A Real-Time Regional Forecasting System Established for the South China Sea and Its Performance in the Track Forecasts of Tropical Cyclones during 2011–13

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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 a real-time run four times a day. Output from the Global Forecast System (GFS) from the 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 a constraint on the development of small- and mesoscale 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 (TCs) during 2011–13 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 forecasting. EPMEF, established primarily for research purposes with the potential to be implemented into operations, provides valuable information not only to the operational forecasters of local marine/meteorological agencies or international TC forecast centers, but also to other stakeholders such as the 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 (TCs) or typhoons form and pass through during the summer and fall seasons. These have the potential to cause damage to property and loss of life in East Asian countries such as the Philippines, Vietnam, and China (Wu and Kuo 1999). For instance, between seven and eight typhoons make landfall in China each year, impacting a population of 250 million with property losses of over $10 trillion (Liu et al. 2009).

Although the forecasting of tropical cyclone tracks and intensity has improved during the past several
decades, considerable uncertainty still exists. This is due to a poor understanding of the physical processes related to tropical cyclone intensity as well as the inherent predictability limit in numerical models, which still falls short in capturing the intricacies of the underlying mechanisms (Fraedrich and Leslie 1989; Plu 2011; Peng et al. 2014). In addition to high quality initial conditions (Kurihara et al. 1995; Leslie et al. 1998; Bender et al. 2007), factors contributing to improvements in the TC forecasting accuracy of a model may include the domain settings related 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). This paper introduces a real-time regional forecasting system established for the SCS whose atmosphere model features a “dynamical downscaling” initialization scheme and an “optimal” combination of the Ferrier microphysics scheme and the Yonsei University (YSU) PBL scheme with two nested domains centered in the SCS, and presents a preliminary evaluation of its performance in TC track forecasts during 2011–13.

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 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 known as the 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 October 2010. The system consists of three main components: an atmosphere model, an ocean model, and a sea wave model. These are the Weather Research and Forecasting (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 2003); and the WAVEWATCH III (WWIII) model (Tolman 1997, 1999, 2002), respectively. Figure 1 shows a flowchart 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), is a next-generation mesoscale 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 mesoscale 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 has been designed, as shown in Fig. 2. The outer domain for the atmosphere 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 (outer domain) and 24 km (inner domains), along with the 27 vertical layers, are chosen mainly because of limited computer resources (currently EPMEF is running on 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 $1° \times 1°$ is used to provide initial conditions (ICs) and lateral boundary conditions (BCs) for the outer domain. The Ferrier microphysics scheme (Ferrier et al. 2002), the Kain–Fritsch cumulus scheme (Kain and Fritsch
1990, 1993), the YSU PBL scheme (Hong et al. 2006), and the Dudhia shortwave (Dudhia 1989) and RRTM longwave (Mlawer et al. 1997) radiation schemes are chosen for both domains. Forecasts of 15 and 3 days are made automatically every 6 h (i.e., four times a day, at 0200, 0800, 1400, and 2000 LT in Beijing) for the outer and inner domains, respectively.

The 10-m-height winds from the inner domain of the WRF Model are used to drive the POM and WWIII. POM is a three-dimensional (3D) ocean model with primitive equations, embedded in a second-moment turbulence closure model [the Mellor–Yamada level 2.5 scheme; Mellor and Yamada (1982)]. The WWIII model is a third-generation wave model developed at NOAA/NCEP (Tolman 1997, 1999, 2002). As 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 detailed descriptions of the setup of the ocean and wave models. The evaluation for the performance of the ocean and wave models will be given in a future publication once enough observations are available.

3. Evaluation of the performance in TC track forecasts during 2011–13

The SCS and the western Pacific Ocean are the regions most frequently affected by typhoons or tropical storms in summer and autumn. For instance, there were 77 named and numbered tropical storms/typhoons occurring in these areas during 2011–13. Therefore, for an initial evaluation of the performance of EPMEF, we focus on the track forecasts of tropical cyclones during 2011–13 by EPMEF and make a comparison with the forecasts by other major agencies, including the U.S. Navy–U.S. Air Force Joint Typhoon Warning Center (JTWC), the Japan Meteorological Agency (JMA), the National Meteorological Center of China (NMCC), and the Central Weather Bureau of Taiwan (CWBT). Since the 2012 TC season, NCEP/Environmental Modeling Center (EMC) has been making real-time forecasts for west Pacific TCs using HWRF (Tallapragada et al. 2013); thus, we also compare our results for 2012–13 TC forecasts with those from NCEP/EMC. Because of 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 at 1/83 resolution to the regional WRF Model at 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 atmosphere model of EPMEF with life cycles longer than 48 h and were forecasted by at least three other agencies are counted in our statistics, which results in counts 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 cycles longer than 48 h. The TC center is tracked by a routine position search available in the fourth release of the Read/Interpolate/Plot (RIP4) WRF postprocess program. This takes into account the criteria in both the upper atmosphere and the sea surface: the predicted minimum sea level pressure, maximum 10-m height winds, maximum vorticities at 650 and 850 hPa as well as some prescribed thresholds for the vorticity at all levels, and the temperature at the surface and 700 hPa. Based on the observed (best) track issued by JTWC, the track position errors (TPEs) for 24-, 48-, and 72-h forecasts by each agency are calculated using the following formula (Neumann and Pelissier 1981; Powell and Aberson 2001):

\[
\text{TPE} = 111.11 \frac{180}{\pi} \cos^{-1}\left[\sin \phi_O \sin \phi_S + \cos \phi_O \cos \phi_S \cos (\lambda_O - \lambda_S)\right],
\]

where \(\phi_O\) and \(\lambda_O\) are the latitude and longitude of the storm center in the best-track data, and \(\phi_S\) and \(\lambda_S\) 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:

\[
R_i = \frac{\text{TPE}_i}{\overline{\text{TPE}}} \quad (i=1, \ldots, N),
\]

where \(\overline{\text{TPE}} = \frac{1}{N} \sum_{i=1}^{N} \text{TPE}_i\) 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 $R_i$ of all TCs for each agency for 24-, 48-, and 72-h forecasts.

Figures 3–5 give the mean TPEs and the relative errors of 10, 16, and 18 TCs for 2011, 2012, and 2013, respectively. The mean TPEs ($R_i$) over the 10 TCs in 2011 from EPMEF are 97.0 km (0.98), 172 km (1.05), and 278 km (1.0) for 24-, 48-, and 72-h forecasts, respectively, ranking as third, fourth, and second among the five agencies. In 2012 and 2013, the forecasts from HWRF are available for comparison alongside the other four agencies. The mean TPEs ($R_i$) from EPMEF are...
83 km (0.87), 133 km (0.85), and 232 km (0.95) for the 16 TC in 2012 (ranking first, first, and second) for 24-, 48-, and 72-h forecasts, respectively; and 86 km (0.98), 129 km (0.87), and 171 km (0.90) for 18 TCs in 2013 (ranking third, first, and first) for 24-, 48-, and 72-h forecasts, respectively. As examples, Figs. 6 and 7 show the performance of each agency for Nanmadol (2011) and Rumbia (2013), which made landfall along the coasts of Jinjiang in Fujian Province and Zhanjiang in Guangdong Province, respectively. For Nanmadol (2011), EPMEF performed slightly better than the 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 August 2011), which is probably due to the 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- and 72-h forecasts with mean TPEs of 137 and 289 km, respectively, especially for the second half of the period. The 72-h predicted track by EPMEF initializing at 1200 UTC 27 August 2011 is very close to the observed track (Fig. 6d). For Rumbia (2013), EPMEF performed much better than the others, with mean TPEs of 53, 64, and 129 km for the 24-, 48-, and 72-h forecasts, respectively. As indicated in Fig. 7d, initializing at 0000 UTC 29 June 2013, the EPMEF predicted a track and a landfall location 3 days ahead that are very close to the observations. In contrast, EPMEF shows the worst performance in some TCs, such as the strong Nesat (2011), of which large TPEs for all forecast times are seen for EPMEF (Fig. 8). In an overall assessment of the three TC seasons of 2011–13, 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 more difficult to predict: Megi (2010) and Roke (2011). Megi was the strongest typhoon observed during 2010 and the strongest one generated in autumn in the western Pacific Ocean for the past 20 years, with maximum wind speed of 72 m s$^{-1}$ and lowest sea level pressure of 895 hPa. The most astonishing feature of its track was the nearly 90$^\circ$ turn from westward to northward at 0000 UTC 20 October 2010 after it passed through the Philippines and entered the SCS. Most of the official agencies did not predict this big turn until 2100 UTC 19 October 2010. EPMEF, however, successfully predicted the big turn as early as 0000 UTC 18 October 2010 (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 through its adjustment to the large-scale circulation. The cold-air intrusion was well predicted by EPMEF and is mainly attributed to the proper selection of the PBL and physical schemes, as indicated by Zhou et al. (2013) and discussed in section 4b. Roke was generated as a tropical storm in the western Pacific (22.1$^\circ$N, 137$^\circ$E) at 1200 UTC 13 September 2011. When it moved westward to the east of Okinawa Island (26.4$^\circ$N, 129.7$^\circ$E) at 0600 UTC 16 September, it turned around and looped cyclonically.
and intensified into a typhoon. After this looping, it moved northward and then northeastward, and made landfall over Shizuoka County in Japan at 0600 UTC 21 September 2011. As early as 1200 UTC 14 September 2011, EPMEF successfully predicted the cyclonical loop that is usually very hard to predict (Fig. 9b). Figures 9c and 9d show the 48- and 72-h TPEs of Roke for each of the forecasting agencies (forecasting data from JTWC are not available), in which the performance of EPMEF is seen to be very encouraging with a minimum mean 48-h TPE of 130.15 km and a 72-h TPE of 194.03 km, compared to the mean 48-h TPEs of 241.3, 195.8, and 219.6 km, and the 72-h TPEs of 342.7, 304.4, and 340.9 km for NMCC, JMA, and CWBT, respectively.

4. Discussion

a. The initialization process

The above results indicate that the performance of EPMEF appears to be comparable to or even better than the performance of most of the official agencies. However, one should be aware of 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 and 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 multilayer dynamical models, single-layer...
trajectory models, consensus models, and statistical models, as well as the experiences of forecasters. Therefore, the comparison here is not strictly 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 forecast made for the 1200 UTC forecast cycle would be considered to be 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; that is, it could not be used to help prepare the 1200 UTC official forecast. Multilayer dynamical models are generally, if not always, late models. To allow the forecast to benefit from a late model as much as possible while keeping it timely, a technique is adopted that 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 an interpolated model. Since the initial and boundary conditions in the real atmosphere may vary significantly at different times, the forecast of a dynamical (late) model starting from the previous forecast cycle (i.e., initializing at 0600 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 in its late releases of forecasts. For instance, at the 1200 UTC forecast cycle, EPMEF waits
until 1515 UTC for the arrival of GFS forecasts initializing at 1200 UTC, which are not available until 1500 UTC. Running on a rack server with 32 cores of Intel Xeon E5 with 2.6 Hz, it generally takes about 1.5 h for EPMEF to download the GFS data, prepare ICs/BCs, and finish a 72-h forecast, so the track forecast from EPMEF could be released at about 1630 UTC [i.e., 1.5 h late compared to the forecast release time (1500 UTC) proposed by the official agencies]. For forecasts longer than 24 h, the negative impact of a 2-h delay in forecast release is nearly negligible. Thus, in our opinion, it is worth to gain an improvement in TC track forecasts at the cost of a ~1-2-h delay in the forecast release (the delaying time may be shortened to less than 1 h if a faster computer is used in the future), especially for a forecast period that is longer than 24 h.

To see how EPMEF may benefit from using the GFS forecasts of the current forecast cycle (i.e., the late model) to create ICs/BCs, we perform an ensemble of hindcasts for the 16 TCs during 2012 using a different initialization scheme (denoted as EPMEF-6). The initialization scheme for EPMEF-6 uses GFS forecasts of the previous forecast cycle (6-h early) for generating ICs/BCs, 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-, 48-, and 72-h forecasts are 96.6, 159.4, and 270.3 km, respectively, an apparent degrade compared to those of 82.8, 133.4, and 232.3 km for EPMEF (Fig. 4). Therefore, the reduction in TPEs in EPMEF is obviously attributed to a better representation of the initial large-scale environmental circulation 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 mesoscale features of the

![Fig. 8. As in Fig. 6, but for Nesat starting at 0000 UTC 24 Sep in (a)–(c) and at 1200 UTC 25 Aug 2011 in (d).](image-url)
meteorological fields in the regional model, but may not be much help in improving the large-scale environmental circulations that steer the TC. Figure 10 displays the steering flows and the 500-hPa potential heights from EPMEF and EPMEF-6 for Typhoon Gaemi (2012) at the initialization time of 1200 UTC 3 October 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 and 300 hPa and over a radial band from 3° to 8° centered at the TC eye, based on the suggestions or experiences in some previously published studies (Chan and Gray 1982; Dong and Neumann 1983). Although the initial vortex position from EPMEF-6 is slightly 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 favorable for a southwestward movement of the cyclone, while that in EPMEF-6 seems to facilitate northeastward movement, which deviates from the observed track of the cyclone. The biases of the zonal $u$ and meridional $v$ components of steering flows from the 72-h forecasts of EPMEF and EPMEF-6 against the NCEP Final Analysis (FNL) are displayed in Fig. 11, which are averaged over an ensemble of model runs initialized at every 6 h from 0000 UTC 2 October to 1200 UTC 5 October 2012. A significant reduction of the biases in the $v$ component of the steering flows is found for EPMEF, implying that the late model used in the initialization of EPMEF can better capture the large-scale environmental circulation not only at the initial time but also at the forecast times. Therefore,
EPMEF benefits from the GFS forecasts of the current forecast cycle (the most updated), which bring better steering flow than those of the previous forecast cycle (6h early), leading to better track forecasts of TCs.

b. The effect of microphysics and PBL schemes

Another important factor contributing to the good performance of EPMEF could be the choice of the Ferrier microphysics scheme and the YSU PBL scheme in the model. As shown in Zhou et al. (2013), various combinations of microphysics and PBL schemes may have different influences on TC track simulation, and the combination of a Ferrier scheme and the YSU scheme is the optimal pairing that leads to a best-track simulation of Supertyphoon Megi. The influence of various combinations of the microphysics and PBL
schemes on TC track forecasts may depend on the model configuration such as the horizontal grid resolution, the domain size, 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 the level-2.5 Mellor–Yamada Nakanishi Niino PBL scheme (MYNN2); see]
a detailed description in Skamarock et al. (2008)] and initializing at every 6 h from 1200 UTC 21 July to 1800 UTC 23 July for Typhoon Vicente (2012). The mean TPEs for various combinations are given in Table 1. It is found that the combination of the Ferrier and YSU schemes yields the smallest mean TPEs for both 24- and 72-h forecasts. Although the combinations of the MYJ PBL scheme with most microphysics schemes perform well, they do not work (blow up) for the 72-h forecast. Therefore, in an overall assessment, the combination of the Ferrier and YSU schemes performed the best among all combinations, as indicated by the rank based on the sum of the 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 the Ferrier and YSU schemes, as indicated in Fig. 12. Considering that 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 and PBL schemes for a number of typhoon cases. The results also show that the combination of the Ferrier and YSU schemes produces more accurate forecasts of the steering flows, which are governed by the large-scale circulations, leading to better TC track forecasts (figures not shown). Hence, EPMEF obviously benefits from the choice of the Ferrier microphysics scheme and the YSU PBL scheme, resulting in a better performance in the TC track forecasts.

Table 1. TPEs (km) and \( R_i \) of 24-, 48-, 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 every 6 h from 1200 UTC 21 Jul to 1800 UTC 23 Jul 2012 for Vicente.

<table>
<thead>
<tr>
<th>Forecast (h)</th>
<th>Ferrier</th>
<th>Goddard</th>
<th>WSM6</th>
<th>Lin</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 YSU</td>
<td>69.9 (0.80)</td>
<td>81.7 (0.93)</td>
<td>84.8 (0.97)</td>
<td>88.0 (1.01)</td>
</tr>
<tr>
<td></td>
<td>MYJ</td>
<td>94.6 (1.08)</td>
<td>90.1 (1.03)</td>
<td>87.4 (1.00)</td>
</tr>
<tr>
<td></td>
<td>MYNN2</td>
<td>83.5 (0.95)</td>
<td>84.3 (0.96)</td>
<td>96.9 (1.11)</td>
</tr>
<tr>
<td>48 YSU</td>
<td>156.2 (0.94)</td>
<td>184.0 (1.10)</td>
<td>170.5 (1.02)</td>
<td>171.1 (1.02)</td>
</tr>
<tr>
<td></td>
<td>MYJ</td>
<td>144.0 (0.86)</td>
<td>149.8 (0.90)</td>
<td>142.4 (0.85)</td>
</tr>
<tr>
<td></td>
<td>MYNN2</td>
<td>185.0 (1.11)</td>
<td>176.9 (1.06)</td>
<td>188.0 (1.13)</td>
</tr>
<tr>
<td>72 YSU</td>
<td>134.5 (0.50)</td>
<td>330.3 (1.22)</td>
<td>325.9 (1.21)</td>
<td>444.2 (1.64)</td>
</tr>
<tr>
<td></td>
<td>MYJ</td>
<td>(—)</td>
<td>(—)</td>
<td>(—)</td>
</tr>
<tr>
<td></td>
<td>MYNN2</td>
<td>182.5 (0.68)</td>
<td>235.2 (0.87)</td>
<td>228.9 (0.85)</td>
</tr>
<tr>
<td>Rank (sum)</td>
<td>YSU</td>
<td>1 (2.23)</td>
<td>7 (3.26)</td>
<td>5 (3.20)</td>
</tr>
<tr>
<td></td>
<td>MYJ</td>
<td>9 (—)</td>
<td>9 (—)</td>
<td>9 (—)</td>
</tr>
<tr>
<td></td>
<td>MYNN2</td>
<td>2 (2.74)</td>
<td>3 (2.89)</td>
<td>4 (3.10)</td>
</tr>
</tbody>
</table>
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 locations (shifting the domain to the east or west), as well as increased resolution (from 24 to 10 km in the inner domain), indicate that, though differences among these experiments exist, they are relatively small compared to those among different combinations 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 locations, as well as the 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 level (say, 10 km in the inner domain), which we believe will benefit the performance of EPMEF.

It is obvious that EPMEF performed much better for the 2012 and 2013 TC seasons than for the 2011 TC season in terms of TC track forecasts. The better performance of the EPMEF may be attributed to the following factors. 1) The large-scale forecasts from GFS are probably improved in the 2012 and 2013 TC seasons.
compared to those in 2011, as a result of the use of ensemble forecast information as background error estimation in NCEP GSI through the hybrid ensemble–GSI, which in turn improves the ICs/BCs in EPMEF and results in more accurate TC track forecasts for the 2012 and 2013 TC seasons. 2) The network for EPMEF was upgraded to a 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 and 2013 TC seasons than during 2011. As demonstrated in section 4a, the performance of EPMEF can benefit from the most updated GFS forecasts.

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 (WWIII). The output from the Global Forecast System (GFS) of NCEP is used as the initial and boundary conditions for WRF, which exerts a constraint on the development of small- and mesoscale 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 and sea wave models. The preliminary results from its near-real-time run (four times a day) for the last 3 years demonstrate that it is stable and reliable during various situations. In particular, the performance of EPMEF in typhoon track prediction during the 2011–13 TC seasons is very encouraging compared to results from other major agencies around the world, although at a cost of about a 2-h delay in forecast release time. 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 forecasting.

EPMEF, established primarily for research with proven operational capability and reliability, can not only provide valuable references to forecasters at local official marine and meteorological forecast agencies in their daily operational forecasts, but also some practical clues or hints for improving TC forecast skill to official forecast agencies worldwide. Moreover, it has also played a role in helping with 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 accuracy since its establishment.

EPMEF, however, is continuously being developed and improved. In the future, a three-way-interactive air–sea–wave coupled system will replace the current one-way-downstream version, with a higher grid resolution for the atmospheric component. Furthermore, a data assimilation package will be incorporated into EPMEF for assimilating both the atmospheric and oceanic observations (including in situ and satellite-derived observations) using three- and four-dimensional variational data assimilation (3DVAR and 4DVAR, respectively). 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 from EPMEF will continue to improve in the 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, which is due to a lack of observations. This is to be reported in our future work.

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REFERENCES


