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Dynamical downscaling forecasts of Western North Pacific tropical cyclone genesis and landfall

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Abstract This study evaluates the potential use of the regional climate model version 3 (RegCM3) driven by (1) the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data during 1982–2001 and (2) the NCEP Climate Forecast System Version 2 (CFS2) hindcast data during 2000–2010 in forecasting Western North Pacific (WNP) tropical cyclone (TC) activity. The first experiment is conducted to investigate the ability of the model in generating a good climatology of TC activity in spatial and temporal scales, so the model could be used in the second experiment to test its ability in forecasting TC genesis and landfall. Both experiments extend through the May to October WNP-TC season. Results show that the use of RegCM3 driven by the CFSR achieves a better simulation on the temporal and spatial variation of WNP-TC genesis during 1982–2001, as compared to previous studies using the same model but driven by the ERA40 reanalysis. In addition, diagnoses on the use of RegCM3 driven by the CFS2 point out that the 2000–2010 WNP-TC genesis locations and numbers from the model are very similar to those from the observations. The skill of RegCM3 in the forecasts of landfalling TCs is higher over the Southeast Asian region than over the other sub-regions of East Asia. Potential causes for such regional differences are discussed. Most importantly, statistical analyses show that the use of RegCM3 driven by the CFS2 gives a better forecast skill than the use of CFS2 alone for the prediction of WNP-TCs making landfall in East Asia. This indicates that the use of a dynamical downscaling method for the global forecast data would likely lead to a higher forecast skill of regional TC landfalls in most of the East Asian region.

Keywords Regional climate model · Tropical cyclone landfall · East Asia

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1 Introduction

An accurate prediction of tropical cyclone (TC) activity, particularly for those making landfall, is important to the regional community to prepare plans for reducing loss of life and serious damages to the economy. Many studies have examined the capability of using a dynamical model (e.g. Camargo and Barnston 2009; Vitart and Stockdale 2001; Vitart 2006) or a statistical method (e.g. Gray et al. 1992, 1994; Nicholls 1992; Chan et al. 1998, 2001) for the seasonal forecasts of TC activities. Most of these studies focused on the prediction of TC genesis over the open oceans but the prediction of TC landfall was rarely discussed. As the landfall of TCs has more direct impact on human life, it is important to evaluate the ability of available dynamical or statistical models for the seasonal prediction of TC landfall. Indeed, more and more recent studies have been made to develop a suitable statistical method for the forecast of TC landfall over different regions (e.g. Lehmiller et al. 1997; Bove et al. 1998; Liu and Chan 2003; Wu et al. 2004; Goh and Chan 2010). In contrast, the possibility of producing seasonal forecasts of landfalling TC using regional climate dynamical models,

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particularly for those making landfall in East Asia, has not been thoroughly examined.

In this study, our particular interest is to evaluate the forecast skill using a regional climate model—regional climate model version 3 (RegCM3)—for the seasonal prediction of WNP (Western North Pacific) TCs making landfall in East Asia. Chan et al. (2004) have modified an earlier version of this regional model (RegCM2) suitable for the simulation of Southeast Asian summer monsoon. Using a modified version of RegCM3, Au-Yeung and Chan (2012) (hereafter AYC12) further studied the ability of the model in the prediction of TC genesis over the WNP region during the 1982–2001 TC seasons. They showed that the RegCM3 driven by the ERA40[1] reanalysis can reasonably represent the TC genesis over the WNP basin. However, AYC12 did not examine the ability of the model in simulating the landfalling TCs. As the temporal evolution of the total number of WNP-TC genesis events from the observations has been shown to be positively correlated to the total number of WNP-TCs making landfall in East Asia (e.g. Chan and Xu 2009), it is likely that the capability of the RegCM3 in simulating TC genesis can be extended to produce reasonable seasonal forecasts of landfalling TCs in East Asia.

The objective of this study is therefore to verify this hypothesis by using a real-time global climate model forecast as boundary conditions for the RegCM3. Kim et al. (2012) employed a hybrid statistical–dynamical prediction method using the real-time global forecast data provided by the National Centers for Environmental Prediction Climate Forecast System (NCEP CFS) to predict the track of the seasonal TC activity and were able to generate skillful seasonal predictions of TC activity. It is therefore likely that the NCEP CFS hindcast data can serve as boundary conditions for the RegCM3 in making reasonable seasonal predictions of landfalling TCs in East Asia.

This study begins with forcing the RegCM3 with the NCEP CFS reanalysis [hereafter climate forecast system reanalysis (CFSR)] (Saha et al. 2010) to investigate the ability of the model in generating a good climatology of TC activity over various spatial and temporal scales. This step is to ensure that the RegCM3 can be used in the next step to examine its ability on the seasonal prediction of TC genesis and landfall by driving the model with the NCEP CFS version 2 (hereafter CFS2) hindcast data (Saha et al. 2013). Such arrangement has been frequently adopted by previous studies (e.g. Knutson et al. 2008; Stowasser et al. 2007; Walsh et al. 2004) to study issues related to the model simulation with the downscaling procedure. Details of the experimental setup, the data and methods employed in this study are described in Sect. 2. Results are presented and discussed in Sect. 3, following by a summary in Sect. 4.

[1] European Centre for Medium-Range Weather Forecasts 40 Year Reanalysis (Uppala et al. 2005).

2 Model, experimental setup and data

2.1 Model

The model used in this study is the RegCM3, an improved version of the RegCM2 (Giorgi et al. 1993). It was developed based on the Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model version 5 hydrostatic dynamical cores coupled with existing and new physics parameterization schemes suitable for climate applications. Details of the model physics and its improvement in RegCM3 were documented in Pal et al. (2007). In this study, the model uses the radiation scheme of the NCAR Community Climate Model Version 3 and the planetary boundary layer scheme developed by Holtslag et al. (1990). The soil–vegetation–atmosphere interaction processes are parameterized using the BATS (Biosphere–Atmosphere Transfer Scheme). During the simulation, terrain characteristics are provided by topography and land-use data derived from the United States Geological Survey and Global Land Cover Characterization, respectively.

The moist processes include both nonconvective and convective parameterization schemes. The subgrid explicit moisture scheme is used to handle nonconvective clouds and precipitation resolved by the model (Pal et al. 2007). For the convective process, the Emanuel scheme (Emanuel and Zivkovic-Rothman 1999), which has been suggested by Huang et al. (2012) to perform better than other schemes available in RegCM3 for the simulation of rainfall formation over the Western North Pacific Ocean, is employed. Note that the Emanuel scheme used in this study includes the relative vorticity and relative humidity suppression criteria proposed by Chow et al. (2006) who showed that such criteria lead to a significant improvement in the simulation of the Asian summer monsoon precipitation compared with the original Emanuel scheme.

2.2 Experimental setup and data

Two types of experiments are conducted in the present work to test the possibility of using RegCM3 in the seasonal forecasts of TC activity. The first experiment (hereafter Exp1) uses the NCEP CFSR (Saha et al. 2010) and the second experiment (hereafter Exp2) uses the real-time global CFS2 hindcast data (Saha et al. 2013) as the boundary conditions of RegCM3. The CFS2 produces a set of 9 month re-forecast initiated from every fifth day of the first month with four ensemble members for the period 1982–2010. It is run in near real time with a very short data cut-off time (Saha et al. 2013). Initial conditions for the atmosphere and ocean in CFS2 come from CFSR (Saha et al. 2010). Other details on the model configurations and the development of CFS2 can be found in Saha et al. (2013) and http://cfs.ncep.noaa.gov/cfsv2/docs.html. Here, in order to compare the results of Exp1 with the simulations of AYC12 that used RegCM3 driven by the ERA40 reanalysis (hereafter EAYC), the examinations of Exp1 focused on the same time period of 1982–2001 chosen in AYC12. For Exp2, simulations during 2000–2010 are investigated because the data quality of CFS2 is better after 1999 (Saha et al. 2013).

The sea surface temperature (SST) data used in Exp1 is the Optimum Interpolation SST V2 weekly mean data obtained from the Climate Diagnostics Center of the US National Oceanic and Atmospheric Administration, whereas the CFS2 hindcast SST is used for Exp2. The construction of SSTs in CFS2 follows that in CFS1 (the earlier version of CFS2), the details of which can be found in Saha et al. (2006). All lateral boundary conditions used to drive the RegCM3 are provided every 6 h via a relaxation method with a 15-grid buffer zone, following Chow and Chan (2009). The model used here has 20 vertical levels from surface level up to 10 hPa and covers the domain between (75°E–170°W, 10°S–45°N). The horizontal resolution is 50 km, which is sufficient to simulate accurately the distribution of precipitation over East Asia (Gao et al. 2006) and to depict properly the TC genesis over WNP (AYC12). It is noted that the purpose of this study is to investigate the number of TC landfalls without regard to intensity so the horizontal resolution of 50 km should be adequate.

In each simulation, the integration period is from 1 April to 30 October. The first month of the simulation (i.e. April) serves as the spin-up period and the downscaling experiments extend through the May to October (hereafter MJJASO) WNP-TC season. To obtain the TC climatology of the model, AYC12 performed the 6 months ensemble (eight runs each) simulations for each year and found that the ensemble average gives very good results compared with observations. The same ensemble method is therefore adopted in this study.

2.3 Criteria for the TC genesis and TC tracks

The observational TC genesis and tracks are obtained from the Joint Typhoon Warning Center (JTWC).[2] For the JTWC dataset, only the records with wind speeds ≥25 knots and genesis location within the region bounded by 0°–40°N, 100°E–170°W are considered. Such a TC detection scheme, which acts like a bias-correction scheme, is often used in dynamical seasonal forecasting to improve prediction skill (e.g. AYC12). In this study, the use of a wind speed of 25 knots as the lower threshold is based on the fact that JTWC generally initiates TC warnings in the WNP region when the estimated maximum sustained wind speeds around a TC-like disturbance is ≥25 knots.[3] For the model simulations, criteria of the identification of TC genesis include: (1) local maximum relative vorticity at 850 hPa $\geq 1 \times 10^{-4}$ s^{-1}; (2) temperature at 300 hPa must be 1 °C higher than the average temperature within 15° latitude radius from the TC center; (3) TC lifetime must be at least 2 days; and (4) genesis must occur over the ocean. The criteria of tracks in the simulations are traced from these identified vortices. Similar criteria have been applied to identify the RegCM3 simulated TC genesis and tracks in AYC12.

3 Results

Using JTWC data, Liu and Chan (2003) examined the TC landfalling activity along the South China coast and indicated that the formation position of TCs is one of the major factors which can provide indications for the behavior of TC landfalling activity. They noted that TCs formed east of 150°E rarely make landfall along the South China coast because it is difficult for such TCs to maintain a generally westward course without recurving throughout their lifetime. This implies that a model performing well on the simulation of characteristics of TC genesis has a better chance to produce a reasonable seasonal forecast of TC landfalling activity. The following analyses are therefore carried out to evaluate the ability of the RegCM3 in the simulation of the spatial and temporal variations of TC genesis (Sect. 3.1) prior to exploring its ability in the simulation of TC landfalling activity (Sect. 3.2).

3.1 WNP-TC genesis from Exp1 and Exp2

Figure 1a shows the climatological distribution of MJJASO TC genesis over the WNP basin derived from the JTWC data during 1982–2001. The results of Exp1 (Fig. 1b) indicate that both maxima of TC occurrence frequency [i.e. one is over the South China Sea (hereafter SCS), the other is over the east of Philippines] observed (Fig. 1a) are correctly simulated. The spatial correlation coefficient [hereafter Scorr; a parameter frequently adopted

[2] Available online at website http://weather.unisys.com/hurricane/w_pacific/index.html.

[3] See http://www.usno.navy.mil/JTWC/frequently-asked-questions-1/frequently-asked-questions.

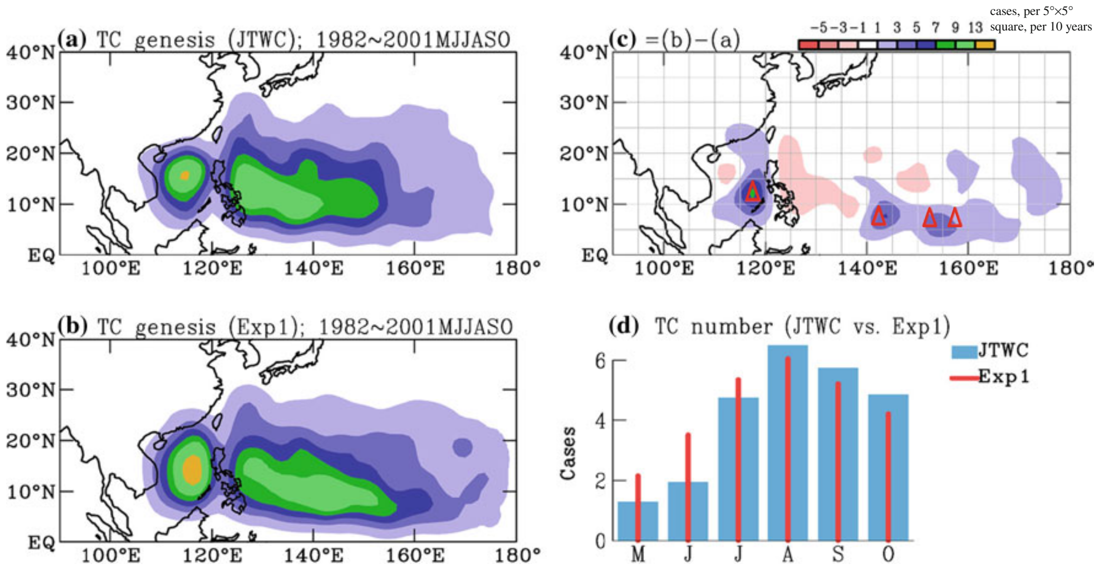

Fig. 1 Spatial distribution of the May to October (MJJASO) accumulated frequency of TC genesis averaged during 1982–2001 in the Western North Pacific (WNP) extracted from **a** the JTWC data; **b** the ensemble of Exp1 (i.e. the RegCM3 driven by CFSR data; see Sect. 2 for the details); **c** is the difference between **b** and **a**. The *color scale* of TC genesis in **a**–**c** is given in the *right top* of **c**. The unit is cases, per 5°×5° square, per 10 years. In **c**, the area with difference significant at the 95 % CI is marked with *red open triangle*; **d** the climatological month-to-month evolution of TC genesis number averaged over the time periods of 1982–2001 obtained from JTWC (*blue bar*) and Exp1 (*red line*)

to quantify the spatial similarity (Daley 1993)] between Fig. 1a, b gives a value of ~0.93, which is significant at the 95 % confidence interval (CI).[4] This implies that the use of RegCM3 driven by the CFSR is able to spin up TCs with a spatial pattern very similar to that from the observational data over the same period. Such a conclusion is also evident from Fig. 1c which shows that the difference between Fig. 1b, a is insignificant for most of the WNP basin.

In addition to the spatial similarity, the results from Exp1 also show that the model is capable of producing a reasonable temporal evolution of WNP-TC genesis. For example, Exp1 does capture the climatological feature of WNP-TC genesis numbers that increase from May to August and decrease from August to October, as in the observations (Fig. 1d). For the interannual variation of WNP-TC genesis (Fig. 2), the temporal correlation coefficient (hereafter Tcorr) between Exp1 and the observation during 1982–2001 is ~0.8, which is significant at the 95 % CI and higher than that using EAYC (Tcorr = 0.65; see AYC12). This suggests that using CFSR instead of ERA40 for driving RegCM3 can lead to a better simulation of past TC changes over the WNP basin, which is consistent with Saha et al. (2010) who pointed out that CFSR was designed for a better simulation of long-term climate change. Most importantly, it is clear from Figs. 1 and 2 that the RegCM3 can be used for generating a good climatology of TC activity in both the spatial and temporal scales. Therefore, this model is then driven by the NCEP CFS2 hindcast data (i.e. Exp2) to understand its utility for the seasonal forecasts of WNP-TC genesis during 2000–2010.

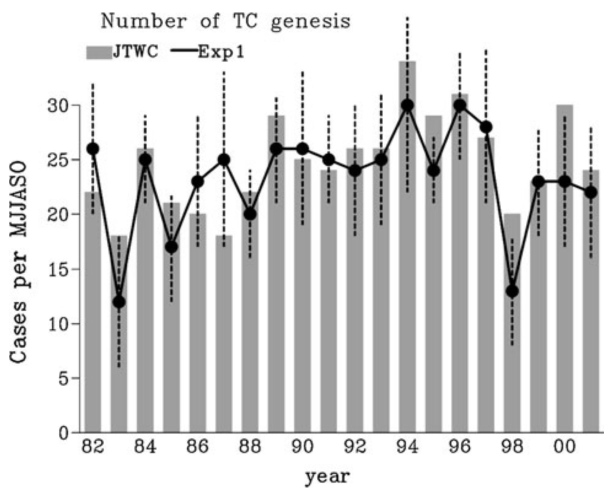

Fig. 2 Year-to-year variations of the MJJASO (May–October) TC genesis numbers over the WNP basin derived from the JTWC data (*grey bar*) and the outputs of Exp1 during 1982–2001 (*solid line* represents the ensemble mean). The spread between the ensemble members are shown by the *dashed lines*

[4] Here, the spatial autocorrelation has been taken into account in the calculation of the number of degrees of freedom for statistical significance.

Figure 3a shows the spatial distribution of climatological MJJASO TC genesis averaged during 2000–2010 derived from the JTWC data. The reason for selecting this time period has been given in Sect. 2. A comparison between Fig. 3a, b indicates that Exp2 is able to capture the locations of two maximum centers of TC genesis over the SCS and east of Philippines (Scorr ∼ 0.87; significant at the 95 % CI). Note that the major spatial difference between Exp2 and the observation appears over 145°E–165°E (Fig. 3c), where more TC genesis is predicted by Exp2. Because TCs form in the eastern part of WNP have more chance to re-curve northward rather than make landfall in South China (Liu and Chan 2003), it is expected that the skill of Exp2 for the forecasts of landfalling TCs in South China might not be affected compared with those for the other regions (to be demonstrated later in Sect. 3.2).

On the other hand, it is noted from Fig. 3d that on the average, Exp2 tends to overestimate the WNP-TC numbers generated during May to July and underestimate the WNP-TC numbers generated during August to October. Nevertheless, the total number of WNP-TCs generated during May to October estimated from Exp2 (∼22.54 cases per MJJASO season) is very close to the observed one (∼22.36 cases per MJJASO season). This implies that Exp2 performs better in predicting WNP-TC numbers on a seasonal timescale (e.g. the entire MJJASO season) than a monthly timescale. Furthermore, a comparison between the Exp2-forecasted annual MJJASO WNP-TC genesis numbers during 2000–2010 and those observed (Fig. 4) gives a Tcorr value of 0.63, which is significant at the 95 % CI. Note also that the apparent decreasing trend in the observed annual number of TC genesis is well captured by the model hindcast as well. All these results suggest that Exp2 could be used to forecast the interannual variation of MJJASO WNP-TC genesis numbers.

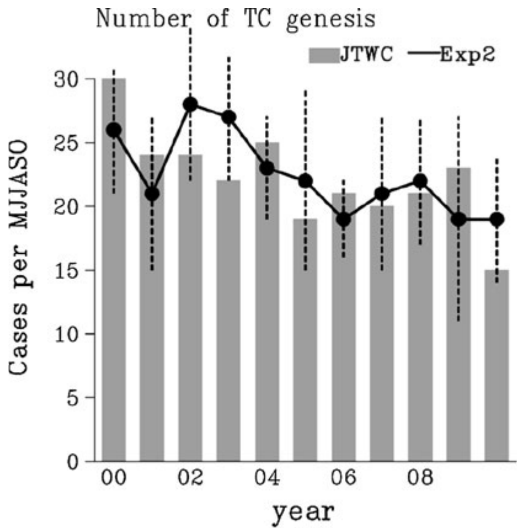

Fig. 4 As in Fig. 2, except for the year-to-year variations of MJJASO TC genesis numbers over the WNP basin during 2000–2010 derived from the JTWC data and the outputs of Exp2

Considering the small number of observations used in Fig. 4, a leave-one-out cross-validation (Michaelsen 1987; Elsner and Schmertmann 1994) method is used here to verify the potential forecast skill of Exp2, following Goh and Chan (2010). It is noted that a comparison between the cross-validated annual MJJASO WNP-TC genesis numbers

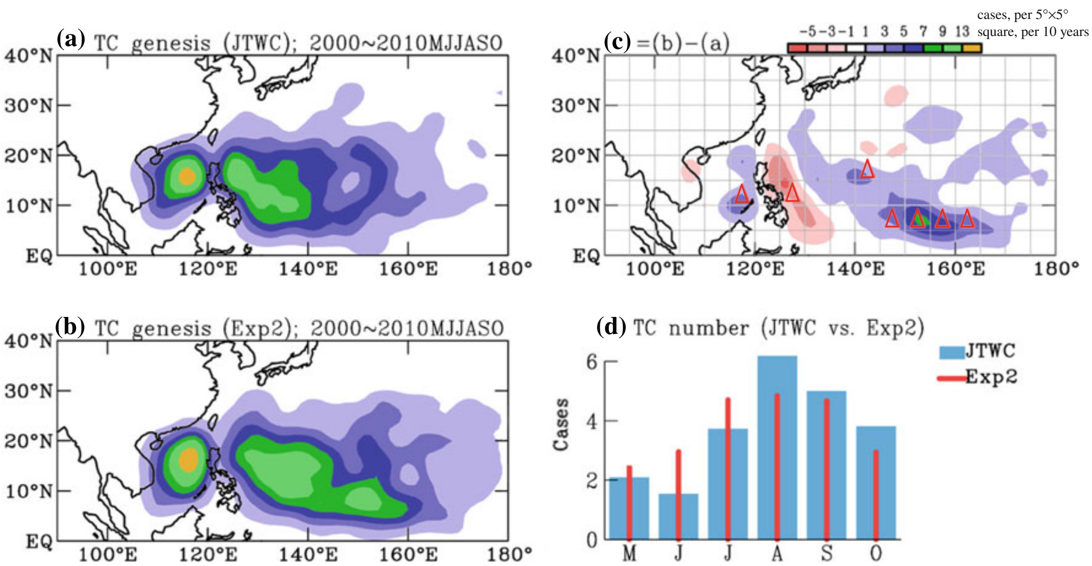

Fig. 3 As in Fig. 1, except for the comparison between the variations of TC genesis derived from the JTWC and the ensemble of Exp2 (i.e. the RegCM3 driven by CFS2 hindcast data; see Sect. 2) during 2000–2010, May–October

during 2000–2010 (not shown) and those observed gives a Tcorr value of 0.55, which is also significant at the 95 % CI. Further evidence for the verification is obtained from the computation of the forecast skill, i.e. $S = (1 - RMSE_{Exp2}/RMSE_{climatology}) \times 100\ \%$, with respect to climatology (Wilks 2006). The $RMSE_{Exp2}$ and $RMSE_{climatology}$ are the root-mean-square errors (RMSE) of the forecasts based on Exp2 and climatology, respectively. The value of S associated with Fig. 4 is found to be ~16 %, which implies that the forecast skill of Exp2 has ~16 % improvement over climatology.

Besides the temporal similarity, Exp2 is also capable of representing the interannual variation of spatial patterns of the MJJASO WNP-TC genesis. In previous observational studies of the characteristics of the interannual variations of TC genesis, a strong relationship with the El Niño/Southern Oscillation (ENSO) events has been found (Chan 1985; Lander 1994; Chen et al. 2006). It is known that during warm ENSO (El Niño) years, the mean genesis location of TCs (Fig. 5a)[5] tends to shift southeastward (Chan 2000; Chia and Ropelewski 2002; Wang and Chan 2002). In contrast, a northwestward shift is generally observed in the mean genesis location of TCs during cold ENSO (La Niña) years (Fig. 5b). More specifically, the main difference between warm and cold ENSO years is that more TCs were generated over the area east of 140°E in the former (Fig. 5c) (e.g. Chan 2000). A visual comparison between Fig. 5a–c and its related Exp2-simulated patterns (Fig. 5d–f) indicates that Exp2 does produce a good simulation on the spatial pattern of TC genesis related to the ENSO events. This conclusion is verified by the statistical evidence that all the values of Scorr between Fig. 5a–c, d–f (Scorr ~ 0.72 for Fig. 5a, d; ~0.78 for Fig. 5b, e; ~0.67 for Fig. 5c, f) are found to be significant at the 95 % CI.

All the results in Figs. 3, 4 and 5 therefore lead to the same conclusion that Exp2 (i.e. a dynamical downscaling forecast using RegCM3) can be adapted to produce reasonable seasonal forecasts of MJJASO WNP-TC genesis on both the spatial and temporal scales. Likely, Exp2 also has some ability on the prediction of TC landfall along the East Asian coastal regions, which is examined in the next sub-section.

3.2 TC landfalls from Exp2 and CFS2

Figure 6a shows the climatology of MJJASO TC occurrence frequency averaged during 2000–2010 derived from the JTWC data. Following Chan and Xu (2009), the connection of the vertices of the percentage contours gives roughly four major tracks: west-northwestward at low latitudes with possible landfall in south China (thick solid curve in Fig. 6a), Vietnam, Philippines, northwestward with possible landfall in East China (including Taiwan) (long-dashed curve in Fig. 6a), northward and northeastward with possible landfall in Korea and Japan (dotted curve in Fig. 6a), and towards the northeast with no landfall anywhere in East Asia. Based on these tracks, Chan and Xu (2009) separated the East Asian region into three sub-regions and the landfalling TCs were accordingly grouped as follows:

- South TCs (STC)—those making landfall in South China, Vietnam and the Philippines.
- Middle TCs (MTC)—those making landfall in East China (Taiwan, Fujian, Zhejiang and Jiangsu provinces, and Shanghai municipality).
- North TCs (NTC)—those making landfall in the Korean peninsula and Japan.
- All TC (ATC)—the total number of landfalling TCs in Asia.

All the four groups of TC landfalls are examined in the present study to evaluate the potential use of Exp2 in the seasonal prediction of landfalling TCs.

Figure 6b shows the average numbers of MJJASO TCs making landfall during 2000–2010 derived from JTWC (grey bar) and Exp2 (solid line) for all the four groups identified above. Following Chan and Xu (2009), two counting procedures are employed here to construct Fig. 6b. First, the case that one TC makes landfall in one sub-region, then re-curves and makes landfall again in another sub-region, an ATC will have only one landfall count. For example, if a TC makes landfall in Taiwan and then re-curves and makes landfall in Japan, then for the landfall in Taiwan it gives one landfall count in the MTC series and one landfall count in the ATC series. As for the landfall in Japan, it only gives one landfall count in the NTC series. In other words, the number ATC for a particular year is not necessarily the sum of the numbers of the NTC, MTC and STC in that year. Second, if one TC makes landfall in two places within the same sub-region (e.g. the Philippines and then Vietnam), it is only counted once. Based on these criteria, ~4.6, 4.2 and 7.4 TCs, respectively, make landfall in the NTC, MTC and STC area per MJJASO season (Fig. 6b). As for the ATC, there are ~14.9 TCs making landfall per MJJASO season.

A visual comparison between these observed and Exp2-forecasted landfalling TCs indicates that Exp2 can reasonably represent the climatological mean of landfalling TC cases in all sub-regions (including NTC, MTC and STC) with a smaller difference in the STC region and a

[5] In Fig. 5, the selection of warm and cold years is based on the ERSST.v3b sea surface temperature anomalies (SSTA) averaged over the Niño 3.4 region (5°N–5°S, 120°–170°W) provided by the National Weather Service Climate Prediction Center. A year with the value of SSTA averaged from May to October larger than 0.8 (smaller than −0.8) standard deviation is identified as a warm (cold) year (e.g. Chan 2000).

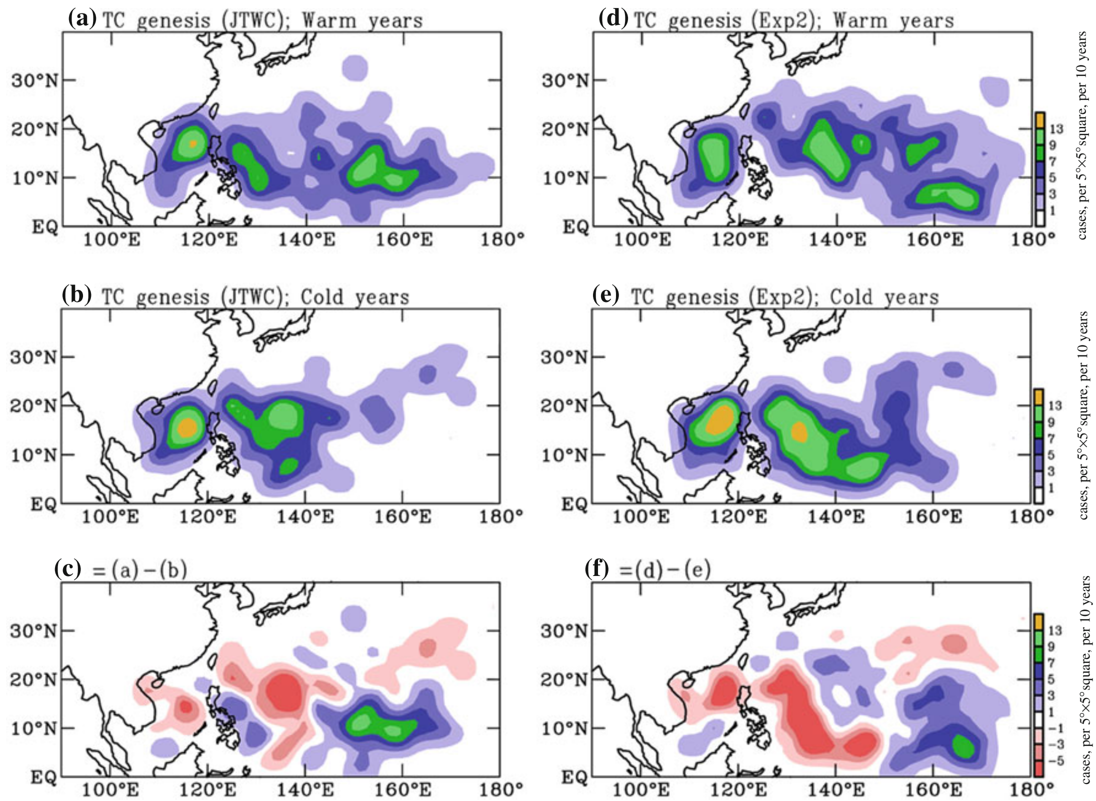

Fig. 5 The composite of the occurrence frequency of TC genesis extracted from JTWC for **a** warm years: 2002, 2004 and 2009; **b** cold years: 2000, 2007 and 2010; **c** the difference between **b** and **a**. Criteria of the selection of the warm and cold years are given in the manuscript; **d**, **e**, **f** are similar to **a–c**, but for the results of Exp2. The *color scale* of **a–c** is given in the *right bottom* of their related **d–f**, respectively

larger difference in the NTC region (Fig. 6b). More specifically, it is noted that Exp2 tends to overestimate the numbers of landfalling TCs in the NTC region. This implies that more re-curving TCs have been predicted by Exp2 during 2000–2010, which is consistent with what has been inferred from Fig. 3c. A possible reason for this model bias is the performance of RegCM3 in the simulation of environmental conditions. AYC12 examined the environmental conditions of the 500 hPa subtropical high over the WNP simulated by EAYC and found that the simulated subtropical high was weaker than the observed one. Similar to AYC12, a weaker-than-observed subtropical high is also seen in the outputs of Exp2 (not shown). As a weakening in the subtropical high could result in more re-curving ocean TCs (Chan and Xu 2009), it is reasonable that more landfalling TCs in the NTC region have been forecasted by Exp2. This could, in turn, result in more than observed climatological mean of ATC cases found in the outputs of Exp2 (Fig. 6b).

Note that the RegCM3 used in the present work was modified for a better simulation of the summer monsoon circulation change over the Southeast Asian regions (Chan et al. 2004). As the large-scale flow conditions are one of the major factors affecting the number of landfalling TCs (Goh and Chan 2010), it is likely that the current setup of RegCM3, which is more suitable for the seasonal forecasts of circulation change over the Southeast Asian region, might not be the best for the prediction of TC making landfalls in the other regions. This suggestion, however, requires more evidence to support, which will be reported in the future.

To evaluate the performance of Exp2 further, we also make a comparison between the landfalling TCs derived from Exp2 and CFS2 (i.e. the boundary conditions of Exp2). Unlike Exp2, CFS2 under-predicts the numbers of landfalling TCs in the STC region (see Fig. 6b).[6] This is consistent with the year-to-year variations of landfalling TCs in Fig. 7a showing that for most of the examined years, the numbers of landfalling TCs in the STC region predicted by the CFS2 forecast data are lower than those

[6] Note, what is being compared here can be seen as the output of the TC detection scheme when applied to the output of CSF2 versus the output of Exp2. Different results might be obtained if different detection schemes were used.

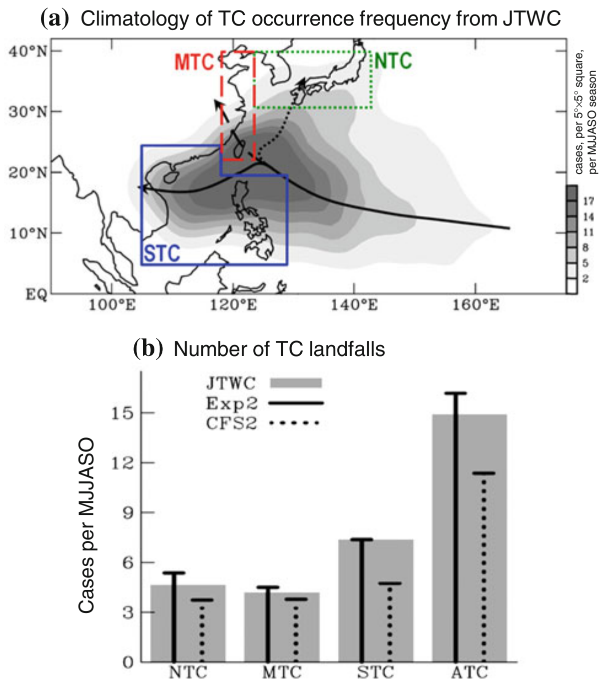

Fig. 6 **a** The climatology of MJJASO TC occurrence frequency averaged over the time period 2000–2010 derived from the JTWC best-track data. The *color scale* of **a** is given in its *right bottom*. In **a**, the *boxes mark* the different groups of landfalling TCs (STC—south TCs, MTC—middle TCs, and NTC—north TCs) studied in the paper, following Chan and Xu (2009). Three *lines* with *arrows* at the end indicate the possible maximum likelihood of tracks associated with each of these groups of landfalling TCs; **b** is the number of MJJASO TCs making landfall in the identified regions averaged over the time period 2000–2010 for JTWC (*grey bar*), Exp2 (*solid line*) and CFS2 (*dotted line*). In **b**, ATC—a fifth group, All TC is also added for discussion (see manuscript for details)

observed. This is likely because CFS2 tends to produce a weaker-than-observed Asian monsoon circulation (e.g. Yang et al. 2008; Drbohlav and Krishnamurthy 2010), which might in turn lead to a lower-than-observed numbers of WNP-TC genesis and TC landfall in the STC region (e.g. Chan and Xu 2009). Such bias, however, is much smaller from the Exp2 outputs (Fig. 7b). On the other hand, because the horizontal resolution of Exp2 ($\sim 0.5° \times 0.5°$) is higher than that of the raw CFS2 ($1° \times 1°$), some of the improvement shown in Exp2 might be due to the improved resolution (e.g. Gao et al. 2008).

Among all the sub-regions, Exp2 seems to gives the best hindcast in the STC region (Figs. 6, 7). Further evidence for supporting this finding can be obtained from the statistical analyses on the Tcorr and the RMSE between the time series of the observed and the simulated landfalling TCs during 2000–2010 MJJASO (Table 1). It is noted that among all the sub-regions, the STC region has the largest increase of Tcorr from 0.28 in CFS2 to 0.70 in Exp2 and the largest decrease of RMSE from 3.85 cases per MJJASO in CFS2 to 2.0 cases per MJJASO in Exp2. Also note from Table 1 that despite the regional difference, the value of Tcorr (RMSE) associated with the Exp2-forecasted landfalling TCs during 2000–2010 is higher (lower) than that associated with the CFS2-forecasted landfalling TCs for all the studied sub-regions including ATC. These results imply that using Exp2 is more suitable than using CFS2 alone in predicting the landfalling TCs in East Asia, particularly in the STC region.

Finally, a value $S = \left(1 - \frac{RMSE_{Exp2}}{RMSE_{CFS2}}\right) \times 100\,\%$—the forecast error of Exp2 with respect to the forecast error of CFS2—is computed to provide a quantitative estimate of the improvement of using Exp2 instead of using CFS2 on the seasonal prediction of landfalling TCs in East Asia. Here, $RMSE_{Exp2}$ and $RMSE_{CFS2}$ are the RMSE of the forecasts based on Exp2 and CFS2, respectively. According to Wilks (2006), a higher value of S indicates a better forecast skill for Exp2 over the CFS2 forecasts. As seen from Table 2, probabilistic forecasts of TC landfalls in NTC, MTC, STC and ATC regions, respectively, have 18.9, 6.2, 48.0 and 11.7 % improvements over the CFS2 forecasts. These are consistent with what has been observed in Table 1 showing that using Exp2 can improve the forecast skill of using CFS2 alone on the seasonal predictions of TC making landfall in most of the East Asian region, particularly for those making landfall in the STC region.

4 Summary

This study evaluates the potential use of the RegCM3 driven by (1) CFSR data (i.e. Exp1) and (2) CFS2 hindcast data (i.e. Exp2) in forecasting the MJJASO WNP-TC activities. Examinations on the outputs of Exp1 indicate that the use of CFSR as the boundary conditions of RegCM3 exhibits a noticeable improvement for generating a more accurate simulation on the spatial and temporal variations of WNP-TC genesis over the time period 1982–2001, as compared to previous studies using the ERA40 reanalysis to drive RegCM3 (AYC12). Based on this result, the RegCM3 is tested for its ability to use CFS2 as initial and boundary conditions in forecasting the WNP-TC genesis and landfall over the time period 2000–2010. Results show that the use of the dynamical downscaling procedure, i.e. Exp2, provides certain improvements in forecast skill over the forecast using CFS2 alone on the TC making landfall in most of the East Asian regions, particularly for those making landfall in the STC region. This information is particularly important for the regional community in Southeast Asia to generate a more accurate seasonal forecast of TC activities to investigate the potential destruction from TC landfall.

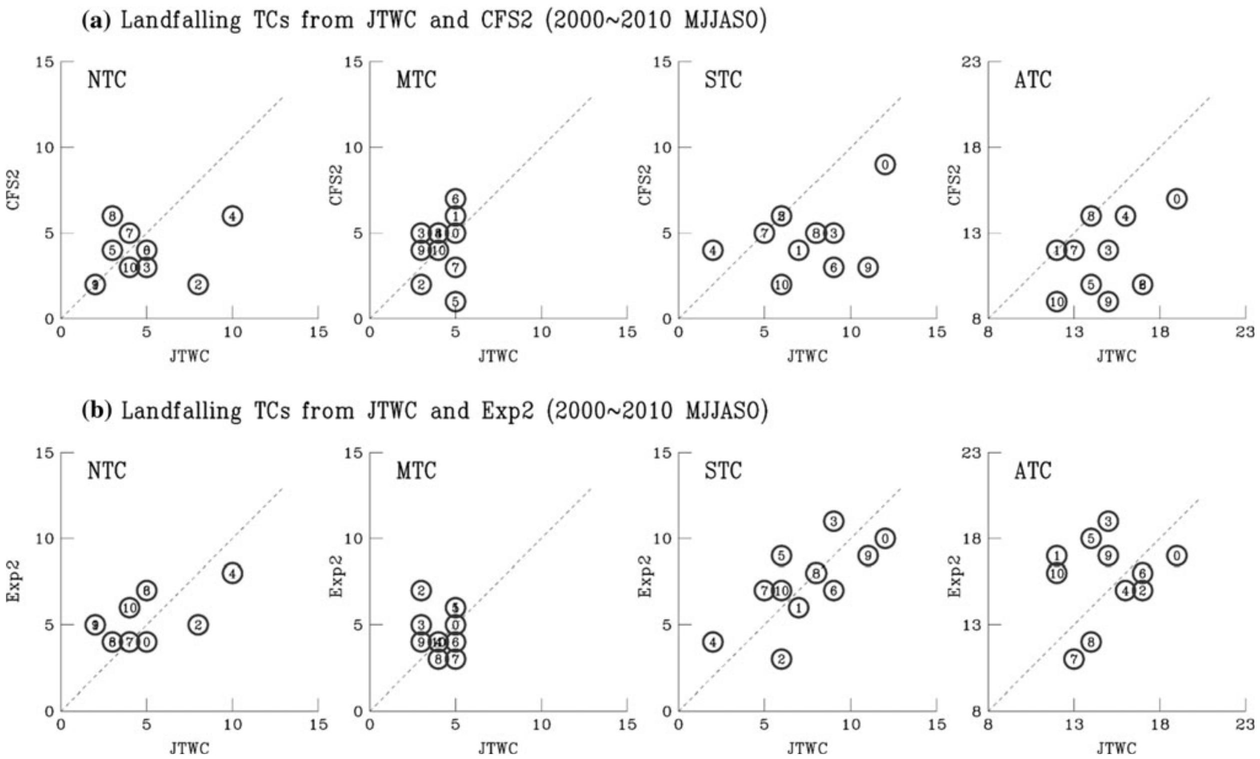

Fig. 7 Year-to-year variations of the cases of MJJASO TCs making landfall in different regions that identified in Fig. 6 during 2000–2010. **a** JTWC versus CFS2; **b** JTWC versus Exp2. Within the *open circle*, the number from 0 to 10 represents the year from 2000 to 2010, respectively

Table 1 Values of the Tcorr and the RMSE for the comparison between time series of landfalling TC derived from the observation JTWC and the models [i.e. Exp2 (the dynamical downscaling forecasts) and CFS2 (the global forecast data)] during 2000–2010

Type of landfalling TCs	Variables	JTWC versus models	
		Exp2	CFS2
NTC	Tcorr	*0.58*	0.30
	RMSE	2.04	2.52
MTC	Tcorr	0.16	0.10
	RMSE	1.57	1.73
STC	Tcorr	*0.70*	0.28
	RMSE	2.00	3.85
ATC	Tcorr	0.27	0.21
	RMSE	3.72	4.20

The value of Tcorr exceeding the 95 % CI is in italic. The unit of RMSE is cases per MJJASO

Note that the current model setup might require additional adjustments for a better prediction of TC landfalls in the MTC and NTC regions. For example, it has been shown in our recent work (Huang et al. 2012) that the cumulus convection scheme suitable for the SCS rainfall simulation may not also suitable for other regions. Likely, the choice of cumulus scheme contributes to the difference of forecast skill of TCs making landfall along the southern part of East Asia and the other sub-regions. This suggestion, however, requires more evidence to support, which will be reported in the future.

Table 2 The skill of forecast for Exp2 compared to CFS2

Type of landfalling TCs	Forecast skill (%) $S = \left(1 - \frac{RMSE_{Exp2}}{RMSE_{CFS2}}\right) \times 100$
NTC	18.9
MTC	6.2
STC	48.0
ATC	11.7

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