

Potential use of a regional climate model in seasonal tropical cyclone activity predictions in the western North Pacific

Andie Y. M. Au-Yeung · Johnny C. L. Chan

Received: 14 April 2011 / Accepted: 5 December 2011
© Springer-Verlag 2011

Abstract This study investigates the potential use of a regional climate model in forecasting seasonal tropical cyclone (TC) activity. A modified version of Regional Climate Model Version 3 (RegCM3) is used to examine the ability of the model to simulate TC genesis and landfalling TC tracks for the active TC season in the western North Pacific. In the model, a TC is identified as a vortex satisfying several conditions, including local maximum relative vorticity at 850 hPa with a value $\geq 450 \times 10^{-6} \text{ s}^{-1}$, and the temperature at 300 hPa being 1°C higher than the average temperature within 15° latitude radius from the TC center. Tracks are traced by following these found vortices. Six-month ensemble (8 members each) simulations are performed for each year from 1982 to 2001 so that the climatology of the model can be compared to the Joint Typhoon Warning Center (JTWC) observed best-track dataset. The 20-year ensemble experiments show that the RegCM3 can be used to simulate vortices with a wind structure and temperature profile similar to those of real TCs. The model also reproduces tracks very similar to those observed with features like genesis in the tropics, recurvature at higher latitudes and landfall/decay. The similarity of the 500-hPa geopotential height patterns between RegCM3 and the European Centre for Medium-Range Weather Forecasts 40 Year Re-analysis (ERA-40) shows that the model can simulate the subtropical high to a large extent. The simulated climatological monthly spatial distributions as well as the interannual variability of TC occurrence are also similar to the JTWC data. These results

imply the possibility of producing seasonal forecasts of tropical cyclones using real-time global climate model predictions as boundary conditions for the RegCM3.

Keywords Regional climate modeling · Seasonal tropical cyclone activity · Western North Pacific

1 Introduction

The western North Pacific is one of the most active tropical cyclone (TC) basins in the world. Good seasonal forecasts of TCs, especially for landfalling TCs, are useful for government planners and disaster preparedness managers in estimating the effects of potential destructive wind and rainfall. Statistical and dynamical seasonal forecasts for different basins have been carried out by different agencies (Camargo et al. 2007a). For the western North Pacific, City University of Hong Kong (Chan et al. 1998, 2001) and Tropical Storm Risk¹ issue real-time statistical TC number forecasts each season, while the International Research Institute for Climate and Society (IRI) (Camargo and Barnston 2009) and European Center for Medium-Range Weather Forecasts (Vitart and Stockdale 2001; Vitart 2006) issue tropical storm frequency forecasts produced by dynamical models.

Past studies (Bengtsson et al. 2007; Vitart et al. 1997; Yokoi et al. 2009) devoted to tropical cyclone (TC) simulations in general circulation models (GCM) have shown that TC structure and tracks can be reasonably reproduced. In light of their smaller requirement for computer resources and time, TC simulation experiments has also been carried out using regional climate models (RCMs) (Camargo et al. 2007b, Landman et al. 2005). In Camargo et al. (2007b),

A. Y. M. Au-Yeung · J. C. L. Chan (✉)
Guy Carpenter Asia-Pacific Climate Impact Centre, School
of Energy and Environment, City University of Hong Kong,
83 Tat Chee Ave., Kowloon, Hong Kong, China
e-mail: Johnny.Chan@cityu.edu.hk

¹ TSR. Tropical Storm Risk, <http://tropicalstormrisk.com/>.

ECHAM4.5 GCM simulations were downscaled and used to force the National Centers for Environmental Prediction (NCEP) regional spectral model for the western North Pacific. From the experiments for a high TC activity year (1994) and a low TC activity year (1998), they suggested that the genesis positions, track density and general circulation can be improved in a regional model with higher resolution compared with a GCM.

Although the main focus of this study is to simulate the seasonal TC occurrence, it is useful to review some past studies (Knutson et al. 2008, Stowasser et al. 2007, Walsh et al. 2004) that examine the effect on TC activity under global warming scenarios with the downscaling method. In these studies, RCMs are first forced with reanalysis to test the model ability for generating good climatology of TC activity in temporal and spatial scales, so that the RCM could be used in the next step where it is forced with warming scenario data from a GCM (Knutson et al. 2008, Stowasser et al. 2007). Although Knutson et al. (2008) used a high-resolution regional climate model (18 km), the domain interior was nudged with the NCEP reanalysis data. Under these circumstances, the ability of the model to simulate good TC climatology is not truly tested and the model performance will depend largely on the performance of the GCM input should the model be used in a future global warming experiment. In this case, the TC occurrence and the related environmental conditions in the GCM should also be compared with observations first. In Stowasser et al. (2007), such a test on a RCM with reanalysis data was also performed without nudging. The study provided comparison between a few environmental conditions with the observation and suggested that the RCM was able to reproduce reasonable climatological low-level winds and sea-surface temperatures when being forced with reanalysis data. However, the interannual TC number occurrence was not included, which is useful in evaluating the performance of the model in responding to large-scale circulation events like the El Niño/Southern Oscillation (ENSO). Evolution of the monthly variation of the environmental conditions could also be an important factor in examining and improving a model performance in seasonal forecast (though these interannual and intraseasonal variations might not be important in a global warming scenario study). These form the motivation for the present study.

Specifically, the potential use of the Regional Climate Model Version 3 (RegCM3) to forecast seasonal tropical cyclone activity in the western North Pacific is explored. With re-analysis data as the boundary forcing, seasonal tropical cyclone activity over the region is simulated in a modified version of RegCM3. The value of using an RCM might be questioned given different GCMs with resolutions higher than 60 km are being used in different studies.

However, many studies have shown that because the physical processes are different in different areas of the world, parameterization schemes need to be tailored to a specific area, which cannot be easily done in a GCM. For example, Chan et al. (2004), Davis et al. (2009) and Seth et al. (2007) have shown that different cumulus parameterization schemes can have huge impacts on the simulated circulations and local weather such as rainfall. For example, Seth et al. (2007) examined the performance of an RCM in simulating summer precipitation by feeding both re-analysis data and a GCM model (ECHAM5) output and found that with even with an 80-km resolution, the RCM can simulate the subtropical high in the south Atlantic better than that in the GCM. Knutson and Tuleya (2004) also pointed out that simulation of TC structure and intensity are sensitive to the choice of parameterization schemes. Because TC genesis and movement depend on the large-scale circulation, and TC genesis mechanisms can be different in different basins, results from these previous studies suggest that it is more suitable to use an RCM designed and modified for an individual basin, rather than using a GCM that generally has one cumulus parameterization scheme.

The objective of this study is therefore to investigate thoroughly the ability of an RCM (a modified version of RegCM3) to simulate TC genesis and tracks over the western North Pacific through a 20-year model climatology by comparing the monthly variations of the environmental conditions and the interannual variations of TC occurrence, which hitherto has not been carried out. It should be noted that with a resolution of 60 km (see Sect. 2), the “intensity” of the model TCs should not be considered to be representative of that in the real world, whether in terms of maximum winds or minimum sea-level pressure. In other words, the objectives of the current study do not include an evaluation of the ability of the model in simulating the climate of TC intensity.

Section 2 describes the model, data used in this study and the experimental setup. Section 3 illustrates how a TC and its track are identified and also the TC structure. Section 4 is the model climatology including average TC number distribution and the average environmental conditions in the model. Section 5 provides a summary.

2 Data and numerical simulation

The regional climate model used in this study, RegCM3, is an upgraded version of Regional Climate Model Version 2 developed by Giorgi et al. (1993a, b). It is a compressible, grid-point model with a dynamical core similar to the Pennsylvania State University/National Center for Atmospheric Research mesoscale model (MM5) (Dudhia et al.

2004). The simulations of RegCM3 are driven by the 6-hourly European Centre for Medium-Range Weather Forecasts 40 Year Reanalysis (ERA-40) (Uppala et al. 2005) as lateral boundary and initial conditions. Here, the ERA-40 dataset is used instead of that from the US National Centers for Environmental Prediction/National Center for Atmospheric Research (NECP/NCAR) because the temperature biases in NCEP data have been found to be much larger than those in ERA-40 in China (Ma et al. 2008). In their study, ground air temperature observations are used to compare with the data from the different reanalyses. Although the main focus of this study is TC simulation over the ocean, the larger temperature bias may introduce other errors in the simulation of the large-scale flow. Indeed, the general circulation patterns (such as the subtropical high) simulated by the RegCM3 with NCEP2 boundary conditions do not appear to be close to observations (not shown).

Weekly Optimum Interpolation Sea Surface Temperatures from the US National Oceanic and Atmospheric Administration (Reynolds et al. 2002) are also used. The 60-km-resolution domain has 112×176 grid points and 18 vertical levels with a top pressure level of 10 hPa. It is implemented over the region from 93°E to 172°W and from 14°S to 41°N . The lateral buffer zone is 12 grid points with a weighting function equal to one at the boundaries and decreasing exponentially inward (Seth and Giorgi 1998). There is no nudging of the reanalysis data as in Feser and von Storch (2008), because the main goal here is to test the model ability to simulate good climatology of the TC occurrence instead of producing short-period forecast of any particular TC.

The Emanuel cumulus parameterization scheme (Emanuel 1991; Emanuel and Zivkovic-Rothman 1999) is employed with the convection suppression criteria proposed by Chow et al. (2006). The convection in the model is suppressed whenever a parameter (e.g. relative vorticity) in the large-scale circulation does not reach the predetermined threshold, which is chosen so that the subtropical high can be better simulated in the model. Other parameterization schemes used include the Pal scheme (Pal et al. 2000) for large-scale precipitation, BATS scheme (Dickinson et al. 1993) for surface processes, Holtslag scheme (Holtslag et al. 1990) for planetary-boundary-layer processes and NCAR CCM3 radiative scheme for radiation transfer (Kiehl et al. 1996).

Six-month ensemble (8 runs each) simulations are performed for May–October each year from 1982 to 2001 so that the TC climatology of the model can be compared to that from the Joint Typhoon Warning Center (JTWC) best-track dataset. 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 in this study.

The choice of the number of ensemble members is always a balance between available computer resources and robustness of the results. In their simulations of rainfall over East Asia using the same model, Chow et al. (2007) found that the average of simulation results from eight ensemble members gives very good results compared with observations. Although that was not a TC simulation study, the domain is also for a similar region and for the summer season. It is for this reason that the number of ensemble members is chosen to be the same as that in their study.

The initial time of each ensemble member is 6 h apart from the next one, starting from May 1st 00UTC each year. Because this study is to explore the possibility of using the model to simulate TC activity for the whole season, simulations start in May before the active TC period, similar to the methodology that would be used for forecast simulations using GCM data as initial and lateral boundary conditions for the model.

3 Tropical cyclones in RegCM3

3.1 Vortex criteria and tracks

In the model, a TC is identified as a vortex with several dynamic and thermodynamic conditions. In the past, efforts have been made in investigating the suitable threshold criteria and tracing method (Walsh et al. 2007, Camargo and Zebiak 2002). In the present study, the thresholds are chosen so that the genesis number each year is closest to that observed. These criteria include.

- local maximum relative vorticity at 850 hPa $\geq 450 \times 10^{-6} \text{ s}^{-1}$,
- temperature at 300 hPa must be 1°C higher than the average temperature within 15° latitude radius from the TC center,
- TC lifetime must be at least 2 days, and
- genesis must occur over the ocean.

Tracks are traced from these identified vortices. As 1997–1998 is one of the strongest El Niño/Southern Oscillation (ENSO) events within the studied period, tracks in these 2 years are chosen to illustrate the ability of the model to simulate TCs in terms of genesis locations and TC movements. From the JTWC data, TC genesis locations in 1997 (Fig. 1a) are far more south and east in the western North Pacific, while those in 1998 (Fig. 1b) appear in higher latitudes and closer to the coast. Also, 1997 (27 TCs) has more TCs than 1998 (20 TCs) and the average life-span of TCs in 1997 is longer than those in 1998. All these results are consistent with those found by Chan (2000) and Wang and Chan (2002). The simulated TC genesis locations in one of the ensemble simulations for

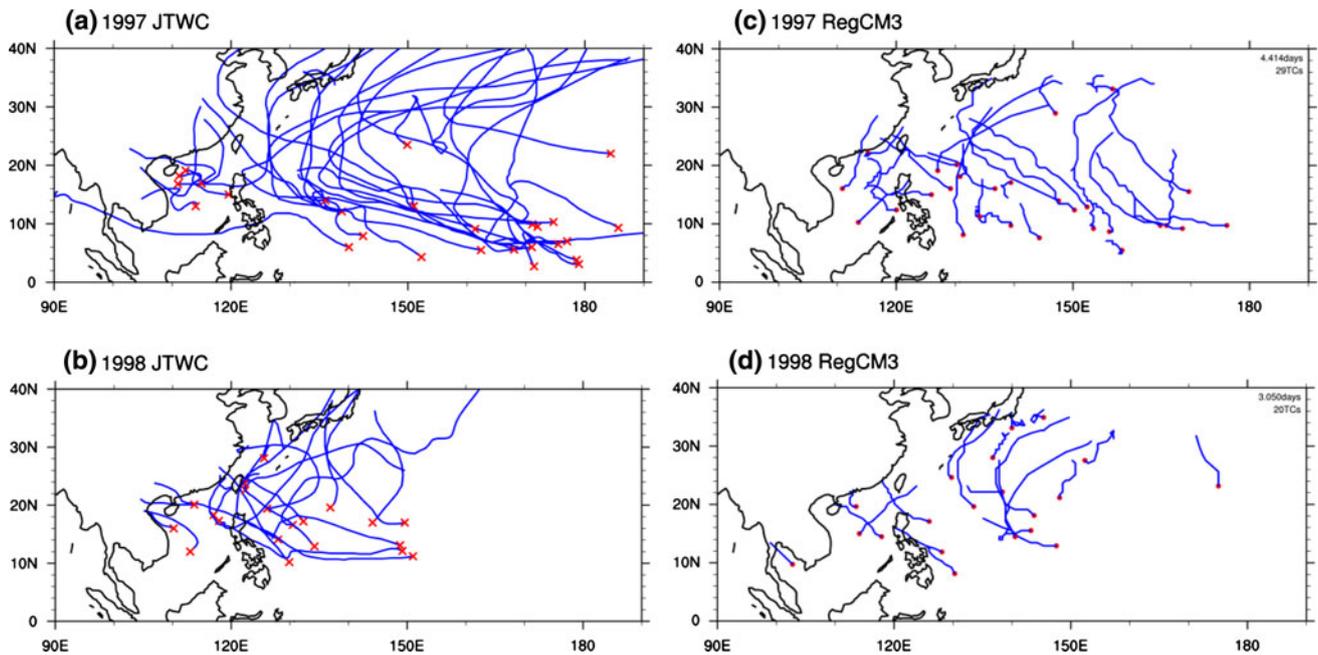


Fig. 1 a, b JTWC TC tracks from May to October 1997 and 1998 respectively. c, d Same as a and b except for tracks in one of the ensemble members in RegCM3

1997 (Fig. 1c) and 1998 (Fig. 1d) also have a southeast/northwest contrast, except both of the simulated years have genesis locations at higher latitudes compared to the observations (see Fig. 1a, b). In terms of TC number, the model also produces more TCs in 1997 (29 TCs) than it does in 1998 (20 TCs), which is similar to the observed. In addition, the model can also give details in the tracks. For example, a reasonable number of simulated TC formations occur in the South China Sea in 1997, which is important to the nearby region as TCs produced in this region are closer to the coast and are likely to make landfall. The recurvature of the tracks in the model in both years also suggests that the subtropical high is fairly well simulated, which will be discussed in Sect. 4.2.

3.2 Tropical cyclone structure in RegCM3

Besides examining the TC tracks, the ability of the model to develop the three dimensional vortex systems is also very important. Dynamical and thermodynamic profiles of one of the TCs simulated in RegCM3 centered at (15°N, 137°E) are shown in Fig. 2. The simulated 850-hPa flow (Fig. 2a) has a feature common to all TCs: cyclonic with a band of maximum wind. The cross-section along 15°N (Fig. 2b) indicates that the cyclonic flow does not only appear at 850 hPa, but also extends to higher vertical levels. This cyclonic flow is accompanied by the positive temperature anomaly from the environment (Fig. 2c), which is the warm core signature of a TC. Although the

warm core simulated appears at a lower vertical level than a TC in the real world, it does show a warm core anomaly area, which is the main evidence for the model ability to form a TC-like vortex without bogussing. The TCs simulated using RegCM3 thus have a wind structure and a temperature profile resembling those in the real world.

4 Model climatology

The model reproduces TC genesis patterns very similar to those observed. In this study, we will try to compare the TC observation to the ensemble average of the model climatology. Because TCs in the model tend not to appear close to the domain boundary, TCs in RegCM3 generally have a shorter lifetime compared with those in the JTWC dataset.

4.1 TC number distribution

The simulated spatial climatological distribution of TC genesis (Fig. 3b) is similar to the JTWC data (Fig. 3a). The TC genesis pattern in RegCM3 shows two maxima—one is in the South China Sea, the other one is east of Philippines (Fig. 3b). However, the genesis rate at higher latitudes region is larger than observed. RegCM3 also has low genesis rate east of 160°E.

The difference between the model and observation in genesis distribution is further studied here. Similar to the comparison in Murakami et al. (2011), a Student t-test is

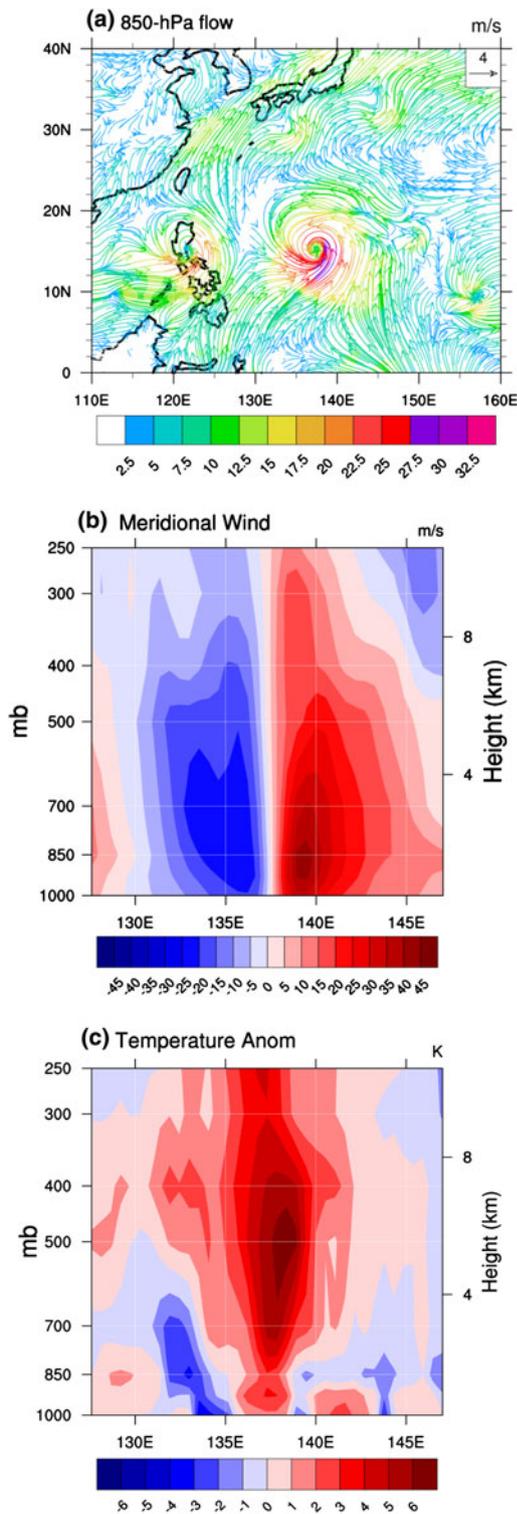


Fig. 2 A simulated TC in the western North Pacific, east of the Philippines. **a** The 850-hPa flow pattern (contour interval: 2.5 m s^{-1}). **b** Cross-section along 15°N showing the meridional winds of the simulated TC (contour interval: 5 m s^{-1}). **c** Cross-section along 15°N showing the temperature anomalies versus the surrounding environment (contour interval: 1 K). The averaged vertical temperature profiles at east, west, north and south $1,000 \text{ km}$ from the TC center is used as the environment temperature

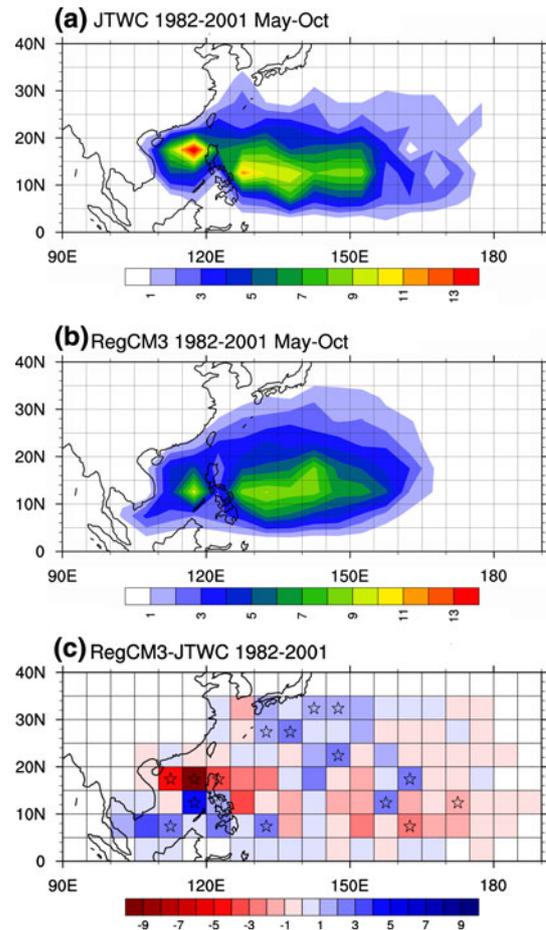


Fig. 3 TC genesis frequency in the western North Pacific (1982–2001, May–Oct) from **a** JTWC data and **b** RegCM3 experiments. The difference between the model and observation is shown in **c**. Statistically significant area at 90% level is marked with stars (Unit: number per $5^\circ \times 5^\circ$ square per 10 years)

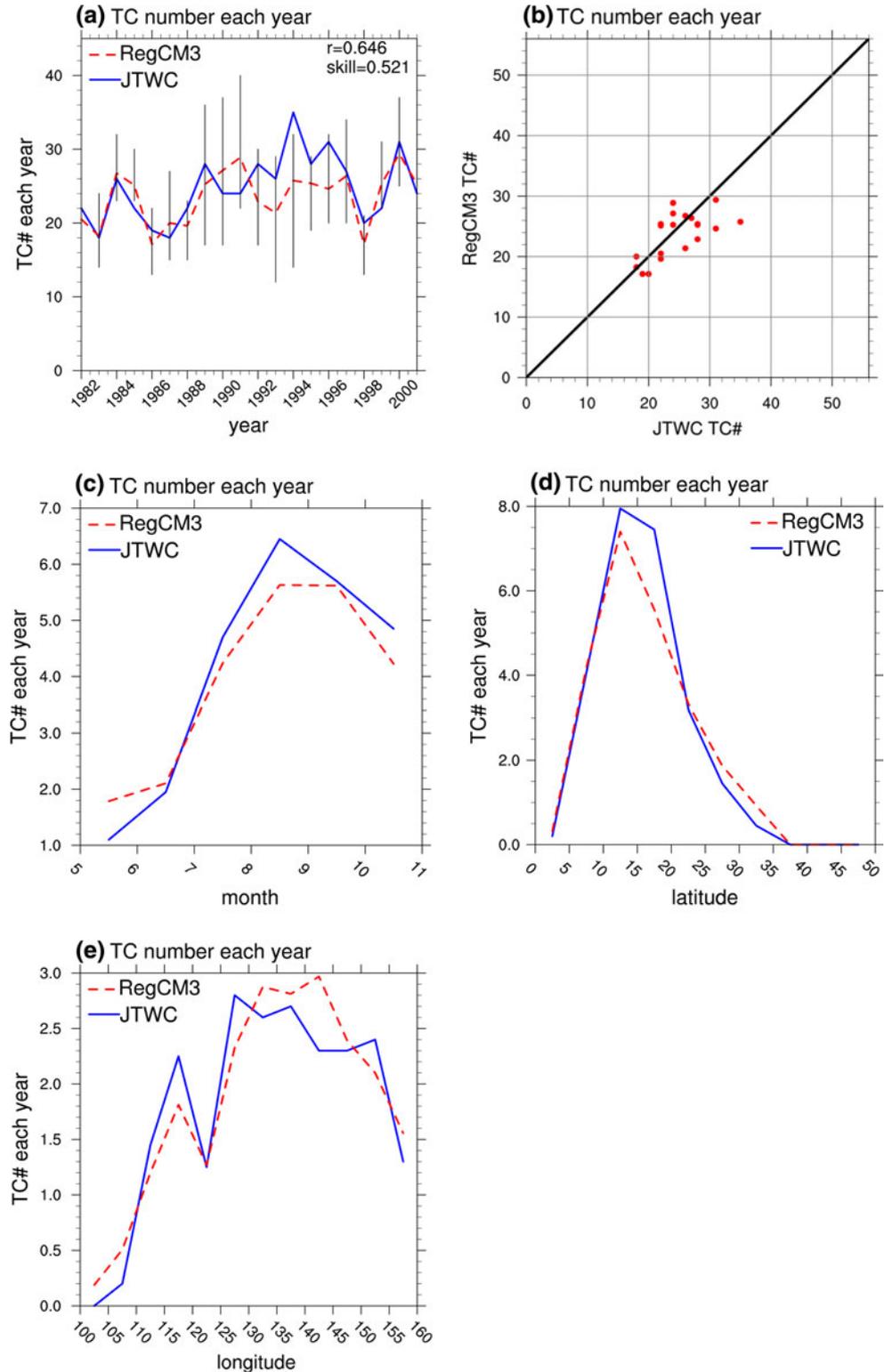
performed on the difference between these two patterns (Fig. 3c). The maximum genesis occurrence over the west of Philippine in the model is simulated $\sim 5^\circ$ south of the maximum in the observation. This contributes to the significant difference between the model and observation in this area. Nevertheless, the difference between the model and the observation proves to be insignificant east of the Philippines, which is another region where most of the TCs form. This result shows that the model is able to simulate TCs in the appropriate regions. This is important in the future study like global warming scenario studies. Any significant difference from observations will lower the credibility of the model for examining regional effects.

Because the model is to be a tool for a seasonal forecast, the interannual variation of the simulated TC numbers should also resemble that in reality. Except for the period between 1992 and 1996, the interannual variation in RegCM3 TC number over different years is similar to that

from JTWC data (Fig. 4a), with a correlation of 0.65 (Fig. 4b). Similar to the observation, the monthly variation of TC number from the model has an increasing trend from May to August and a decreasing trend from August to October (Fig. 4c). The latitudinal and longitudinal

distributions of the simulated TC genesis numbers (Fig. 4d, e respectively) suggest that the north–south and the east–west contrasts are well simulated, except that the model underestimates (overestimates) in the lower (higher) latitudes and eastern (western) part of the domain. Much heavier

Fig. 4 **a** Annual number of TC genesis in May–October, from 1982 to 2001. The spread between the ensemble members are shown. **b** Scatterplot comparing the number of TC genesis between JTWC and RegCM3. The straight line represents a perfect fit. **c** Average genesis distribution in different months and **d**, **e** average genesis distribution along longitude and latitude respectively during genesis in RegCM3 experiments (red line) and number in JTWC dataset (blue line) in May–October, from 1982 to 2001



precipitation also occurs in the model which will be discussed in the next section.

4.2 Environmental conditions

The simulated large-scale circulation in a model has great influence on TC formation and the steering flow (Cheung 2004; Liu and Chan 2003). The monthly averaged 500-hPa geopotential height from ERA40 re-analysis is used to evaluate the performance of RegCM3 (Fig. 5). RegCM3 is able to generate the 500-hPa anticyclonic flow over the western North Pacific with the similar positions as in

ERA40. The simulated subtropical high is related to how well the model produces TCs in the May to October period (see Fig. 3). However, it is rather weak with respect to the extent of the 5,880 hPa contour. In fact, the simulated geopotential heights have generally lower values. The model seems to overestimate the extension of the polar low (not shown), which is likely the case where the subtropical high is weaker than observed. A sensitivity test has been performed on the choice of the northern boundary so that the polar low would not extend too much to the north (not shown). The importance of the choice of domain on simulating TC-like vortices has also been

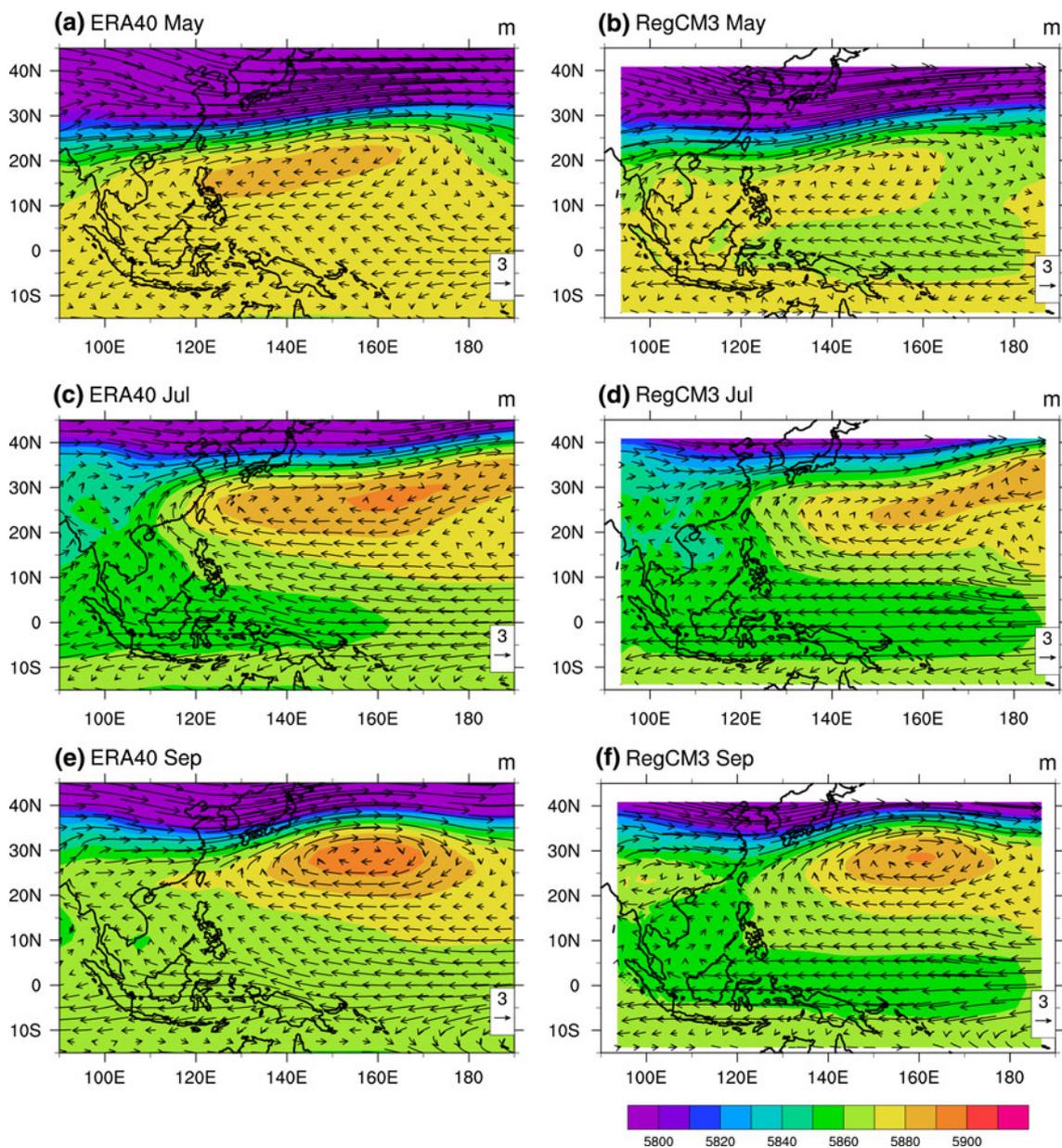


Fig. 5 Averaged ERA40 geopotential height at the 500-hPa level for **a** May, **c** July and **e** September from 1982 to 2001, and same graphs for RegCM3 are shown in **b**, **d**, **f** respectively. The flow pattern at 500-hPa level is shown by vectors

discussed by Seth and Giorgi (1998) and Landman et al. (2005).

The flow pattern and relative vorticity over 850 hPa are also very much related to TC formation (Fig. 6). The southeast-northwest orientation of the positive band is obtained in RegCM3 (Fig. 6d, f) as in the re-analysis average (Fig. 6c, e), though the band is disconnected for most of the time during the season. A southwesterly flow over the South China Sea is also found in the model, contributing to the genesis occurrence maximum there (see Fig. 3b). Rainfall band in the 0° – 10° N (Fig. 7a) is well

simulated in the model (Fig. 7b). The northward movement of this band is also captured in the following months (Fig. 7) while the rainfall rate is overestimated due to the weaker subtropical high in the model.

4.3 ENSO (El Niño/Southern oscillation) effect

As one major forcing in RegCM3 is the observed sea surface temperature (SST), the effect of ENSO on the TC activity is also examined. The El Niño and La Niña events are defined as years with Niño-3.4 region (5° S– 5° N,

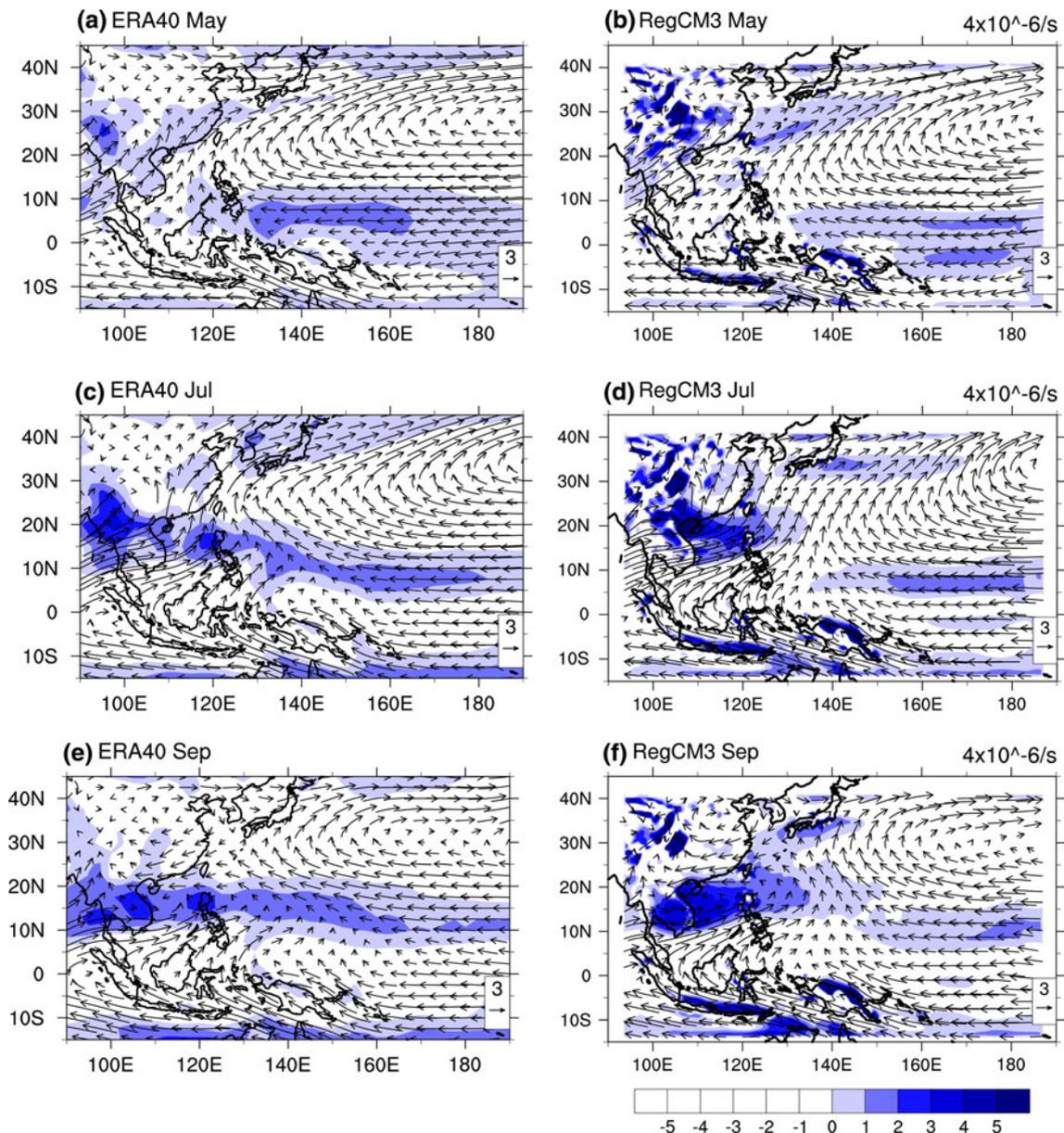


Fig. 6 Averaged ERA40 positive relative vorticity (unit: $4 \times 10^{-6} \text{ s}^{-1}$) for **a** May, **b** July and **c** September from 1982 to 2001 period, and same graphs for RegCM3 are shown in **b**, **d**, **f** respectively. The flow pattern at 850-hPa level is shown by vectors

170°W–120°W) SST anomaly (SSTA) $>0.5^{\circ}\text{C}$ and $<0.5^{\circ}\text{C}$ respectively as in Liu and Chan (2003). In this study, the warm years (El Niño years) are 1982, 1986, 1987, 1991, 1994 and 1997; the cold years (La Niña years) are 1984, 1988, 1995, 1998, 1999 and 2000. From the observation in the same period, the genesis distribution in warm years (Fig. 8a) tends to be on the east while that in cold years (Fig. 8c) tends to be further the west, as discussed in Wang and Chan (2002). This east–west difference can also be seen in RegCM3 (Fig. 8b, d). In cold years, more TCs

form at higher latitudes (see Fig. 8c), which also can be found in RegCM3 (see Fig. 8d). A t-test performed on the difference in the TC genesis numbers between the model and JTWC shows the difference to be insignificant for both cold years and warm years, with the exception of one grid box.

The similarity between the observation and the model suggests that given a good prediction of SST from a GCM, RegCM3 can produce reasonable pattern of TC formation and good TC formation rates for the whole season.

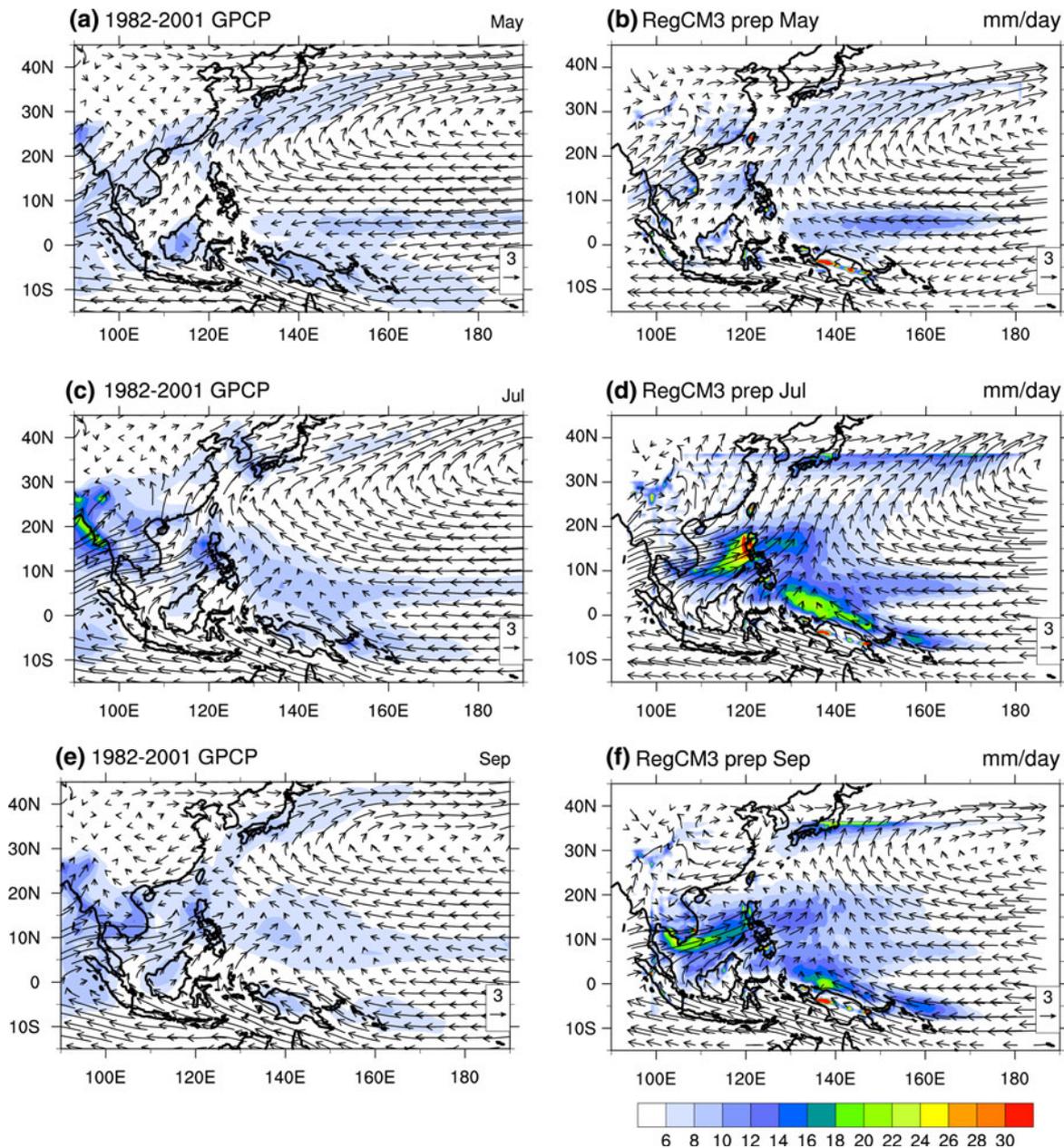


Fig. 7 As in Fig. 6 except the shading in a, c, e shows the GPCP rainfall data averaged from 1982 to 2001 and b, d, f shows rainfall per day in RegCM3. The flow pattern at 850-hPa level is shown by vectors. Vectors in a, c, e are data from ERA40

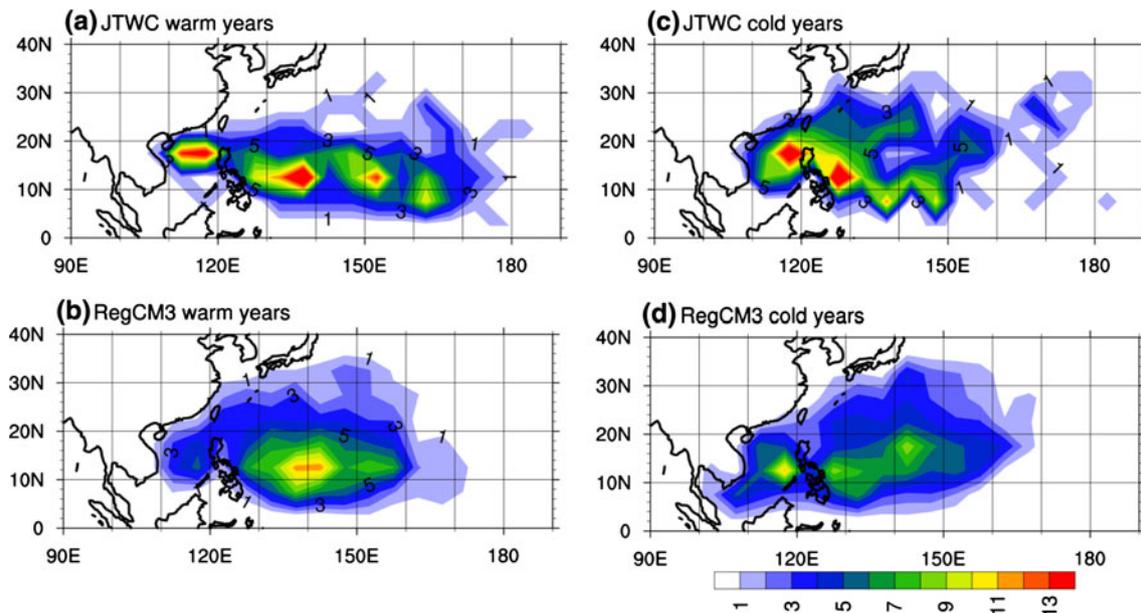


Fig. 8 Same as Fig. 3 except for years **a, b** 1982, 1986, 1987, 1991, 1994 and 1997. **c, d** 1984, 1988, 1995, 1998, 1999 and 2000

5 Discussion

In previous model studies (e.g. Bengtsson et al. 2007; Oouchi et al. 2006; Sugi et al. 2002) TCs were detected and tracked with different criteria. Among these criteria, the highest vorticity threshold is $35 \times 10^{-6} \text{ s}^{-1}$, which is about one order of magnitude smaller than the one used in this study ($450 \times 10^{-6} \text{ s}^{-1}$). In order to investigate into the reasons for this apparently large difference, distributions of different parameters are studied (Fig. 9). To illustrate the effect of selecting different vorticity thresholds, a lower criterion ($300 \times 10^{-6} \text{ s}^{-1}$) is used to compare with the chosen one ($450 \times 10^{-6} \text{ s}^{-1}$). The average annual TC days with different maximum wind speed are counted in the model under vorticity thresholds $300 \times 10^{-6} \text{ s}^{-1}$ (Fig. 9a) and $450 \times 10^{-6} \text{ s}^{-1}$ (Fig. 9b). JTWC data are also counted (Fig. 9a). In Fig. 9b, only data points with maximum wind speed $\geq 25 \text{ m s}^{-1}$ are shown. Figure 9a is quite similar to the comparisons done by Sugi et al. (2002) (their Fig. 6) and Zhao et al. (2009) (also their Fig. 6), all of which show that TCs in the models generally have lower maximum wind speeds and fail to generate TCs with higher wind speeds. The TCs in the current study from RegCM3 are not more intense than those in the other studies even though a higher threshold is used. Rather, the TC number found in the model is much larger than that in the real world, if a lower criterion (e.g., $300 \times 10^{-6} \text{ s}^{-1}$) is used.

However this still could not explain fully the large difference in the vorticity threshold between the current study and that in the other studies. As a selection parameter, the low-level vorticity does not only involve the horizontal

shear, but also the radius of maximum wind. In Fig. 3c of Bengtsson et al. (2007), the cross section of tangential wind composite from a T213 ($\sim 60 \text{ km}$) GCM was shown. The radius of maximum wind is at 1.5° lat ($\sim 160 \text{ km}$) and the wind speed is over 30 m s^{-1} . These numbers give a value of $\partial v / \partial x$ of $\sim 370 \times 10^{-6} \text{ s}^{-1}$. The same graph of vorticity in the paper (Fig. 4e) shows that vorticity for the most 100 most intense storms is actually $>300 \times 10^{-6} \text{ s}^{-1}$ (their Fig. 15a). A similar graph for the current study is shown in Fig. 9c. Even with the $300 \times 10^{-6} \text{ s}^{-1}$ vorticity criterion, TCs in the model tend to have higher vorticity (number in 400–500 bin is larger than number in 300–400 bin). Actually the distribution ($300 \times 10^{-6} \text{ s}^{-1}$) is quite similar to the one shown in Fig 15a of Bengtsson et al. (2007), which peaks at $400 \times 10^{-6} \text{ s}^{-1}$. Again, the reason for using $450 \times 10^{-6} \text{ s}^{-1}$ instead of lower values is that a lower vorticity criterion would give very large and unreasonable annual TC numbers.

6 Summary

In this study, a regional climate model, RegCM3, is forced by the initial and boundary conditions from EAR40 reanalysis data to simulate TCs in the western North Pacific between 1982 and 2001, and May to October each year. Over the period 1982–2001, the model is able to spin up TCs with a spatial pattern very similar to that from the JTWC data. The similarity of interannual variation of TC numbers in RegCM3 to that observed implies the possibility of seasonal forecasting of tropical cyclones using real-time global climate model predictions as boundary

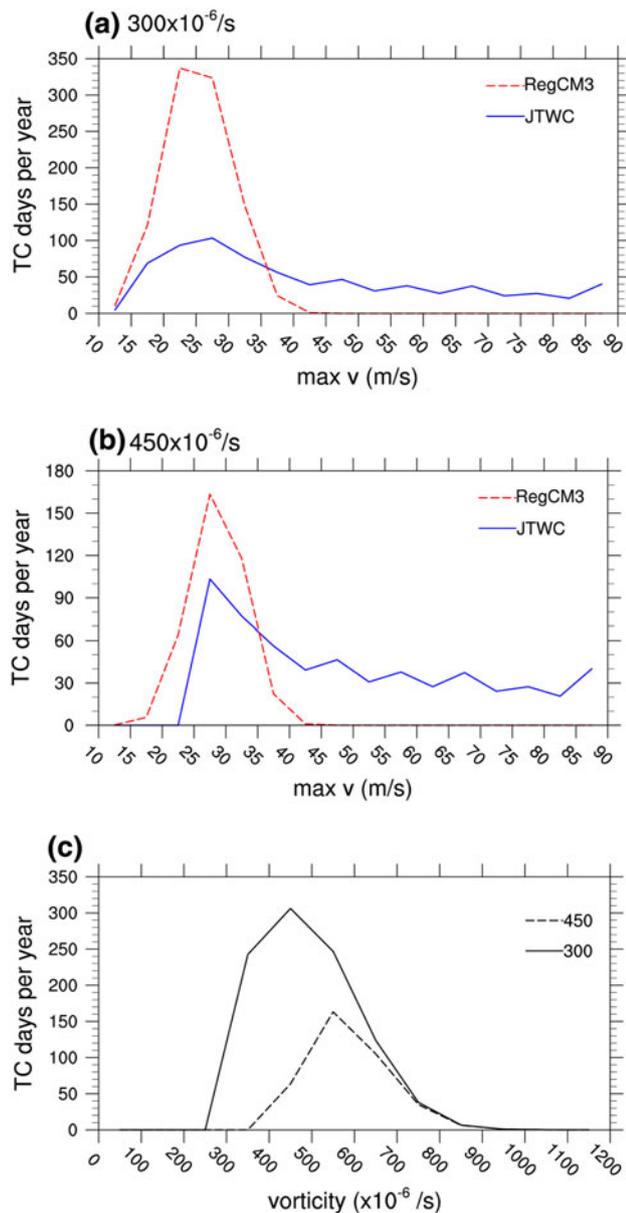


Fig. 9 **a** TC days per year per ensemble member with different maximum wind speed under the vorticity threshold $300 \times 10^{-6} \text{ s}^{-1}$ (dashed line), and the same number counted from JTWC data each year (solid line). **b** same as **a** except the model vorticity threshold is $450 \times 10^{-6} \text{ s}^{-1}$ (dashed) and JTWC data with maximum wind speed larger than or equal to 25 m s^{-1} . **c** TC days per year per ensemble member with different maximum vorticity under the vorticity threshold of $450 \times 10^{-6} \text{ s}^{-1}$ (solid) and $300 \times 10^{-6} \text{ s}^{-1}$ (dashed line)

conditions for RegCM3. Further studies on regional climate change can also be considered by nesting RegCM3 in this region with GCM Intergovernmental Panel on Climate Change (IPCC) scenario simulations.

Acknowledgments This research is supported by City University of Hong Kong Grant 7002361.

References

- Bengtsson L, Hodges KI, Esch M (2007) Tropical cyclones in a T159 resolution global climate model: comparison with observations and reanalysis. *Tellus* 59A:396–416
- Camargo SJ, Barnston AG (2009) Experimental dynamical seasonal forecasts of tropical cyclone activity at IRI. *Wea Forecast* 24: 472–491
- Camargo SJ, Zebiak SE (2002) Improving the detection and tracking of tropical cyclones in atmospheric general circulation models. *Wea Forecast* 17:1152–1162
- Camargo SJ, Barnston AG, Klotzbach PJ, Landsea CW (2007a) Seasonal tropical cyclone forecasts. *WMO Bull* 56:297–309
- Camargo SJ, Li H, Sun L (2007b) Feasibility study for downscaling seasonal tropical cyclone activity using the NCEP regional spectral model. *Int J Clim* 27:311–325
- Chan JCL (2000) Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events. *J Clim* 13:2960–2972
- Chan JCL, Shi JE, Lam CM (1998) Seasonal forecasting of tropical cyclone activity over the western North Pacific and the South China Sea. *Wea Forecast* 13:997–1004
- Chan JCL, Shi JE, Liu KS (2001) Improvements in the seasonal forecasting of tropical cyclone activity over the western North Pacific. *Wea Forecast* 16:491–498
- Chan JCL, Liu Y, Chow KC, Ding Y, Lau WKM, Chan KL (2004) Design of a regional climate model for the simulation of south China summer monsoon rainfall. *J Meteor Soc Jpn* 82: 1645–1665
- Cheung KKW (2004) Large-scale environmental parameters associated with tropical cyclone formations in the western North Pacific. *J Clim* 17:466–484
- Chow KC, Chan JCL, Pal JS, Giorgi F (2006) Convection suppression criteria applied to the MIT cumulus parameterization scheme for simulating the Asian summer monsoon. *Geophys Res Lett* 33:L24709. doi:10.1029/2006GL028026
- Davis N, Bowden J, Semazzi F, Xie L, Öno B (2009) Customization of RegCM3 regional climate model for Eastern Africa and a Tropical Indian Ocean Domain. *J Clim* 22:3595–3616
- Dickinson RE, Henderson-Sellers A, Kennedy PJ (1993) Biosphere-atmosphere transfer scheme (BATS) version 1e as coupled to the NCAR community climate model. NCAR Tech. Note 387 + STR, 72 pp
- Dudhia J, Gill D, Manning K, Wang W, Bruyere C, Kelly S, Lackey K (2004) PSU/NCAR mesoscale modeling system tutorial class notes and user's guide: MM5 modeling system version 3, NCAR
- Emanuel KA (1991) A scheme for representing cumulus convection in large-scale models. *J Atmos Sci* 48:2313–2335
- Emanuel KA, Zivkovic-Rothman M (1999) Development and evaluation of a convection scheme for use in climate models. *J Atmos Sci* 56:1766–1782
- Feser F, von Storch H (2008) A dynamical downscaling case study for typhoons in Southeast Asia using a regional climate model. *Mon Weather Rev* 136:1806–1815
- Giorgi F, Marinucci MR, Bates GT (1993a) Development of a second-generation regional climate model (RegCM2). Part I: boundary-layer and radiative transfer processes. *Mon Weather Rev* 121:2794–2813
- Giorgi F, Marinucci MR, Bates GT, De Canio G (1993b) Development of a second-generation regional climate model (RegCM2). Part II: convective processes and assimilation of lateral boundary conditions. *Mon Weather Rev* 121:2814–2832
- Holtslag AAM, de Bruijn EIF, Pan H-L (1990) A high resolution air mass transformation model for short-range weather forecasting. *Mon Weather Rev* 118:1561–1575

- IRI (International Research Institute for Climate Prediction) Tropical cyclone activity experimental dynamical forecasts. http://iri.columbia.edu/forecast/tc_fcst/wn_pacific/
- Kiehl JT, Hack JJ, Bonan GB, Boville BA, Breigleb BP, Williamson D, Rasch P (1996) Description of the NCAR community climate model (CCM3). NCAR Tech. Note NCAR/TN-420 + STR, 152 pp
- Knutson TR, Tuleya RE (2004) Impact of CO₂-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective parameterization. *J Clim* 17:3477–3495
- Knutson TR, Sirutis JJ, Garner ST, Vecchi GA, Held IM (2008) Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. *Nat Geosci* 1: 359–364
- Landman WA, Seth A, Camargo SJ (2005) The effect of regional climate model domain choice on the simulation of tropical cyclone-like vortices in the Southwestern Indian Ocean. *J Clim* 18:1263–1274
- Liu KS, Chan JCL (2003) Climatological characteristics and seasonal forecasting of tropical cyclones making landfall along the South China coast. *Mon Weather Rev* 131:1650–1662
- Ma L, Zhang T, Li Q, Frauenfeld OW, Qin D (2008) Evaluation of ERA-40, NCEP-1, and NCEP-2 reanalysis air temperatures with ground-based measurements in China. *J Geophys Res* 113:D15115. doi:10.1029/2007JD009549
- Murakami H, Wang B, Kitoh A (2011) Future change of western North Pacific typhoons: projections by a 20-km-mesh global atmospheric model. *J Clim* 24:1154–1169
- Oouchi K, Yoshimura J, Yoshimura H, Mizuta R, Kusunoki S, Noda A (2006) Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: frequency and wind intensity analyses. *J Meteorol Soc Jpn* 84:259–276
- Pal JS, Small EE, Eltahir EAB (2000) Simulation of regional-scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM. *J Geophys Res* 105(D24):29579–29594
- Reynolds RW, Rayner NA, Smith TM, Stokes DC, Wang W (2002) An improved in situ and satellite SST analysis for climate. *J Clim* 15:1609–1625
- Seth A, Giorgi F (1998) The effects of domain choice in summer precipitation simulation and sensitivity in a regional climate model. *J Clim* 11:2698–2712
- Seth A, Rauscher S, Camargo S, Qian J-H, Pal J (2007) RegCM3 regional climatologies for South America using reanalysis and ECHAM global model driving fields. *Clim Dyn* 28(5):461–480. doi:10.1007/s00382-006-0191-z
- Stowasser M, Wang Y, Hamilton K (2007) Tropical cyclone changes in the western North Pacific in a global warming scenario. *J Clim* 20:2378–2396
- Sugi M, Noda A, Sato N (2002) Influence of global warming on tropical cyclone climatology: an experiment with the JMA global model. *J Meteorol Soc Jpn* 80:249–272
- Uppala SM et al (2005) The ERA-40 re-analysis. *Q J R Meteorol Soc* 131:2961–3012
- Vitart F (2006) Seasonal forecasting of tropical storm frequency using a multi-model ensemble. *Q J R Meteorol Soc* 132:647–666
- Vitart F, Stockdale TN (2001) Seasonal forecasting of tropical storms using coupled GCM integrations. *Mon Weather Rev* 129: 2521–2537
- Vitart F, Anderson JL, Stern WF (1997) Simulation of interannual variability of tropical storm frequency in an ensemble of GCM integrations. *J Clim* 10:745–760
- Walsh KJE, Nguyen K-C, McGregor JL (2004) Fine-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia. *Clim Dyn* 22:47–56
- Walsh KJE, Fiorino M, Landsea CW, McInnes KL (2007) Objectively determined resolution-dependent threshold criteria for the detection of tropical cyclones in climate models and reanalyses. *J Clim* 20:2307–2314
- Wang B, Chan JCL (2002) How strong ENSO events affect tropical storm activity over the western North Pacific. *J Climate* 15:1643–1658
- Yokoi S, Takayabu YN, Chan JCL (2009) Tropical cyclone genesis frequency over the western North Pacific simulated in medium-resolution coupled general circulation models. *Clim Dyn* 33: 665–683
- Zhao M, Held I, Lin S-J, Vecchi GA (2009) Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50 km resolution GCM. *J Clim* 22: 6653–6678