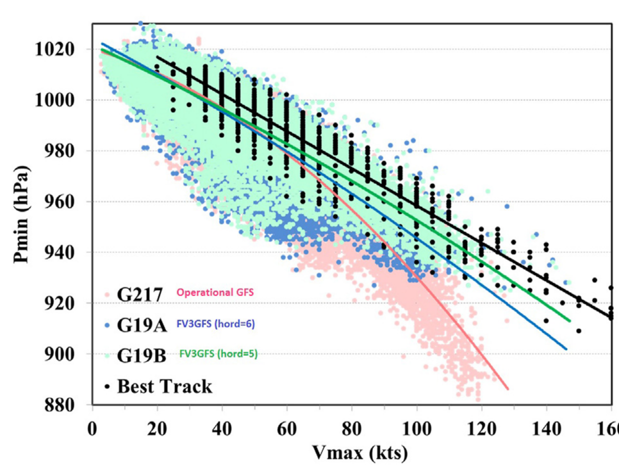

Fig. 17. Comparison of wind-pressure relationship between GFSV14 (G217) and two versions of GFSv15s. G19A uses the hord = 6 horizontal advection scheme while G19B uses the hord = 5 horizontal advection scheme. The final version of GFSV16 uses G19B configuration.

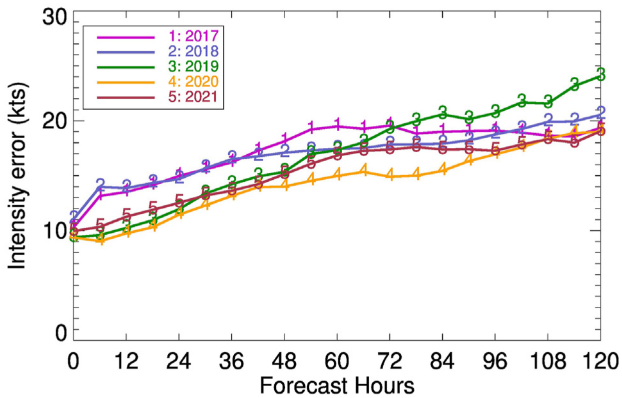

Fig. 18. Intensity RMSEs of NATL and EPAC TCs forecasted by the US NOAA NCEP operational GFS during the hurricane seasons from 2017 to 2021.

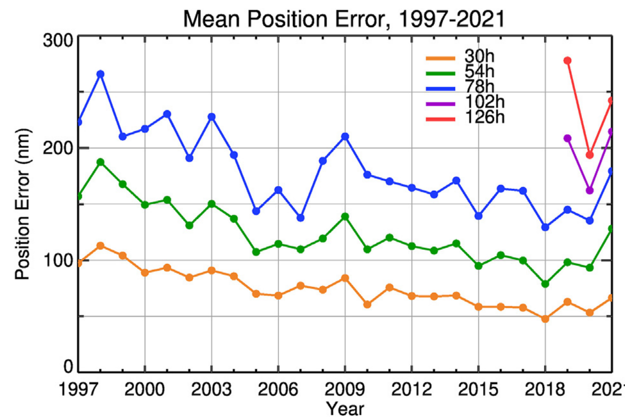

Fig. 19. JMA GSM annual mean position errors since 1997.

ensemble prediction system based on an atmosphere-ocean coupled model, and other NWP models for specific targets such as ocean waves and sea ice extent. TC forecasts are mainly from GSM and GEPS. The specifications of the GSM and GEPS are listed in Table 5. More detailed information for the models is available at JMA's website: https://www.jma.go.jp/jma/en/Activities/nwp.html.

Fig. 19 shows JMA GSM annual mean position errors at forecast lead times since 1997. Those for 30-, 54-, 78-, 102- and 126-h predictions in 2021 were 65, 125, 178, 213, and 240 nm, respectively. A trend of improvement is seen, with 2021 as a notable exception. Fig. 20 shows GSM annual mean intensity errors observed since 2009. No clear trend is present. JMA will increase the horizontal resolution of GSM from the current 20 km–13 km and enhance its physical processes optimized for the increased resolution. The aim is to enhance the representation of smaller scale features of meteorological phenomena including TCs. This will likely improve forecast accuracy.

4. Challenges

Despite recent improvements, global dynamical models still have a high intensity bias compared to observations, especially for strong storms. Therefore, global models are not yet used for intensity change forecast guidance. Regional dynamical models are capable of forecasting rapid intensity change and progress has been made in the last four years, but they still often suffer from high positive biases in intensity, false prediction of RI, miss the onset of RI, and underpredict intensity change. This is one of the challenges to regional hurricane dynamical models frequently raised by forecast centers. Table 6 lists some well-known storms in which regional dynamical models struggled in predicting RI events. It is interesting to note that the peak intensities of many 2021 Atlantic TCs are over-forecasted. Even though the reasons for the over-intensification are not clear, it could be closely related to above-PBL processes such as microphysics and/or cumulus convection parameterization schemes. I is found that the over-intensification is somewhat sensitive to the deep convection entrainment coefficient of the scale-aware SAS convection scheme in HWRF. Experiments show that the over-intensification issue can be mitigated by adjusting convection entrainment and detrainment rates (e.g., Shin et al., 2022). Fig. 21a shows the time series of intensity for several cycles forecasted by the operational HWRF model, indicating the model forecasted the intensity and RI much higher than the best-track analysis. With the entrainment rate increased from 10^{-4} to 0.0018 m^{-1}, the intensity and intensity change are much closer to the best-track analysis (Fig. 21b).

Another challenge that has been identified by model developers is that the intensity forecasts predicted by regional dynamical models sometimes have large cycle-to-cycle variation, referred to as the “windshield wiper” effect, especially for early cycles in a TC's lifecycle at its potential tropical cyclone (PTC) stage (Zhang and Alaka 2020; Zhang et al., 2021a). Fig. 22 is an example from the operational HWRF, which shows the intensity forecasts for two consecutive cycles of INVEST 94L, 12 UTC and 18 UTC, August 08, 2021. INVEST 94L later developed into Hurricane FRED 06L. HWRF predicted that INVEST 94L would become a Category-

Table 5
Specifications of JMA GSM and GEPS.

Model	*Resolution (Grid Spacing)*	Vertical Levels	*Forecast Range (Initial Time)*	Initial Condition	*Number of Ensemble Members*
GSM	TL959 (0.1875°, 20 km)	128 layers (top: 0.01 hPa)	132 h (06, 18 UTC) 264 h (00, 12 UTC)	4D-Var Analysis	N/A
GEPS	TQ479 (0.25°, 27 km)	128 layers (top: 0.01 hPa)<	132 h (06, 18 UTC) 264 h (00, 12 UTC)	Global analysis with ensemble perturbations	51

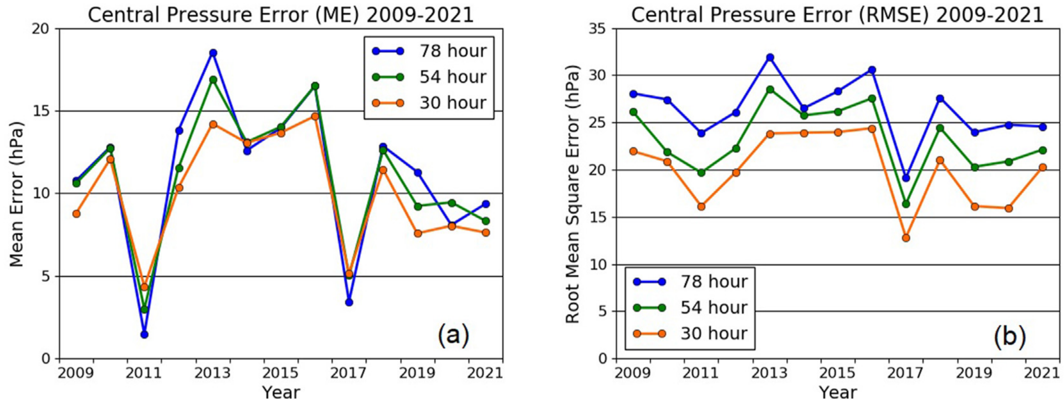

Fig. 20. JMA GSM annual mean central pressure errors since 2009. (a) Mean Error (bias), (b) Root Mean Square Error.

Table 6
Difficult cases for regional models.

Challenges	Storms
overpredict peak intensity or RI	Elsa 05L (2021), Fred 06L (2021), Grace 07L (2021) Henri 08L (2021), Larry 12L (2021), Sam 18L (2020)
underpredict peak intensity or RI	Florence 06L (2018). Michael 14L (2018), Dorian 05L (2019), Iota 31L (2020)

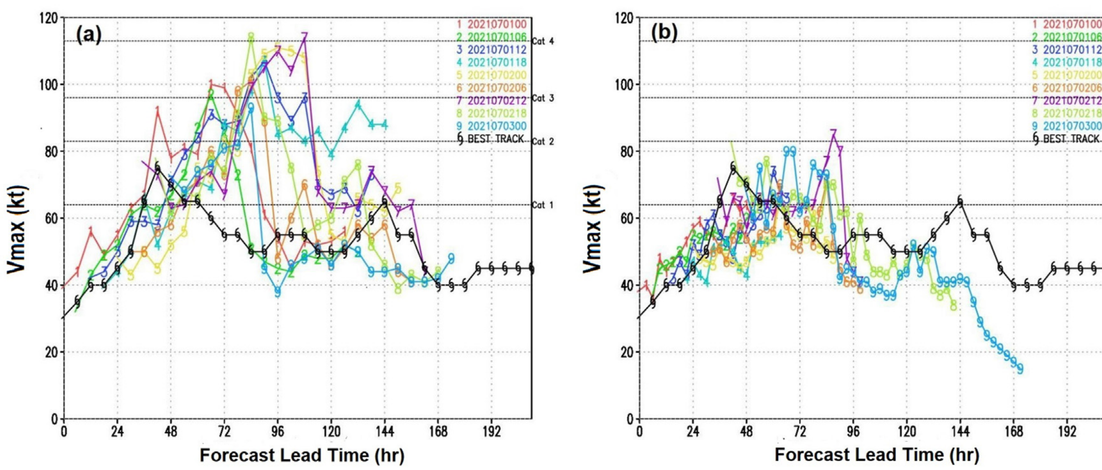

Fig. 21. Time series of intensity for several cycles (in colors) of Hurricane Elsa (05L), 2021 forecasted by (a) the operational HWRF model and (b) HWRF model with the adjusted entrainment rate in the scale-aware convection scheme. The intensity from the best-track analysis is in black.

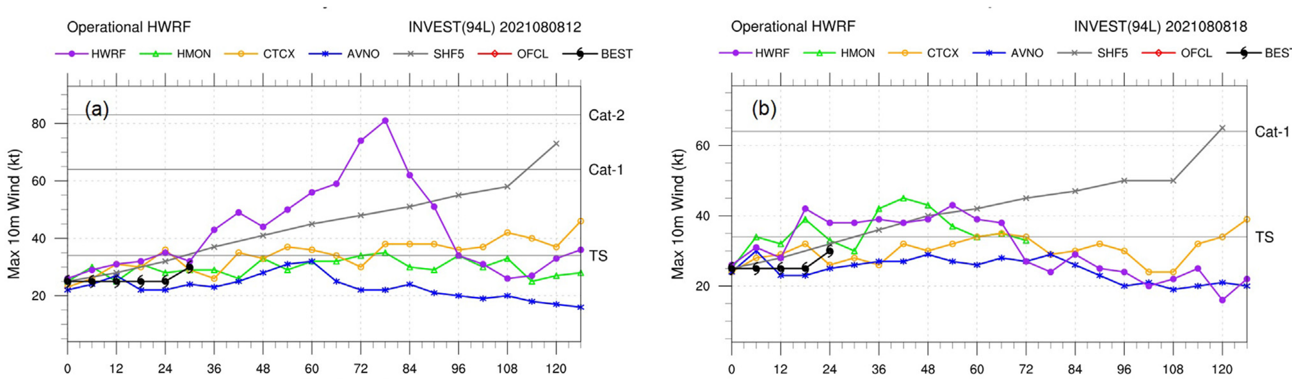

Fig. 22. Intensity forecasts initialized on August 08, 2021, 12 UTC (a) and 18 UTC (b), from HWRF (purple), HMON (green), CTCX (orange), GFS (blue), SHF5 (gray), and NHC official forecast (red), compared to the best track (black).

2 hurricane by 72-h lead time (initialized) at the 12 UTC cycle on August 08, 2021, while it predicted the storm maintaining its Tropical Storm stage at the 18 UTC cycle.

Operational centers also reported that regional hurricane models tended to produce core convection that is too symmetric in sheared or dry environments which results in a high-biased intensity forecasts, and often overpredicted intensity in low shear environments (Brennan and Cowan 2021). These issues could be related to the simulated vortex structure and model physics parameterizations. DeMaria and Brennan (2018) suggested that the hurricane model should improve DA to use all available observations including targeted observations and improve physics schemes that are scale-aware allowing for smooth transitions to very high spatial and temporal resolutions. The research community can help with investigations to improve these model deficiencies. A more complete list of difficult cases identified by operational centers can be found in Part II of the review (Wang et al., 2023b).

5. Summary and future direction

This paper is part I of the review summarizing the progress made in the past four years (2018–2021) from the perspective of operational TC intensity forecasts, as presented to the 10th IWTC. It has been documented that the TC intensity forecast skill has been greatly improved from operational centers, which are largely attributed to the following three aspects: 1) advancement and improvement of TC dynamical models, 2) new techniques and methods used by forecasters, 3) more high-resolution real time observations available to TC forecasters at operational centers. This part focuses on the improvements of TC intensity forecast guidance from both global and regional dynamical models since the 9th IWTC held in 2018. There are several factors that lead to the reduction of TC intensity forecast errors in TC dynamical models, including increases of both horizontal and vertical resolutions, observation-based and scale-aware model physics, inner-core data assimilation, and improved ocean model coupling. Two developments are worthy of highlighting. First, FNMOC implemented the 11-member COAMPS-TC ensemble (Komaromi et al., 2021) into operations in 2020. This marks the first time that an operational TC model, with convection-allowing resolution, is capable of producing probabilistic forecasts of TC track, intensity and structure. Second, NCEP's new-generation hurricane model HAFS, to be operational in 2023, has been tested retrospectively, showing capability to further improve dynamic model guidance for TC track and intensity.

Despite the improvement of the intensity forecast, RI forecasts remain a challenge (DeMaria et al., 2021). The RI forecast skill of regional dynamical TC models has been substantially improved in recent years, but the utility of TC models (including statistical and dynamical models) is still limited for RI forecasts (i.e., having low detection rates and high false alarm rates). Difficulties include underprediction and overprediction, large cycle-to-cycle variability, and timing of rapid intensity change. Thus, more effort is needed to improve operational TC dynamical models to provide better RI guidance. Research and developments in the following areas are recommended for dynamical models from operational perspectives:

1. Further improvements are needed in data assimilation and vortex modification techniques so that the three-dimensional structure of the initial vortex such as height, size, and titling angle is more realistic, which is important to forecast the intensity and eyewall replacement (e.g., Green et al., 2022; Li et al., 2022; Peng and Fang 2021; Wang et al., 2021). The initial cloud field also needs to be adjusted in the VI procedure.
2. Efforts should be made to understand and improve grid and sub-grid scale model physics. The surface and PBL schemes need to be improved by using large eddy simulations in conjunction with available observations in the TC environment. The air-sea interaction, such as drag coefficient (Cd) and heat exchange coefficient (C_H) should be further calibrated based on observations in high wind situations. Uncertainty in the microphysics scheme needs to be taken into account. All model physics schemes need to be scale-aware and can be applied to any model grid-spacing.
3. The application of ensemble systems based on regional dynamical models can be further investigated to support operational RI guidance.
4. The application of machine learning techniques needs to be further explored to improve physics parameterizations, DA systems, and post-processing.
5. Analysis tools of intensity and RI forecasts can be further developed to help model developers and forecasters identify and categorize modeling challenges and recognize scenarios where a model is likely to perform particularly well or poorly.

With the close collaboration between research and operation communities and support from Research-to-Operation and Operation-to-Research projects, we are confident that dynamical models will be further improved and provide better guidance to operation centers.

Acknowledgements

Thanks are due to Drs. J Steffen and J. Shin for their comments and suggestions. EMC hurricane models (HWRF, HMON, and HAFS) are supported by NOAA/NWS/OSTI UFS R2O project, NOAA/OAR/WPO Hurricane Supplemental projects (FY18 and FY19), and HFIP. Drs. J. Doyle, J. Moskaitis, and W. Komaromi acknowledge the support of the Office of Naval Research, as well as computational support from a grant of High Performance Computing (HPC) time from the Navy Defense Resource Center (DSRC). COAMPS-TC® is a registered trademark of the Naval Research Laboratory. J. Knaff would like to thank the leadership of NOAA's Center for Satellite Applications for their support of this activity. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of NOAA or the US Department of Commerce.

Acronyms

4DEnVar four-dimensional ensemble variational
AMV Advanced Motion Vector
AVNO ATCF model identifier for NCEP GFS
Cd momentum exchange coefficients
Ch enthalpy exchange coefficients
COAMPS-TC Coupled Ocean-Atmosphere Mesoscale Prediction System – Tropical Cyclone
CMA-TYM Chinese Meteorological Agency Typhoon Model
COTC ATCF model identifier for NAVGEM-based deterministic COAMPS-TC
CPHC Central Pacific Hurricane Center
CPAC Central Pacific
CTCX ATCF model identifier for NCEP GFS-based deterministic COAMPS-TC
DA Data Assimilation
DTOPS Deterministic to Probabilistic Statistical model
ECMWF European Centre for Medium-Range Weather Forecasts
EDMF Eddy Diffusivity Mass Flux
EPAC Eastern Pacific
ESG Extended Schemit Grid
FAR False Alarm Rate
FNMOC Fleet Numerical Meteorology and Oceanography Center
FRIA Forecast Rapid Intensification Aid
FV3 Finite-Volume Cubed-Sphere Dynamical Core
GEFS Global Ensemble Forecast System
GEPS Global Ensemble Prediction System
GFS Global Forecast System
GFDL NOAA Geophysical Fluid Dynamics Laboratory
GOES Geostationary Operational Environmental Satellite
GRAPES-TY Global and Regional Assimilation and PrEdiction System for typhoon
GSM Global Spectral Model
GWD Gravity Wave Drag
HFA1 Early model of HFSA
HFB1 Early model of HFSB
HAFS Hurricane Analysis and Forecast System
HFIP Hurricane Forecast Improvement Project
HFSA Configuration A of HAFS
HFSB Configuration B of HAFS
HWRF Hurricane Weather Research and Forecasting System
HMON Hurricanes in a Multi-scale Ocean coupled Non-hydrostatic model
HYCOM HYbrid Coordinate Ocean Model
IFS Integrated Forecasting System
IGBP International Geosphere-Biosphere Programme
IOC Initial Operational Capability (IOC)
IWTC international workshop on TC
JMA Japan Meteorological Agency
JTWC Joint Typhoon Warning Center
LFM Local Forecast Model
MOGM Met Office Global Model
MP Moist Physics
NATL Northern Atlantic
NAVGEM Navy Global Environmental Model
NCEP US National Centers for Environmental Prediction
NHC National Hurricane Center
NIO Northern Indian Ocean
NMM Non-Hydrostatic Mesoscale Model
NMMB Non-Hydrostatic Mesoscale Model on a B grid
NOAA National Oceanic and Atmospheric Administration
NWP Numerical Weather Prediction
NWS National Weather Service
PBL Planetary Boundary Layer
POD Probability of Detection
POM Princeton Ocean Model
PTC potential tropical cyclone
RMSE Root Mean Square Error
RTOFS Global Real-Time Ocean Forecast System
RI Rapid Intensification
RRTMG Rapid Radiative Transfer Model for General Circulation Model
SAS Simplified Arakawa Schubert
SE Southeast
SFMR Stepped Frequency Microwave Radio
SH Southern Hemisphere
SHF5 A Statistical Hurricane Intensity Forecast model for intensity, also known as SHIFOR5 (5-day version)
TC Tropical Cyclone
TDR Tail Doppler Radar
UFS Unified Forecast System
Vmax Maximum wind speed at 10 m
VI Vortex initialization
WCSSP Weather and Climate Science for Service Partnership
WPAC Western Pacific
WW3 Wave Watch 3 model

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