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A real-time regional forecasting system established for the South China Sea and its performance in the track forecasts of tropical cyclones during 2011-2013

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Abstract

A real-time regional forecasting system for the South China Sea (SCS), called the experimental platform of marine environment forecasting (EPMEF), is introduced in this paper. EPMEF consists of a regional atmosphere model, a regional ocean model and a wave model, and performs real-time run four times a day. The output of the Global Forecasting System (GFS) from the U.S. National Centers for Environmental Prediction (NCEP) is used as the initial and boundary conditions of two nested domains of the atmosphere model which can exert constraint on the development of small- and meso-scale atmospheric perturbations through dynamical downscaling. The forecasted winds at 10-m height from the atmosphere model are used to drive the ocean and wave models. As an initial evaluation, a census on the track predictions of 44 tropical cyclones (TC) in 2011-2013 indicates that the performance of EPMEF is very encouraging and comparable to those of other official agencies worldwide. In particular, EPMEF successfully predicted several abnormal typhoon tracks including the sharp recurving of Megi (2010) and the looping of Roke (2011). Further analysis reveals that the dynamically downscaled GFS forecasts from the most updated forecast cycle and the optimal combination of different microphysics and PBL schemes primarily contribute to the good performance of EPMEF in TC track forecast. EPMEF, established primarily for research purpose with potential to implement into operation, provides valuable information not only to the operational forecasters of the local marine/meteorological agencies or the international TC forecast centers, but also to other stake-holders such as fishing industry and insurance companies.

1. Introduction

Being the largest tropical marginal sea and connecting the western Pacific Ocean and the eastern Indian Ocean, the South China Sea (SCS) plays an important role in the exchange of water mass and energy between the two ocean basins (Qu et al. 2005; Qu and Du 2006; Wang et al. 2006; Du and Qu 2010). It is also an area where tropical cyclones (TC) or typhoons form and pass in the summer and fall seasons, which causes huge damage of property and loss of life in the East Asian countries such as Philippines, Vietnam and China (Wu and Kuo 1999). For instance, about 7-8 typhoons make landfall in China per year, impacting a population of 250 million with property loss of over 10 trillion dollars (Liu et al. 2009).

Although the forecasts of the tropical cyclone track or intensity have been improved during the past several decades, large uncertainties still exist. This is due to the poor understanding of physical processes about tropical cyclone intensity as well as the inherent predictability limit in numerical models which still fall short in capturing the intricacies of the underlying mechanisms (Fraedrich and Leslie 1989; Plu 2011; Peng et al. 2013). Besides high-quality initial conditions (Kurihara et al. 1995; Leslie et al. 1998; Bender et al. 2007), factors contributed to improve the TC forecasting accuracy of a model may include: the domain settings regarding to size and location (Landman et al. 2005; Giorgi 2006), the choice of horizontal resolutions for the nested domain, the selected microphysics parameterization scheme (Rao and Prasad 2007, Kanada et al. 2012, Kepert 2012) or/and Planetary Boundary Layer (PBL) parameterization scheme (Khain and Lynn 2011, Pattanayak et al. 2012) as well as their combination (Zhou et al. 2013), and so on. This paper introduces a real-time regional forecasting system established for the SCS whose atmosphere model features with two nested domains centered in the SCS, a "dynamical downscaling" initialization scheme and an "optimal" combination of the Ferrier microphysics scheme and the YSU PBL scheme, and presents a preliminary evaluation of its performance in TC track forecasts during 2011-2013.

The paper is organized as follows. Section 2 gives a brief description to the establishment of the real time forecasting system. An evaluation of the performance of the forecasting system in TC track forecasts is presented in Section 3, followed by a detailed a discussion in Section 4. A summary is given in the final section.

2. Establishment of EPMEF

A real-time air-sea-wave forecasting system for the SCS, also named experimental platform of marine environment forecasting (EPMEF), was established in the State Key Laboratory of Tropical Oceanography (LTO), South China Sea Institute of Oceanology (SCSIO) in Oct. 2010. It consists of three main components, i.e., an atmospheric model, an ocean model and a sea wave model, which are the Weather Research and Forecasts (WRF) model Version 3.2 (Michalakes et al. 1998; Skamarock et al. 2008), the Princeton Ocean Model (POM) 2002 version (Blumberg and Mellor 1987; Mellor et al. 2003) and the WAVEWATCH III (WW III) model (Tolman 1997, 1999, 2002), respectively. Fig. 1 shows the flow chart of EPMEF.

The WRF model (Version 3.2), developed by the National Center for Atmospheric Research (NCAR) and the National Centers for Environmental Prediction (NCEP) in the U. S., is a next-generation meso-scale numerical weather prediction system that was designed to serve both operational forecasting and atmospheric research needs (Michalakes et al. 1998; Skamarock et al. 2008). Dynamical downscaling techniques are commonly used for a regional atmospheric model to obtain higher-resolution output with small- and meso-scale features from the lower-resolution output of a global atmospheric model (Lo et al. 2008; Zhang et al. 2009). To realize this, a two-domain-one-way-nested configuration is designed, as shown in Fig. 2. The outer domain for the atmospheric model covers the western Pacific Ocean, the entire SCS, and the eastern Indian Ocean, with a horizontal grid resolution of 72 km. The inner domain covers the entire SCS and southern China, with a horizontal grid resolution of 24 km. Both domains have 27 layers in the vertical. The horizontal resolutions of 72 km (outer domain) and 24 km (inner domains) and 27 vertical layers are chosen mainly due to the limited computer resources (currently EPMEF is running in a Rack Server with 32 cores of Intel Xeon E5 with 2.6 Hz), and they can be updated to higher resolutions in the future when more computer resources are available. The output from the Global Forecast System (GFS) maintained by NCEP with horizontal grid resolution of $1^{\circ}\times1^{\circ}$ is used to provide initial conditions (IC) and lateral boundary conditions (BC) for the outer domain. The Ferrier microphysics scheme (Ferrier et al. 2002), Kain-Fritsch cumulus scheme (Kain and Fritsch 1990, 1993), YSU PBL scheme (Hong et al. 2006), and Dudhia short wave (Dudhia 1989) and

RRTM long wave (Mlawer et al. 1997) radiation scheme are chosen for both domains. A 15-day forecasting and a 3-day forecasting are made automatically every 6 hours (i.e., 4 times a day at 0200, 0800, 1400, 2000 Beijing time) for the outer and inner domains, respectively.

The 10-m height winds from the inner domain of WRF model are used to drive the ocean model POM (2002 version) and the wave model WW III. POM is a three-dimensional (3-D) ocean model with primitive equations, embedded a second moment turbulence closure model (the 2.5 Mellor-Yamada scheme; Mellor and Yamada, 1982). The WW III model is a third generation wave model developed at NOAA/NCEP (Tolman, 1997, 1999, 2002). As the an initial evaluation of EPMEF, we focus on the performance of EPMEF in the TC track forecasts in this paper, and thus here we omit the detailed descriptions of the set up for the ocean model and wave model. The evaluation for the performance of the ocean and wave models will be given in our future publication once enough observations are available.

3. Evaluation of the performance in TC track forecasts during 2011-2013

The SCS and the western Pacific Ocean are the regions affected by typhoons or tropical storms most frequently in summer and autumn. For instance, there are 77 named and numbered tropical storms/typhoons occurring in these areas during 2011-2013. Therefore, as an initial evaluation of the performance of EPMEF, we focus on the track forecasts of tropical cyclones during 2011-2013 by EPMEF and make comparison with the forecasts by other major agencies, including the U.S.

Navy/Air Force Joint Typhoon Warning Center (JTWC), the Japan Meteorological Administration (JMA), the National Meteorological Center of China (NMCC), and the Central Weather Bureau of Taiwan (CWBT). Since 2012 TC season, the Environmental Modelling Center (EMC) of the National Center of Environment Prediction (NCEP) in U.S. began to make real-time forecasts for West Pacific TCs using HWRF model (Tallapragada et al. 2013), thus we also compare our results of 2012-2013 TC forecasts with those from NCEP/EMC. Due to limited computer resources, EPMEF only makes 72-h track forecasts for TCs entering the inner domain. TC vortexes are initialized by downscaling the "first guess" from GFS in $1^{o} \times 1^{o}$ resolution to regional model WRF in 24-km resolution. There are 21, 25 and 31 named tropical cyclones in 2011, 2012 and 2013, respectively. For all of these TCs, only those that entered the inner domain of the atmospheric model of EPMEF with life cycle longer than 48 hours and were forecasted by at least 3 other agencies are counted in our statistics, which results in a count of 10, 16 and 18 TCs for 2011, 2012 and 2013, respectively. As an example, Fig. 2 shows the tracks of the 18 TCs for 2013 that entered the inner domain with life cycle longer than 48 hours. The TC center is tracked by a routine of position search available in the WRF post-process program RIP4, which takes into account the criteria in both upper atmosphere and sea surface: the predicted minimum sea level pressure, maximum 10-m height winds, maximum vorticity at 650 hPa and 850 hPa, as well as some prescribed thresholds for the vorticity at all levels and the temperature at surface and 700 hPa. Based on the observed track ("best" track) issued by JTWC, the track position errors (TPE) for

24-h, 48-h and 72-h forecasts by each agency are calculated using the following formula (Neumann and Pelissier 1981; Powell and Aberson 2001):

$$\text{TPE}=111.11\ \frac{180}{\pi}\cos^{-1}\left[\sin\phi_0\sin\phi_s+\cos\phi_0\cos\phi_s\cos\left(\lambda_0-\lambda_s\right)\right]\ , \qquad (1)$$

where λ_O and φ_O are longitude and latitude of the storm center in the best track data, and λ_S and φ_S are those of the forecasted storm center from each agency. To make a relatively fair comparison among the agencies, we calculate the relative errors of each TC track predicted by each agency using the following formula:

$$R_i = TPE_i / \overline{TPE} \quad (i=1,..,N), \qquad (2)$$

where $\overline{TPE}=\frac{1}{N}\sum_{i=1}^{N}TPE_i$ and N denotes the number of agencies. If an agency has no forecasting result available for a TC, 1.0 is assigned to it. It is obvious that, the smaller the value of R_i is, the better the corresponding agency performs. We define the relative forecasting skill as the mean of R_i of all TCs for each agency for 24-h, 48-h and 72-h forecasts, respectively.

Figs. 3-5 give the mean TPE of and the relative error R_i of 10, 16 and 18 TCs for 2011, 2012 and 2013, respectively. The mean TPE (R_i) over the 10 TCs in 2011 from EPMEF reads 97.0 km (0.98), 172 km (1.05) and 278 km (1.0) for 24-h, 48-h and 72-h forecasting, respectively, ranking the third, the fourth and the second among the five agencies. In 2012 and 2013, the forecasts from NCEP-HWRF are available for comparison besides the other four agencies. The mean TPE (R_i) from EPMEF reads 83 km (0.87), 133 km (0.85) and 232 km (0.95) for the 16 TC in 2012 (ranking the 1st, 1st, and 2nd) and 86 km (0.98), 129 km (0.87) and 171 km (0.90) for 18 TC in 2013 (ranking the 3rd, 1st and 1st) for 24-h, 48-h and 72-h forecasting, respectively. As examples, Figs. 6-7 show the performance of each agency for Nanmadol (2011) and Rumbia (2013) which made landfall on the coasts of Jinjiang, Fujian province and Zhanjiang, Guangdong province, respectively. For Nanmadol (2011), EPMEF performed slightly better than others for the 24-h forecast with a mean TPE of 84 km, although the TPE increased quickly at the last initialization time (0000 UTC 30 Aug. 2011) probably due to initialization quality associated with the accuracy of the GFS forecasts at that time when the TC was going to make landfall. EPMEF performed significantly better than others for the 48-h and 72-h forecasts with a mean TPE of 137 km and 289 km, respectively, especially for the second half of the period. The 72-h predicted track by EPMEF initializing at 1200 UTC 27 Aug. 2011 is very close to the observed one (Fig. 6d). For Rumbia (2013), EPMEF performed much better than others with a mean TPE of 53 km, 64 km and 129 km for the 24-h, 48-h and 72-h forecasts, respectively. As indicated in Fig. 7d, initializing at 0000 UTC 29 Jun. 2013, the EPMEF predicted a track and a landfall location three days ahead which are very close to the observations. In contrast, EPMEF shows the worst performance in some TCs, such as the strong typhoon Netsat (2011), of which large TPEs for all forecast times are seen for EPMEF (Fig. 8). In an overall assessment for the three TC seasons of 2011-2013, the performance of EPMEF is very encouraging compared to those of some official agencies.

Now let us look into a couple of cases that have “abnormal” tracks and are most difficult to be predicted: Megi (2010) and Roke (2011). Megi (2010) is the strongest typhoon in the world in 2010 and the strongest one generated in western Pacific

Ocean at autumn in the past 20 years, with maximum wind speed of 72 m/s and lowest sea level pressure of 895 hPa. The most astonishing feature of its track is its nearly 90-degree turn from westward to northward at 0000 UTC 20 Oct. 2010 after it passed through Philippines and entered the SCS. Most of the official agencies did not predict this “big turn” until 2100 UTC 19 Oct. 2010. EPMEF, however, successfully predicted the “big turn” as early as 0000 UTC 18 Oct. (Fig. 9a). As revealed by Peng et al. (2014), the cold air intrusion from the northwest played a key role in the “big turn” of Megi (2010) through adjusting the large scale circulation. The cold air intrusion was well predicted by EPMEF, mainly attributed to the proper selection of PBL and physical schemes as indicated by Zhou et al. (2013) and discussed in Subsection 4.2. Roke (2011) generated as a tropical storm in the location (137°E, 22.1°N) of the western Pacific at 1200 UTC 13 Sep. 2011, when it moved westward to the east of Okinawa Island (129.7°E, 26.4°N) at 0600 UTC 16 Sep., it turned around and looped cyclonically and intensified to a typhoon; after the looping, it moved northward and then northeastward, and made landfall on Shizuoka county of Japan at 0600 UTC 21 Sep. 2011. As early as 1200 UTC 14 Sep. 2011, EPMEF successfully predicted the cyclonical loop that is usually very hard to predict (Fig. 9b). Figs. 9c-d show the 48-h and 72-h TPE of Roke (2011) for each forecasting agencies (forecasting data from JTWC are not available), in which the performance of EPMEF is seen very encouraging with a minimum mean 48-h TPE of 130.15 km and 72-h TPE of 194.03 km, compared to the mean 48-h TPE of 241.3

km, 195.8 km, 219.6 km and 72-h TPE of 342.7 km, 304.4 km, 340.9 km for NMCC, JMA and CWBT, respectively.

4. Discussion

4.1 The initialization process

The above results indicate that the performance of EPMEF appears comparable to or even better than most of the official agencies. However, one should be aware the following points: 1) the comparison is based on only those TCs that entered the inner domain of EPMEF and lasted longer than 48 h in the domain; 2) the track forecasts from EPMEF are purely from its numerical model initialized at the starting time of the current forecast cycle, but those released online by the official agencies are usually based on results from a number of guidance models including multi-layer dynamical models, single-layer trajectory models, consensus models, and statistical models, as well as the experiences of forecasters. Therefore, the comparison here is not the one purely among numerical models. Guidance models are characterized as either early or late, depending on whether or not they are available to forecasters during the forecast cycle. For example, the GFS forecasts made for the 1200 UTC forecast cycle would be considered a late model since it is not complete and available to forecasters until about 1600 UTC, or about an hour after the NHC forecast is released, i.e., it could not be used to prepare the 1200 UTC official forecast. Multi-layer dynamical models are generally, if not always, late models. To make the forecast benefit from a late model as much as possible while keep it timely, a technique is adopted which adjusts the most recent available run of a late model to the current synoptic time and initial conditions. The adjustment process produces an “early” version of a late model for the current forecast cycle that is based on the most current available guidance. The adjusted version of a late model is known, mostly for historical reasons, as “interpolated” model. Since the initial and boundary conditions in the real atmosphere may vary significantly at different time, the forecast of a dynamical (late) model starting from previous forecast cycle (i.e., initializing at 0600 UTC or 0000 UTC) for the current forecast cycle (1200 UTC) (on which the “interpolated” model is based) is generally less accurate than that starting from the current forecast cycle (i.e., initializing at 1200 UTC). This may be the main reason why the forecasts of EPMEF are generally more accurate than those of most official agencies based on “interpolated” models. However, EPMEF achieves this in a cost of about 2-h late release of forecasts. For instance, at the 1200 UTC forecast cycle, EPMEF waits until 1515 UTC for the coming of GFS forecasts initializing at 1200 UTC which are not available until 1500 UTC. Running in a Rack Server with 32 cores of Intel Xeon E5 with 2.6 Hz, it generally takes about one and half an hour for EPMEF to download the GFS data, prepare IC/BC and finish a 72-h forecasting, so the track forecast from EPMEF could be released at about 1630UTC, i.e., one and half an hour late compared to the forecast release time (1500 UTC) by the official agencies. For forecasts longer than 24 hours, the negative impact of a 2-h delay of forecast release is nearly negligible. Thus, in our opinion, it is worth to gain an improvement for TC track forecasts in the cost of about one or two hours delay of forecast release (the delaying time may be shortened to less than one hour if a faster computer is used in the future), especially for a forecast period of longer than 24 hours.

To see how EPMEF may benefit from using the GFS forecasts of the current forecast cycle (i.e., the “late model”) to create IC/BC, we perform an ensemble of hindcasts for the 16 TCs of 2012 using a different initialization scheme to create IC/BC (denoted as EPMEF-6). The initialization scheme for EPMEF-6 uses GFS forecasts of the previous forecast cycle (6-h early) for generating IC/BC, which is similar to the “early model” except that it does not carry out any adjustment or projection to the GFS forecasts of the previous forecast cycle. For EPMEF-6, the mean TPEs for 24-h, 48-h and 72-h forecasts are 96.6 km, 159.4 km, and 270.3 km, respectively, an apparent degrade compared to those of 82.8 km, 133.4 km, and 232.3 km for EPMEF (Fig. 4). Therefore, the reduction of TPEs in EPMEF is obviously attributed to a better representation of the initial large-scale environmental circulations in the “late model”. The adjustment or projection according to the latest information of the live TC implemented in the standard “early model” is believed to improve the small- and meso-scale features of the meteorological fields in the regional model, but may not be much helpful on improving the large-scale environmental circulations which steer the TC. Fig. 10 displays the steering flows and the 500-hpa potential height from EPMEF and EPMEF-6 for the typhoon Gaemi (2012) at the initialization time of 1200 UTC 3 Oct. 2012 and 30-h forecast time, imposed by the TC best track and the simulated tracks. The steering flows are obtained through averaging the wind field between 925 hPa and 300 hPa and over a 3~8^{o} radial band centered at the TC eye, based on the suggestions or experiences in some studies (Chan and Gray 1982; Dong and Neumann 1983). Although the initial vortex position from EPMEF-6 is a little bit closer to the one from the best track than that from EPMEF, the northward component of steering flows from EPMEF-6 makes the cyclone move to the north, while the southward component of steering flows from EPMEF drives the cyclone to the south which is closer to the best track. The field of geopotential height in EPMEF also appears to be in favor of a southwestward movement of the cyclone, while that in EPMEF-6 seems to facilitate the northeastward movement which deviates from the observed track of the cyclone. The biases of u- and v-components of steering flows from the 72-h forecasts of EPMEF and EPMEF-6 against the FNL analysis are displayed in Fig. 11, which are averaged over an ensemble of model runs initialized at every 6-h from 0000 UTC 2 Oct. to 1200 UTC 5 Oct. 2012. Significant reduction of biases in the v-component of steering flows is found for EPMEF, implying that the “late model” used in the initialization of EPMEF can better capture the large-scale environmental circulations not only in the initial time but also in the forecasting times. Therefore, EPMEF benefits from the GFS forecasts of the current forecast cycle (the most updated) which bring a better steering flow than those of the previous forecast cycle (6-h early), leading to better track forecasts of TCs.

4.2 The effect of microphysics and PBL schemes

Another important factor contributed to the good performance of EPMEF could be the choice of the Ferrier microphysics scheme and the YSU Planetary Boundary Layer (PBL) scheme in the model. As shown in the study of Zhou et al. (2013), various combinations of microphysics schemes and PBL schemes may have different influence on TC track simulation, and the combination of Ferrier scheme and YSU scheme is the “optimal” one that leads to a best track simulation of super typhoon Megi (2010). The influence of various combinations of the microphysics schemes and PBL schemes on TC track forecasts may depend on the model configuration such as the horizontal grid resolution, the domain size and topography, etc.. To investigate their influences on TC track forecasts in the configuration of EPMEF, we carry out a number of experiments using different combinations of four microphysics schemes (i.e., Ferrier, Goddard, WSM6, and Lin, see a detailed description in Skamarock et al. 2008) and three PBL schemes (i.e., YSU, MYJ, and MYNN2, see a detailed description in Skamarock et al. 2008) and initializing at every 6 hours from 1200 UTC 21 Jul. to 1800 UTC 23 Jul. for the typhoon Vicnte (2012). The mean TPEs for various combinations are given in Table 1. It is found that the combination of Ferrier scheme and YSU scheme has the smallest mean TPE for both 24-h and 72-h forecasts. Although the combinations of the MYJ PBL scheme with most microphysics schemes performs well, they do not work (blow up) for the 72-h forecast. Therefore, in an overall assessment, the combination of Ferrier scheme and YSU scheme performed the best among all combinations, as indicated by the rank based on the sum of relative errors of all forecast periods for each combination

(Table 1). This can be attributed to a more accurate forecasting of the large-scale environmental circulations (i.e., the steering flows) from the combination of Ferrier scheme and YSU scheme as indicated in Fig. 12. Considering the influence of various combinations may be case-dependent in the configuration of EPMEF, we have carried out an ensemble of experiments using different combinations of microphysics schemes and PBL schemes for a number of typhoon cases. The results also show that the combination of Ferrier scheme and YSU scheme produces a more accurate forecasting of the steering flows which are governed by the large scale circulations, leading to better TC track forecasts (figures not shown). Hence, EPMEF benefits obviously from the choice of the Ferrier microphysics scheme and the YSU PBL scheme, resulting in a better performance in TC track forecasts.

4.3 Other factors influencing the performance of EPMEF

There may be other factors influencing the performance of EPMEF, such as the domain settings regarding to size and location, the choice of horizontal resolutions for the nested domain, and so on. As indicated in the study of Landman et al. (2005), model domain choice is important in the simulation of TC-like vortices in the southwestern Indian Ocean. Giorgi (2006) also pointed out that one should carefully consider the choice of domain size and location in relation to model resolution and the placement of domain boundaries in the design of regional climate simulation experiments. Nevertheless, the results from a set of experiments with different domain sizes and location (shifting the domain to the east or west) as well as an increased resolution (from 24 km to 10 km in the inner domain) indicate that, though differences among these experiments exist, they are relatively small compared to those among different combination of PBL and microphysics schemes (figure omitted). Considering both the model performance and the computation cost, the current model configuration regarding the domain sizes and location as well as horizontal resolution are thus nearly optimal. With more computer resources available in the future, we will update the current horizontal resolution of EPMEF to a higher one (say, 10km in the inner domain) which we believe will benefit the performance of EPMEF.

It is obvious that the EPMEF performed much better for the 2012 and 2013 TC seasons than for the 2011 TC season in TC track forecasts. The better performance of the EPMEF could attributed to the following factors: 1) the large-scale forecasts from GFS are probably improved in the 2012-2013 TC seasons compared to those in the 2011 one due to the use of ensemble forecast information as background error estimation in NCEP GSI through the hybrid ensemble-GSI system, which in turn improves the IC/BC in EPMEF and results in more accurate TC track forecasts for the 2012-2013 TC seasons; 2) the network for EPMEF was updated with higher speed since 2012, which allows more most-updated GFS data to be downloaded before the starting of the model run for each forecast cycle in the 2012-2013 TC seasons than in the 2011 one. As demonstrated in Subsection 4.1, the performance of EPMEF can benefit from the most updated GFS forecast.

5. Summary

A real-time air-sea-wave regional forecasting system for the SCS has been established. It consists of a regional atmosphere model WRF, a regional ocean model POM and a sea wave model WW III. The output from the Global Forecasting System (GFS) of NCEP is used as the initial conditions and boundary conditions of WRF which exerts constraint on the development of small and meso-scale atmosphere perturbations through dynamical downscaling in two nested domains. The wind field at 10-m height forecasted by WRF is used to drive the ocean model and the sea wave model. The preliminary results from its near real-time run (four times a day) for the last three years demonstrate that it is stable and reliable under various situations. In particular, the performance of EPMEF in typhoon track prediction during 2011-2013 TC seasons is very encouraging compared to other major agencies in the world, although in a cost of about two-hour delay of forecast release. The dynamically downscaled GFS forecasts from the most updated forecast cycle and the optimal combination of different microphysics and PBL schemes primarily contribute to the good performance of EPMEF in TC track forecast.

EPMEF, established primarily for research with proven capability and reliability to apply into operational, can provide not only valuable references to the forecasters of the local official marine and meteorological forecast agencies in their daily operational forecasts, but also some practical clues or hinds for improving TC forecast skills to the world-wide official forecast agencies. Moreover, it has also played a role in serving for some important social activities and scientific marine surveys in the SCS and its surrounding regions by providing the necessary environmental forecasts (especially the TC track forecast) with relatively high accurateness since its establishment.

EPMEF, however, is still under continuously developing and improving. In the future, a three-way-interactive air-sea-wave coupled system will replace the current one-way-down-stream one, with a higher grid resolution for the atmospheric component. Furthermore, data assimilation package will be incorporated into EPMEF for assimilating both the atmospheric and oceanic observations (including in-situ and satellite-derived observations) using 3-dimensional and 4-dimensional variational data assimilation approaches (3DVAR/4DVAR). In particular, a “scale-selective data assimilation” (SSDA) scheme (Peng et al. 2010) will be employed to assimilate the large-scale atmospheric circulation from the forecasts of a global model into WRF for improving the track prediction of tropical cyclones (Xie et al. 2010). It is expected that, the TC track forecasts by EPMEF will be improved in the coming future. On the other hand, the forecasts of storm surges and waves from the ocean and wave model appear good when compared to a few limited observations, but an overall assessment is still not ready yet due to lack of observations. This is to be reported in our future work.

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Figure captions

Fig. 1 The flow chart for the system of EPMEF. Here the 'OPTS' means the 'Tidal Data Prediction Software'.

Fig. 2 The model domains of WRF and the JTWC "best" tracks of18 tropical cyclones of 2013 that entered the inner domain with life cycle longer than 48 hours and were forecasted by at least 4 agencies (of JTWC, JMA, NMCC, CWBT, NCEP and EPMEF).

Fig. 3 The mean track position errors (TPE, unit: km) and the relative errors with their standard deviations (black vertical lines) of the predicted track for the 10 tropical cyclones in 2011 from different agencies for (a) 24-h, (b) 48-h, and (c) 72-h forecasts, respectively. Here JTWC denotes the U.S. Navy/Air Force Joint Typhoon Warning Center, JMA the Japan Meteorological Administration, NMCC the National Meteorological Center of China, and CWBT the Central Weather Bureau of Taiwan (CWBT).

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Fig. 6 The track position errors (TPE, unit: km) of Nanmadul (2011) from different agencies for multiple (a) 24-h forecast, (b) 48-h forecast and (c) 72-h forecast initializing every 6 hours starting at 0000 UTC 24 Aug. 2011 (the interval of abscissa is 6 hours), and (d) the “best” and predicted tracks of Nanmadul (2011) from different agencies for a single 72-h forecast initializing at 1200 UTC 27 Aug. 2011.

Fig. 7 The track position errors (TPE, unit: km) of Rumbia (2013) from different agencies for multiple (a) 24-h forecast, (b) 48-h forecast and (c) 72-h forecast initializing every 6 hours starting at 1200 UTC 28 Jun. 2013 (the interval of abscissa is 6 hours), and (d) the “best” and predicted tracks of Rumbia (2013) from different agencies for a single 72-h forecast initializing at 0000 UTC 29 Jun. 2013.

Fig. 8 The same as Fig. 6, except for Nesat (2011) from different agencies for multiple (a) 24-h forecast, (b) 48-h forecast and (c) 72-h forecast initializing every 6 hours starting at 0000 UTC 24 Sep. 2011, and (d) the “best” and predicted tracks o initializing at 1200 UTC 25 Aug. 2011.

Fig. 9 The “best” track and the predicted tracks for a single 72-h forecast from different agencies for (a) Megi (2010) initializing at 0000 UTC 18 Oct. 2010 and (b) Roke (2011) initializing eat 0600 UTC 14 Sep. 2011, and the track position errors (TPE, unit: km) of Roke (2011) from different agencies for (c) 48-h forecast and (d) 72-h forecast initializing every 6 hours starting at 1800 UTC 13 Sep. 2011 (the interval of abscissa is 6 hours).

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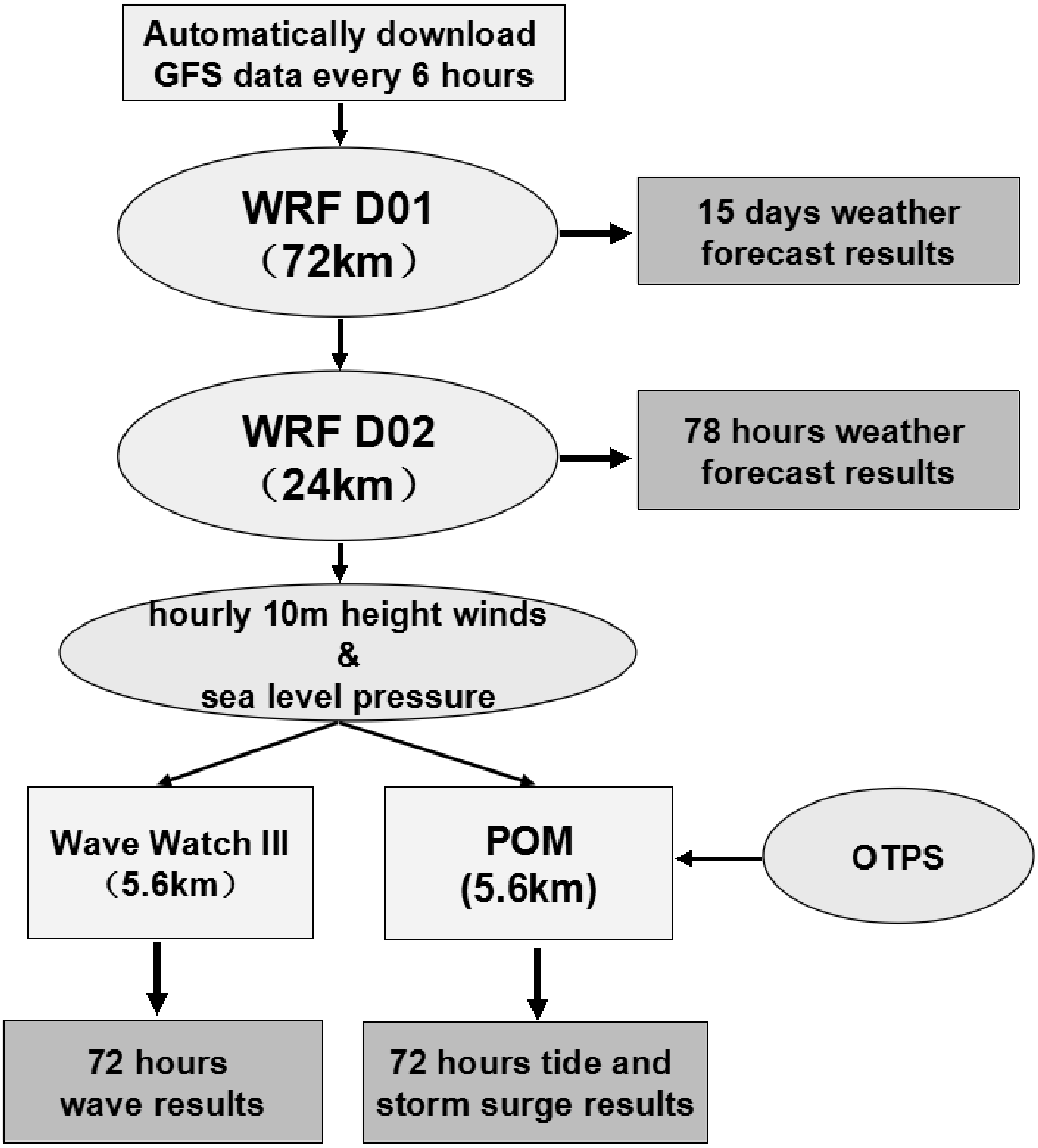
Fig. 11 The mean biases of (a) u-components and (b) v-components of steering flows from the 72-h forecasts of EPMEF and EPMEF-6 against the FNL analysis averaged over an ensemble of model runs initialized at every 6-h from 0000 UTC 2 Oct. to 1200 UTC 5 Oct. for the typhoon Gaemi (2012).

Fig. 12 The mean biases of (a) u-components and (b) v-components of steering flows from the 72-h forecasts by different combinations of 4 microphysics schemes (Ferrier, Goddard, WSM6, Lin) and three PBL schemes (YSU, MYJ, MYNN2) against the FNL analysis for typhoon Vicnte (2012), which are averaged over an ensemble of model runs initialized at every 6-h from 1200 UTC 21 Jul. to 1800 UTC 23 Jul..

Table 1. The mean track position errors (TPE, unit: km) and relative errors (indicated in blanket) of 24-h, 48-h and 72-h forecasts as well as the total rank for different combinations of four microphysics schemes and three PBL schemes, averaged over an ensemble of forecasts initializing at every 6 hours from 1200 UTC 21 Jul. to 1800 UTC 23 Jul. for typhoon Vicnte (2012).

		Ferrier	**Goddard**	**WSM6**	**Lin**
24h fcst	**YSU**	69.9 (0.80)	81.7 (0.93)	84.8 (0.97)	88.0 (1.01)
	MYJ	94.6 (1.08)	90.1 (1.03)	87.4 (1.00)	93.5 (1.07)
	MYNN2	83.5 (0.95)	84.3 (0.96)	96.9 (1.11)	95.2 (1.09)
48h fcst	**YSU**	156.2 (0.94)	184.0 (1.10)	170.5 (1.02)	171.1 (1.02)
	MYJ	144.0 (0.86)	149.8 (0.90)	142.4 (0.85)	157.3 (0.94)
	MYNN2	185.0 (1.11)	176.9 (1.06)	188.0 (1.13)	178.8 (1.07)
72h fcst	**YSU**	134.5 (0.50)	330.3 (1.22)	325.9 (1.21)	444.2 (1.64)
	MYJ	--- (---)	--- (---)	--- (---)	--- (---)
	MYNN2	182.5 (0.68)	235.2 (0.87)	228.9 (0.85)	280.7 (1.04)
RANK (SUM)	**YSU**	1 (2.23)	7 (3.26)	5 (3.20)	8 (3.67)
	MYJ	9 (---)	9 (---)	9 (---)	9 (---)
	MYNN2	2 (2.74)	3 (2.89)	4 (3.10)	6 (3.20)



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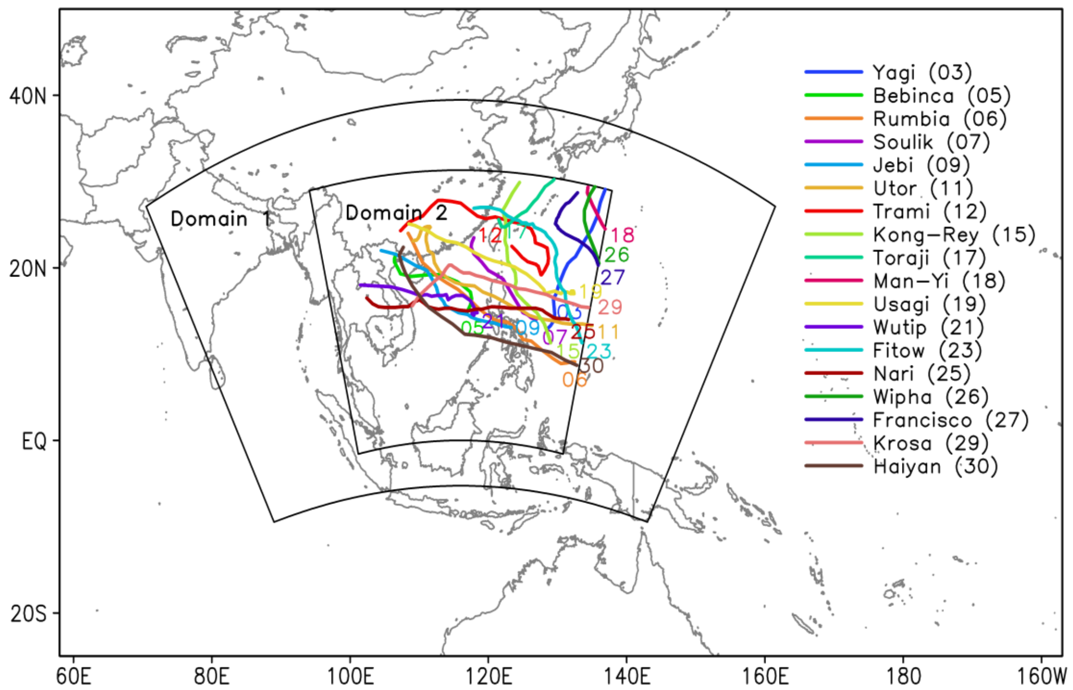

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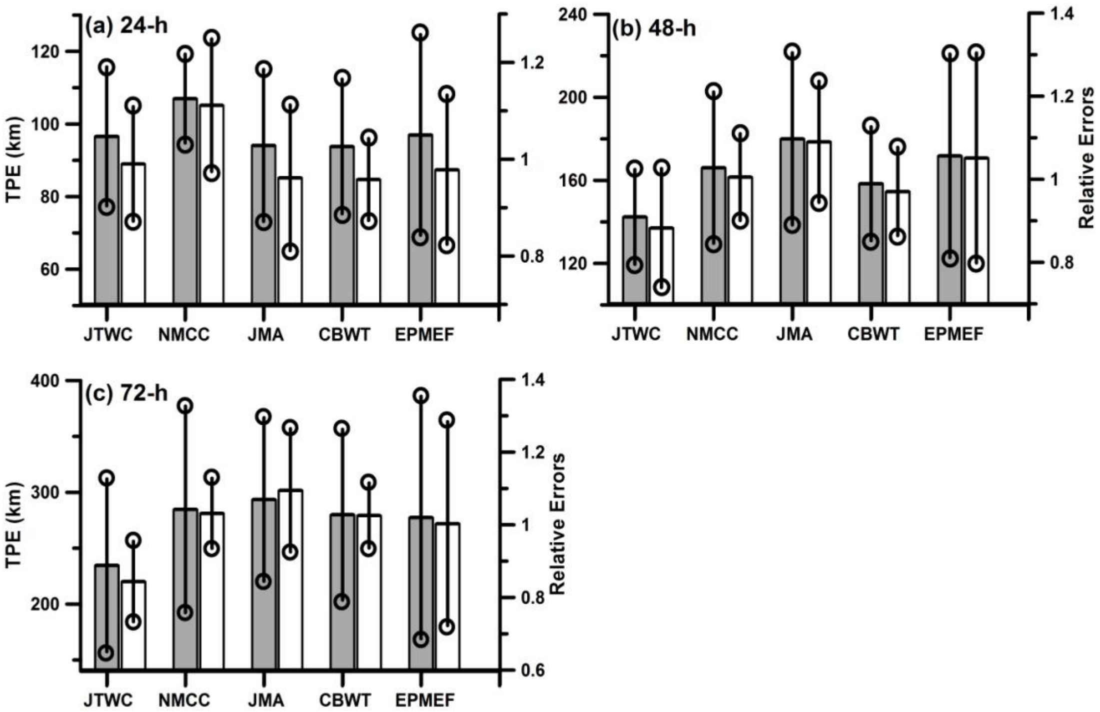

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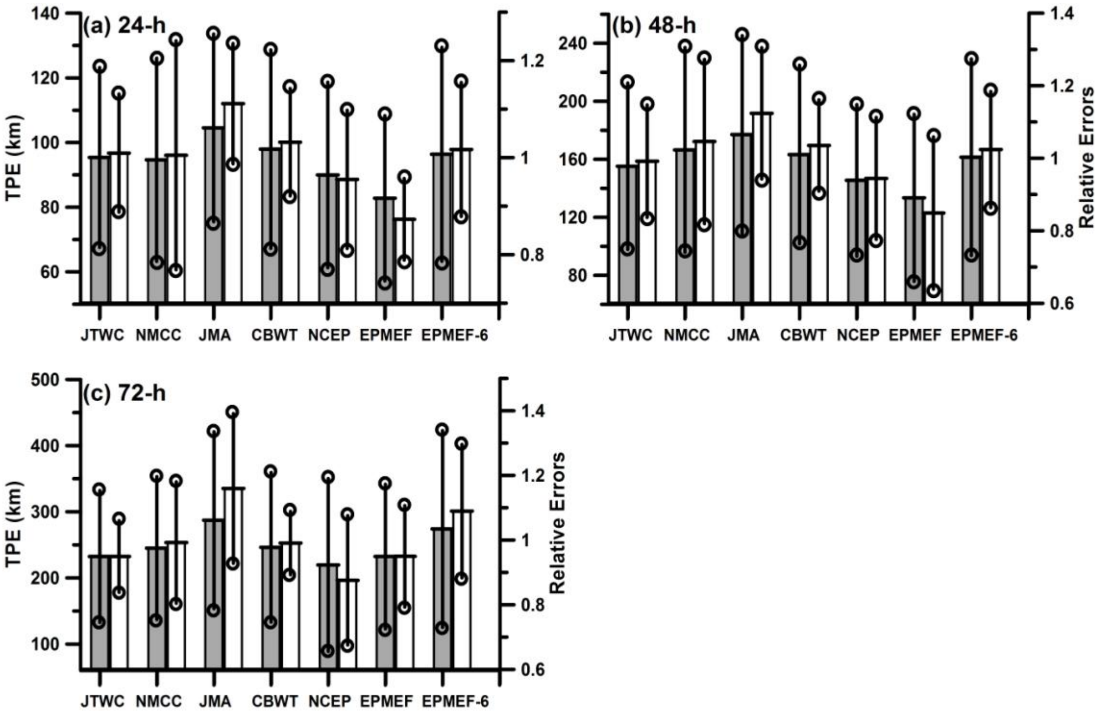

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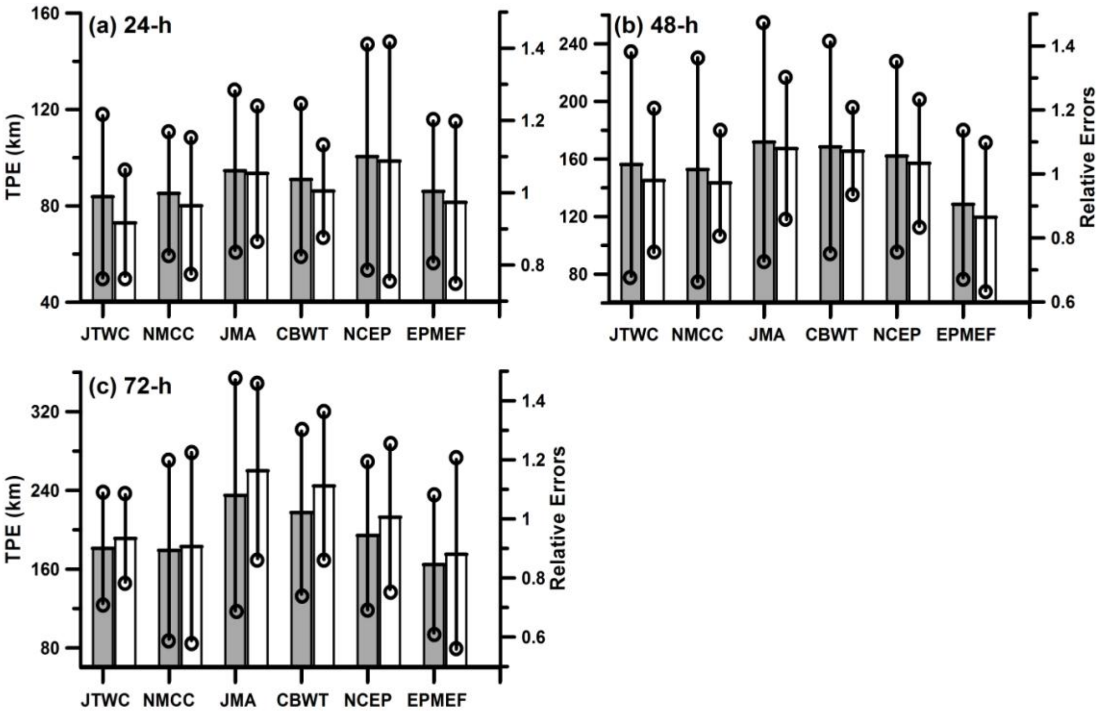

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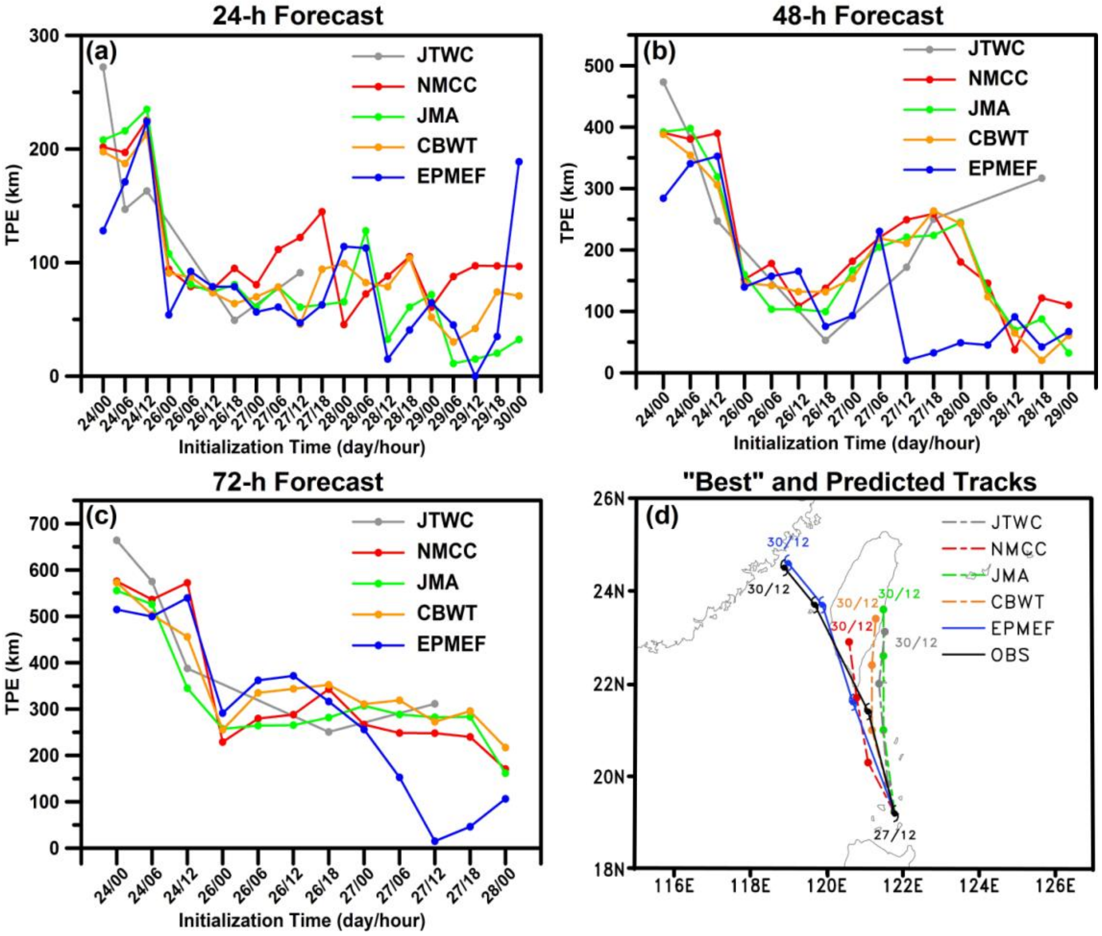

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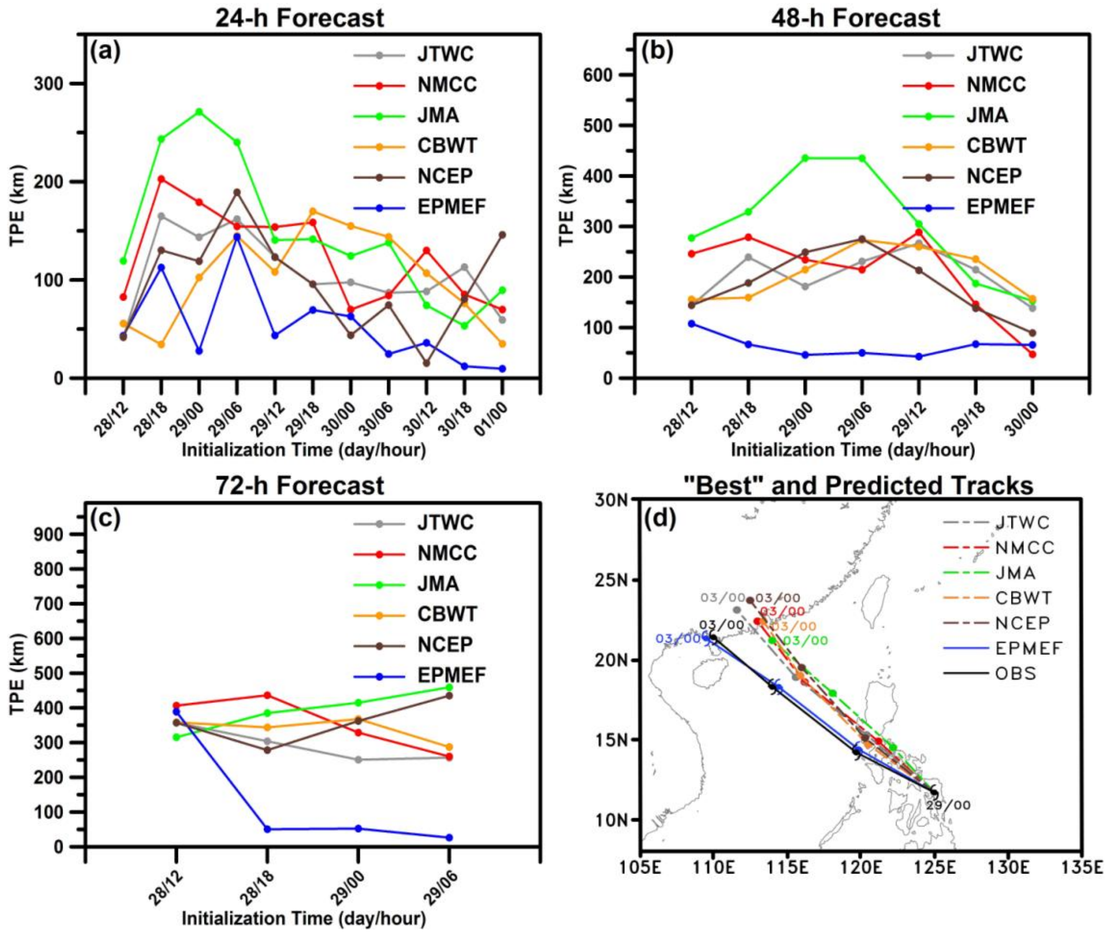

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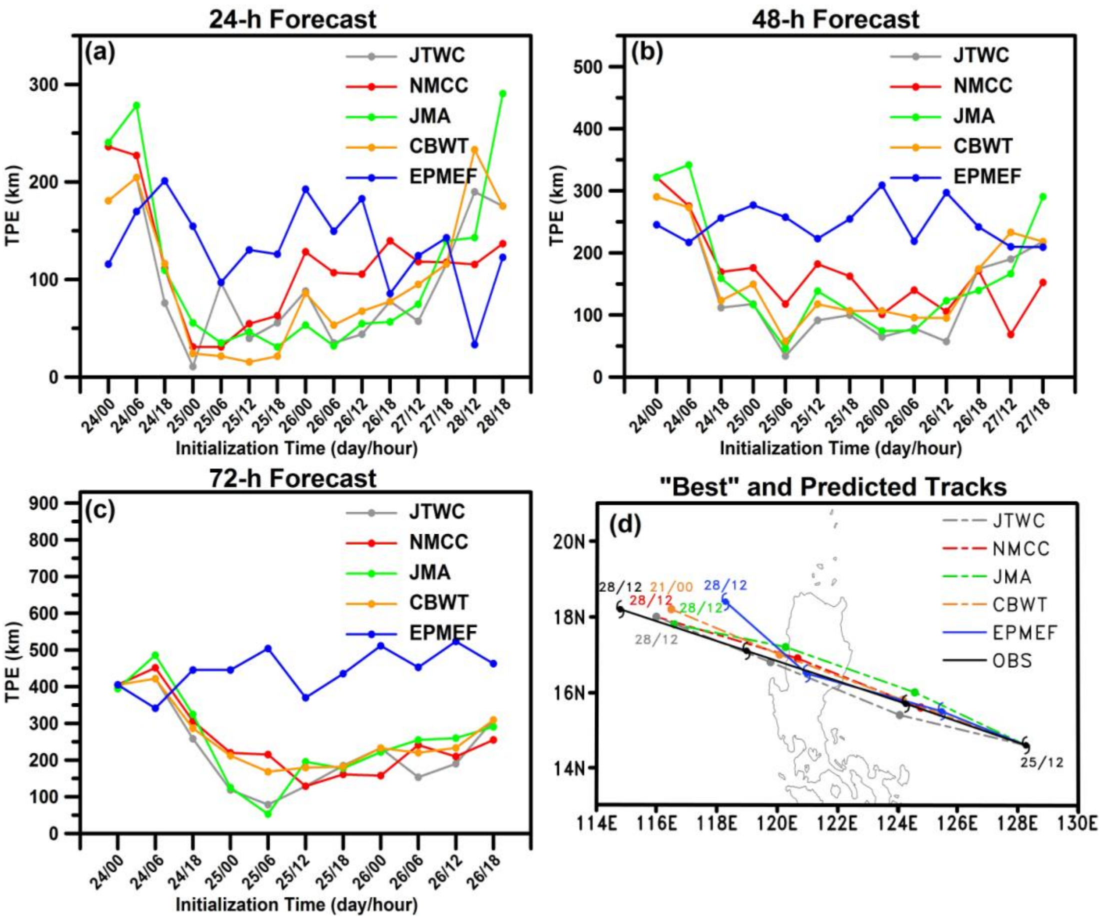

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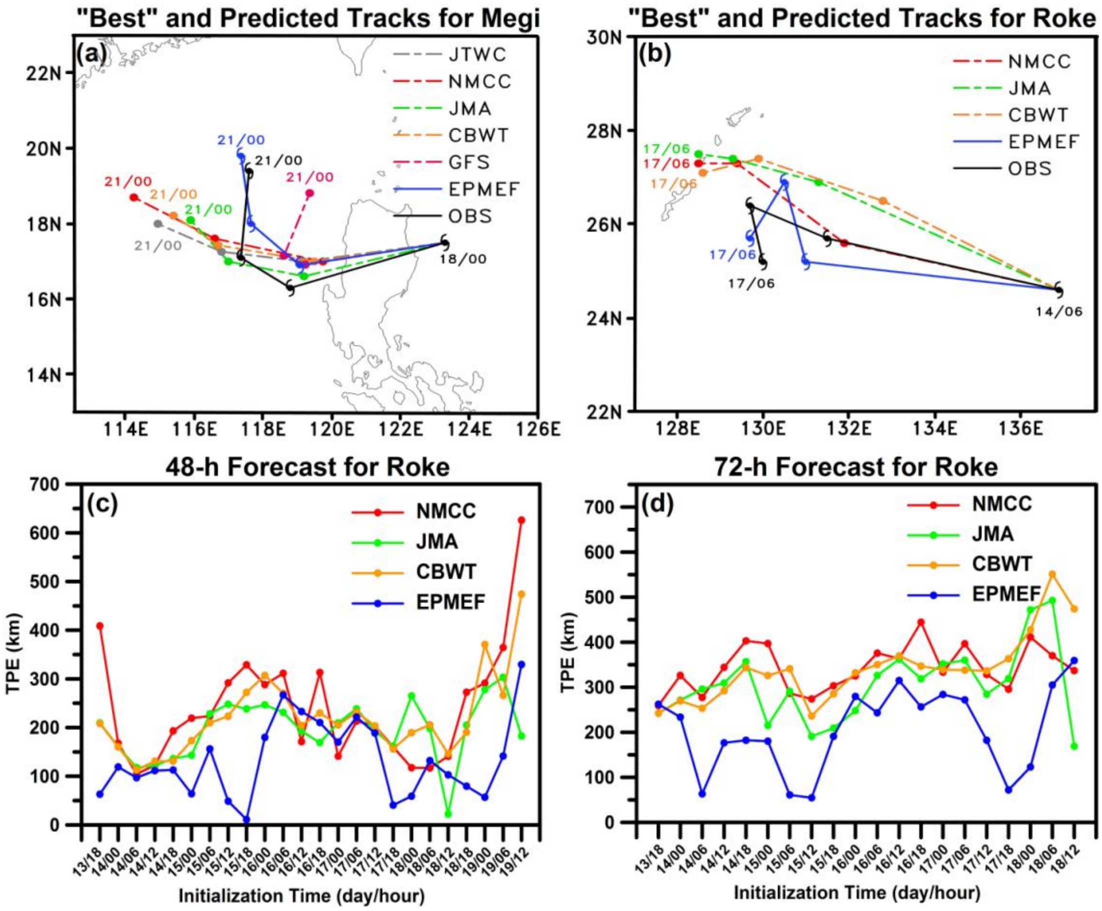

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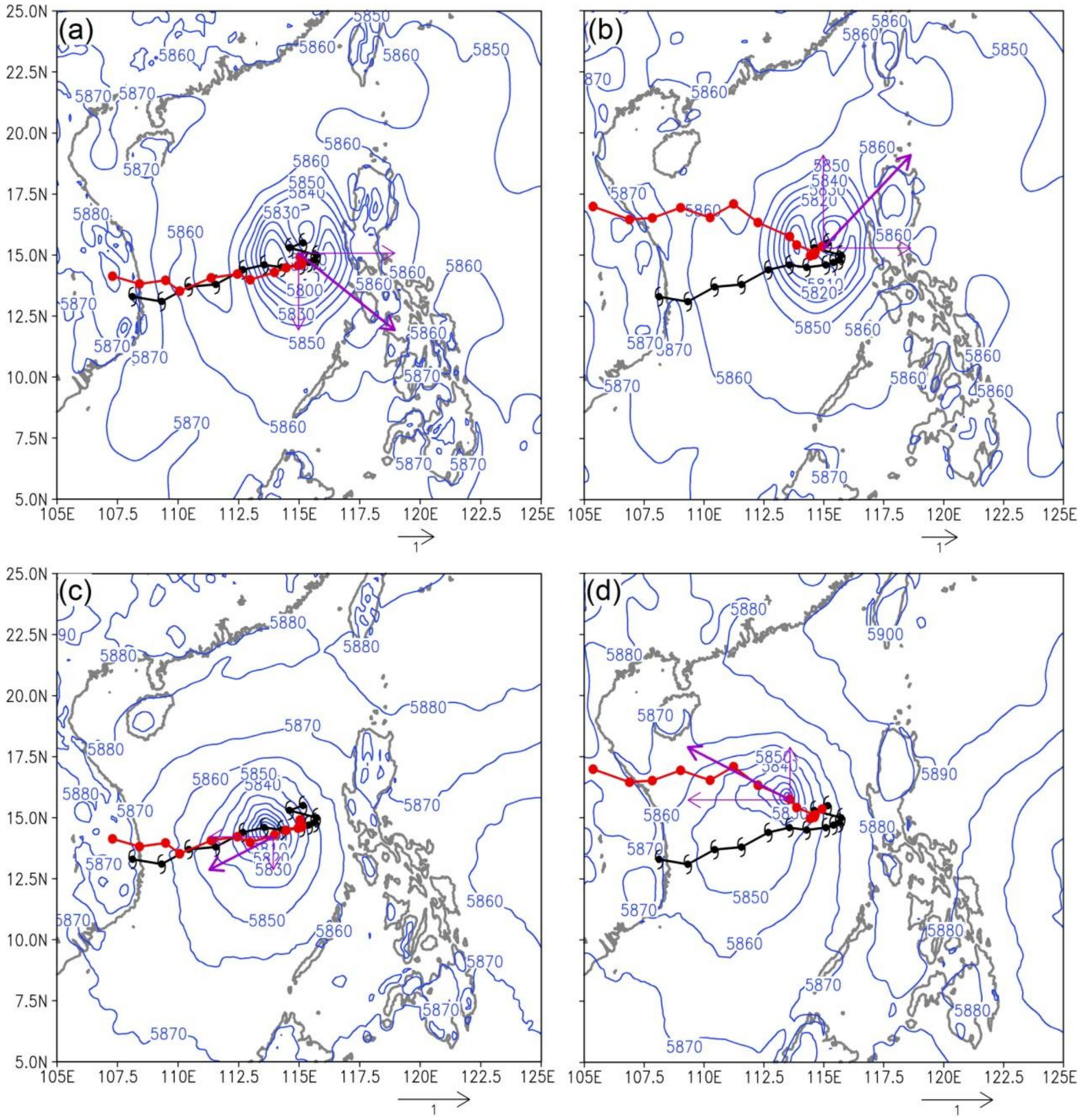

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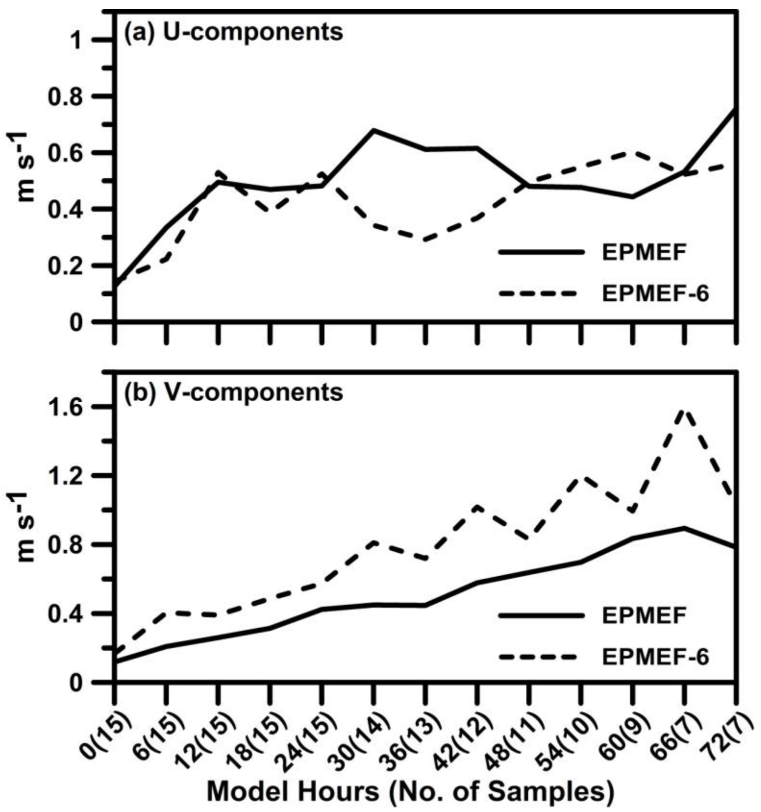

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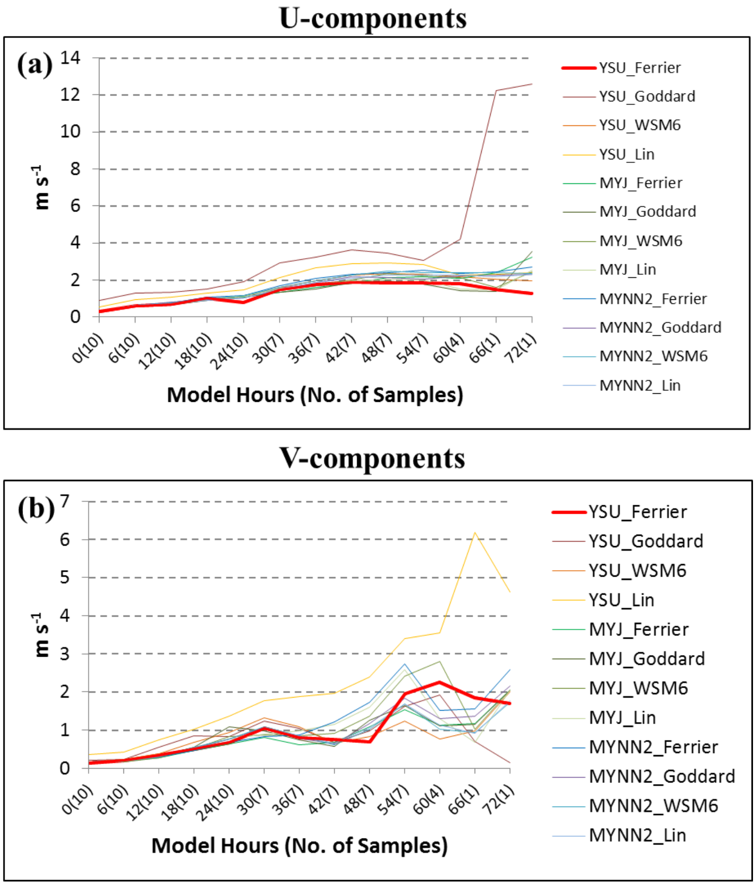

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