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Impact of Tropical Cyclone on Regional Climate Modeling over East Asia in Summer and the Effect of Lateral Boundary Scheme

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1. Introduction

Regional climate models (RCMs) have been increasingly used to simulate the realistic characteristics of the regional climate and to evaluate the related multiscale interactions [1-4]. A fundamental requirement for the development of RCMs is to examine their capability in simulating the seasonal evolution and interannual variabilities on a regional scale. This seems more important for the simulation of RCMs over East Asia due to the distinct Asian monsoon climate feature. The larger variability and uncertainty of the Asian monsoon system confirmed by extensive observational studies and numerical simulations [5, 6] suggest that the modeling research will be a challenging task because of the complex scale interactions involved.

China is strongly influenced by the Asian monsoon circulation. The complexity and regional diversities of the summer precipitation over China is a universally accepted understanding in literatures. Because of the complex terrain and great variability of the monsoon climate in East Asia, simulation of the East Asian climate is sensitive to physical schemes [7, 8] and the skill is still limited [9-10]. One of the main atmospheric systems affecting the summer precipitation over China is the western Pacific subtropical high (WPSH). The seasonal extension and withdrawal of the WPSH are responsible for the rainfall distribution over eastern China. Therefore, the simulated precipitation is directly dependent on the capability of the models to capture the activities of the WPSH and the corresponding regional circulations. In general, both RCMs and general circulation models (GCMs) can reproduce the seasonal evolution of the WPSH [11]. However, the simulated high in summertime is either weaker [12] or stronger [13] than the observed one depending on the observational driven fields and the specific monsoon case. On the other hand, it is more difficult to simulate reasonably well the behavior

of the WPSH over a shorter time scale during the summer monsoon period, which plays a significant role in the simulation of the precipitation over eastern China [14].

For an East Asian summertime case in 1994, the seasonal scale simulations using the Regional Climate Model version 3 (RegCM3), developed by the International Centre for Theoretical Physics (ICTP), was conducted with three cumulus parameterization schemes (CPSs), i.e., the Emanuel scheme [15], Grell scheme [16] and Kuo scheme [17]. It was found that the model is capable of reproducing the mean summer circulation over East Asia, as has been demonstrated by previous works [12, 13, 18–21]. However, the model shows a failure simulation over shorter time scale. Figure 1 depicts the temporal evolution of the spatial abnormal correlation coefficients (ACCs) for geopotential height of 500 hPa between the observation and simulations. The averaged ACCs in Figure 1 are 0.89, 0.88 and 0.84 corresponding to different CPS, and the temporal tendency of the ACCs is basically similar in the three experiments. However, the evolution of the ACCs exhibits a sharp oscillation with three lower-value periods. This suggests that the model can reasonably reproduce the regional circulation pattern with all the three CPSs in most of the periods, but it yields some unsuccessful simulations in the cases with lower ACCs. What kind of circulation systems cannot be reproduced well by the model in the periods with lower ACCs? To gain insight into the possible cause for these lower ACCs, the selected four periods shown in Figure 1, i.e., June 8–12 (period A), July 18–22 (period B), July 24–28 (period C) and August 27–31 (period D), are analyzed in detail.

The mean geopotential height of 500 hPa and the wind field for the observation and simulation with three CPSs during period B (July 18–22) are shown in Figure 2. In this period, when the strong WPSH dominates over the western North Pacific (WNP) and the southwest and south monsoon flow prevail over eastern China, the mean circulation system over the eastern part of the model domain is evidently different from that in summertime. The observed circulation clearly shows that the WPSH is interrupted by a TC and the main body of the WPSH withdraws eastward. The cyclonic circulation system holds over the WNP, whereas a split anticyclonic cell from the main body of the WPSH is over eastern China and the southern Korean Peninsula (Figure 2a). Obviously, the model with all the three CPSs cannot suitably reproduce the invading process of the TC and the associated split of the WPSH due to the deficient simulations of the TC activity (Figures 2b–2d).

Moreover, it can be seen that the simulated TC with the Emanuel and Grell schemes is stronger and turns northeastward in advance over the WNP to the east of Japan, whereas the simulation with the Kuo scheme gives a lower pressure system over Japan. Over the WNP where the observed TC is located, the anticyclonic circulation appears clearly. The similar situation also occurred for period C and period D in Figure 1 when TC was over WNP. Therefore, for the amelioration of RCMs, the important problem of model development on how to enhance the capacity for portraying the activity of TCs in summertime over the WNP should be solved.

On the contrary, during period A with higher ACCs as shown in Figure 1, the regional circulation systems are suitably portrayed in the model because this period is in the intermittent period of the TCs in the model domain (Figure 3). This clearly indicates that the simulated trough and ridge in the middle and high latitudes resemble the observed ones. The simulated WPSH in the lower latitude is also largely consistent with the observation, although the simulated one seems

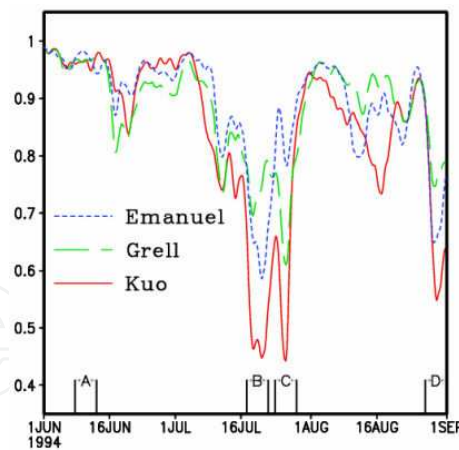


Figure 1. Temporal evolution of spatial abnormal correlation coefficients (ACCs) of 500hPa geopotential height with CPSs of Emanuel scheme, Grell scheme and Kuo scheme, respectively (A represents the period with higher ACC, whereas B, C and D represents the period with lower ACC, respectively).

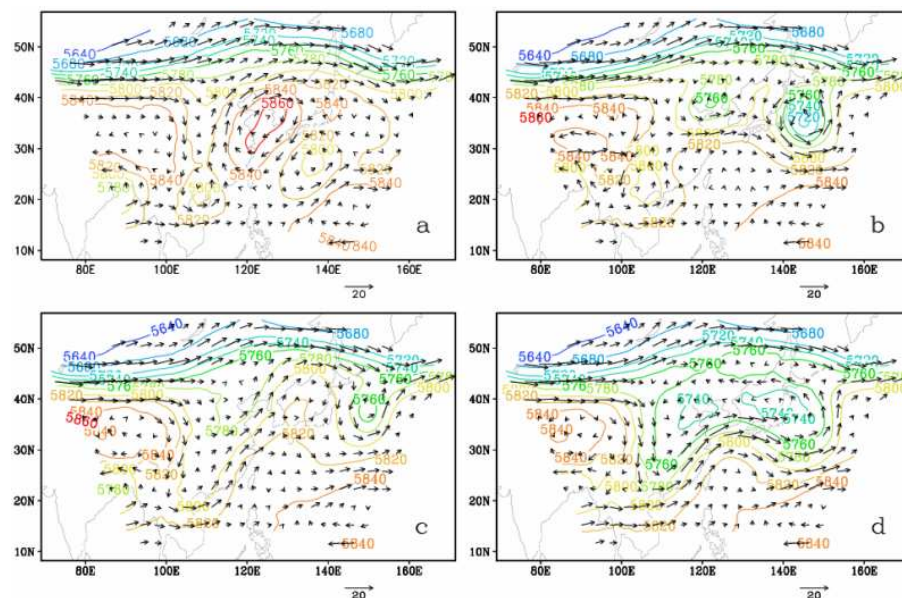


Figure 2. The temporal mean geopotential height and wind vector at 500hPa observed (a) and simulated with Emanuel scheme (b), Grell scheme (c) and Kuo scheme (d), respectively, during period B in Figure 1.

slightly weaker, with each of the three individual CPSs. Overall, the simulations with the Emanuel scheme or Grell scheme exhibits better results than that with Kuo scheme; the latter generates a weakened WPSH and an abnormal split trough in the middle latitude, which implies that the regional climate modeling is sensitive to model physics, such as CPS.

In spite of the examples of the tropical storms as [18], the model can generally reproduce their intensity and track, the regional climate modeling over East Asia in summertime on the impact of bogus typhoons implies that the model cannot suitably reproduce the impact of TCs without a special bogus technique [22]. TCs hinder the precise simulation of the summer monsoon circulation over East Asia [23]. It is a challenge for regional climate modeling to overcome the

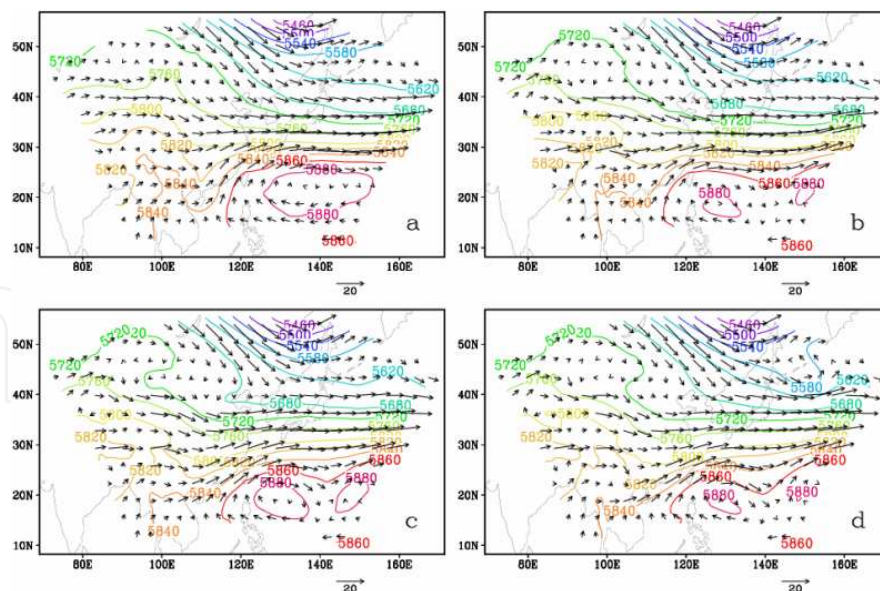


Figure 3. Same as figure 2, except for the period A shown in Figure 1.

disadvantage of the failure simulation when TCs are active over the WNP for the simulation over East Asia. In addition to the TC bogus technique, which is complicated for long-term simulation, improvements in both the treatment for lateral boundary conditions and model physical parameterizations could be helpful to more suitably represent the behavior of TCs in the model domain. The possible improvement may include selecting the proper buffer zone size, adopting different nudging coefficients in the lower and upper troposphere, etc. With the amelioration, the TCs over the WNP would be regulated in the right manner, even though the climate model at a coarser resolution cannot describe the detailed structure and intensity of TCs.

2. Effects of lateral boundary scheme on the TC track simulation in RCM

The lateral boundary condition (LBC) is one of the basic issues of the RCM, generally, a good performance of the RCM is dependent to the good LBCs. The success of the RCM depends on the adoption of appropriate lateral boundary technique [2, 24, 25]. Previous studies have shown that it is more important to provide a good lateral boundary condition for the RCM than to improve the physical process schemes. A broader buffer zone size (BZS) had been recommended for the simulation of the East Asian summer monsoon using the RCM [26]. Majority of RCMs developed to date use the so-called nudging technique as in [27] to develop a meteorological LBC that involves the application of a Newtonian term and a Laplace diffusion term to drive the model solution toward large-scale driving fields over the lateral boundary buffer zones, in insuring a smooth transition between LBC-dominated and model-dominated regimes and in reducing noise generation [28]. As the climate of the regional model is the equilibrium of the atmospheric physical and dynamical processes and the information

provided by the LBCs [2], then, whether or not the lateral boundary scheme affects the track of the TC in the model domain is a technical problem of the RCM [29].

Tropical cyclone Winnie (1997), which developed over the central Pacific on August 8, 1997, was the strongest TC in the Western Pacific in that year. It brought considerable loss of life and property and adversely affected China's national economy because Winnie passed through eastern China after its landfall at Wenling, Zhejiang Province, on August 18. Taking August of 1997 as an example and using RegCM3, we will examine the impact of lateral boundary buffer zone scheme on the ability of the RCM to describe TC activity in an effort to provide a basis for improvement of the simulation of the East Asian summer monsoon climate.

2.1. Model description and experimental design

RegCM3 is an upgraded version of the model originally developed by Giorgi et al. [28, 30] and then improved upon as discussed by Giorgi and Mearns [2] and Pal et al. [31]. The dynamic core of RegCM3 is equivalent to the hydrostatic version of the NCAR/Pennsylvania State University mesoscale model, MM5 [32]. The physical parameterizations employed in this simulation include the comprehensive radiative transfer package of the NCAR Community Climate Model CCM3 [33], the nonlocal boundary layer scheme of Holtslag et al. [34], the BATS land surface model [35], and the cumulus parameterization scheme of Grell with the Fritsch-Chappell-type closures [32]. As shown in Figure 4, the model domain is centered at (32.5°N, 120°E) with 121 east-west points and 80 north-south points and a horizontal grid spacing of 60 km. The top of the model is at 50 hPa with 18 uneven levels in the vertical and the buffer zone size is 14 grid-point width.

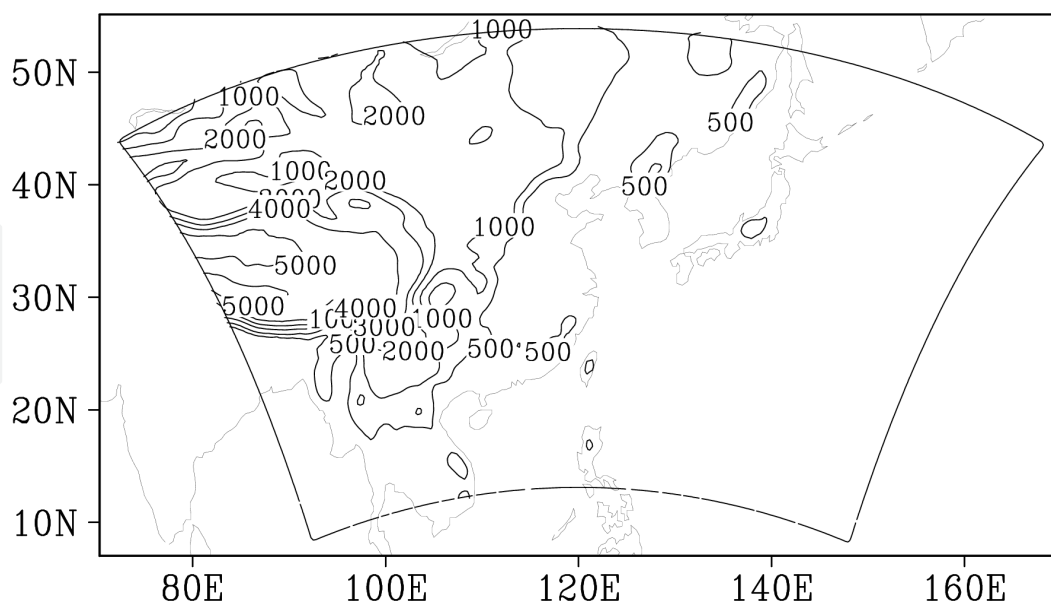


Figure 4. Model domain and topography (units: m).

RegCM3 adopts nudging technology to introduce the large-scale forcing in the buffer zone of lateral boundaries. For a variable α , the nudging equation in the buffer zone can be written as

$$\frac{\partial \alpha}{\partial t}(n) = F(n)F_1(\alpha_L - \alpha_M) - F(n)F_2\nabla^2(\alpha_L - \alpha_M) \quad (1)$$

In equation (1), subscripts L and M refer to the large-scale forcing field and model simulation field, respectively. $F(n)$ is a function of the buffer zone ordinal n . $F_1 = \frac{a}{\Delta t}$ and $F_2 = \frac{(\Delta s)^2}{b\Delta t}$. Nudging parameters a and b , which has a default value of 0.1 and 50, respectively, can be adjusted to make a strong nudging (approaching to forcing fields rapidly) or weak nudging (approaching to forcing fields slowly). Δt and Δs are the time step and horizontal grid spacing of the model, respectively. A total of 25 experiments were conducted to address the nudging parameters of the model prognostic equations within the buffer zone, where a is set at 0.05, 0.075, 0.1, 0.15 and 0.2 and b at 100, 66.7, 50, 33.3 and 25, respectively. Table 1 lists the experimental names and the corresponding configurations of nudging parameters a and b .

name	NP01	NP02	NP03	NP04	NP05
a / b	0.05/100	0.05/66.7	0.05/50	0.05/33.3	0.05/25
name	NP06	NP07	NP08	NP09	NP10
a / b	0.075/100	0.075/66.7	0.075/50	0.075/33.3	0.075/25
name	NP11	NP12	NP13	NP14	NP15
a / b	0.10/100	0.10/66.7	0.10/50	0.10/33.3	0.10/25
name	NP16	NP17	NP18	NP19	NP20
a / b	0.15/100	0.15/66.7	0.15/50	0.15/33.3	0.15/25
name	NP21	NP22	NP23	NP24	NP25
a / b	0.20/100	0.20/66.7	0.20/50	0.20/33.3	0.20/25

Table 1. Experimental names corresponding to the configuration of nudging parameter a and b

The model was employed to conduct the 1 month long simulation for August 1997, examining the effect of adjusting nudging parameters a and b in the buffer zone on TC track simulation. Each experiment starts at 00:00 GMT on August 1 and ends at 18:00 GMT on August 31. The initial and LBCs were provided by National Centres for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis data, and the LBCs were updated at 6 h interval. Sea surface temperature data are taken from the Global Ocean Surface Temperature (GISST) of the Hadley Center and updated once a week. In addition, the daily precipitation from Global Precipitation Climatology Project (GPCP) data at 1° resolution was used to evaluate the precipitation distribution during the simulation period. The integration time step is 180 s. We specifically analyze the simulation result for Winnie in the model region from August 12 to August 20, whereas the simulations for the first 11 days are not considered to allow for the spin-up of the model [36].

2.2. Effects of nudging parameters

2.2.1. The track of Winnie

Figure 5 presents the simulated Winnie tracks for 25 experiments with different configuration of the nudging parameters a and b . It clearly shows that the nudging parameter has a great impact on the simulation of Winnie track, and an appropriate configuration can effectively improve the track simulation. Among all experiments, NP19 ($a=0.15$ and $b=33.3$) shows its well performance for the westward track of Winnie entering the East China Sea, though the track error is still significant.

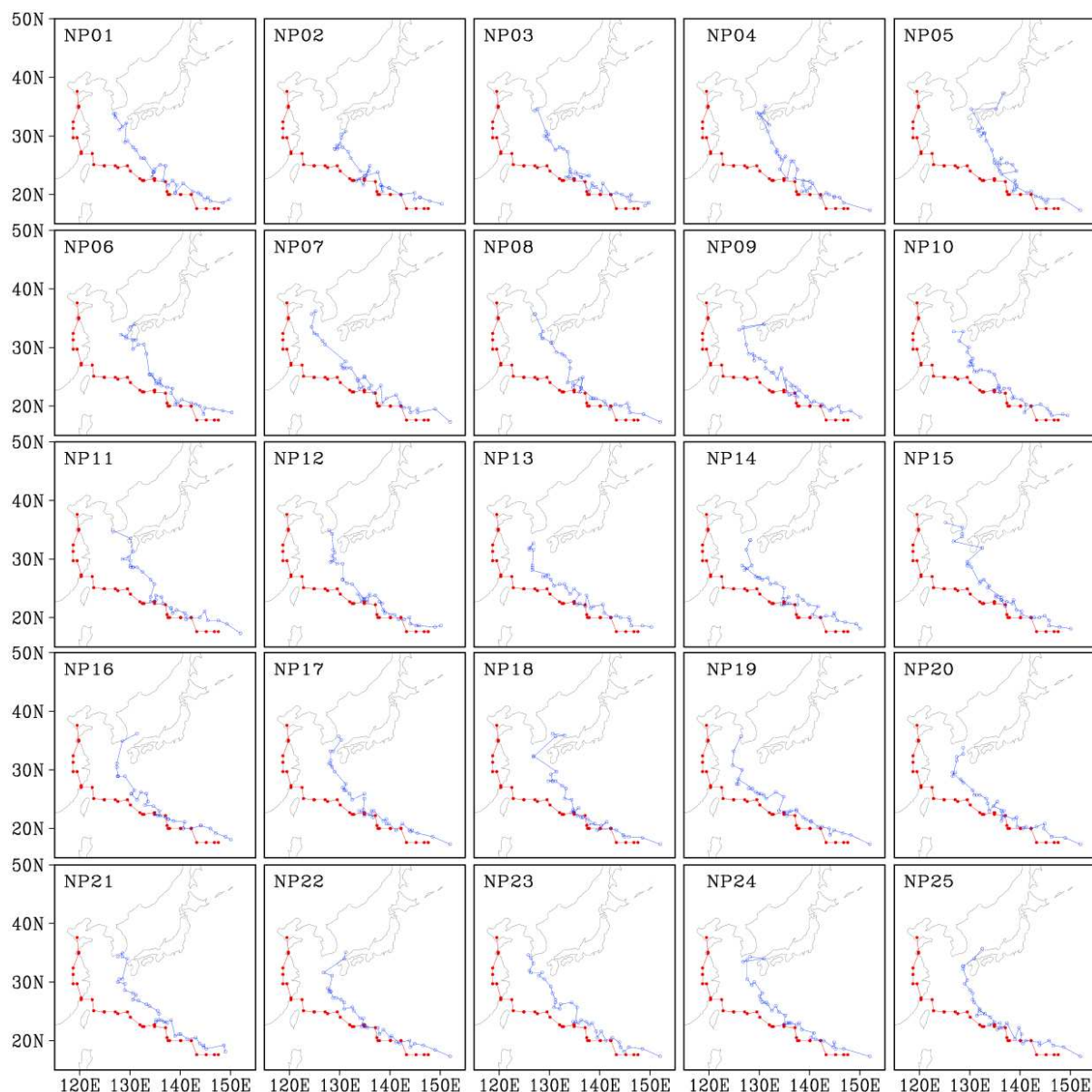


Figure 5. Observed (filled circle) and simulated (open circle) tracks of Winnie at 6 h interval from 00:00 GMT on August 12 to 12:00 GMT on August 20, 1997, for 25 experiments with different configurations of nudging parameters.

However, an inappropriate configuration results in a much greater error in simulating the track; accompanying with a more obvious turning ahead of time and landfall on southern Japan. The RMSEs of 25 experiments are listed in Table 2, which also presents that NP19 performed best among all experiments with different nudging parameter configurations, and its RMSE is less than half of the NP05. Therefore, although the problem of the turning ahead of time in the simulation cannot be solved fundamentally by configuring the nudging parameters, an appropriate configuration can effectively reduce the simulation error of TC track. On the other hand, It can also be seen from Table 2 that the ratio of the two nudging parameters a and b is an important reference in the configuration of nudging parameter. It suggests that if a smaller value is selected for a , then a larger value must be selected for b , and vice versa, which implies that, within the buffer zone, two additional terms with equilibrium relationship in nudging equation (1) are necessary for the better performance of the model. In contrast, the track simulation would be suboptimal. Furthermore, the default setting of the two nudging parameters of the model keeps the equilibrium relationship. When the equilibrium relationship is achieved, either strong nudging experiment (a is big and b is small) or weak nudging experiment (a is small and b is large) is beneficial for the simulation of the Winnie track. When a or b exceeds the value range in Table 1, the model integration would be overflow, which is in accordance with that proposed by Marbaix et al. [37].

a						
	b	25	33.3	50	66.7	100
0.05		512.6	436.1	367.8	409.0	334.9
0.075		377.6	327.9	365.8	276.8	412.3
0.1		357.1	309.8	297.6	332.8	374.7
0.15		308.6	248.6	418.9	366.2	346.1
0.2		389.0	360.3	303.6	353.6	339.8

Table 2. RMSE between the observed and simulated track of Winnie for the experiment with different configuration of nudging parameter a and b

2.2.2. The intensity of WPSH

Figure 6 shows the observed and simulated temporal variation of the intensity index of WPSH (IWPSH), defined as the number of grid points with a geopotential height being greater than 5880 gpm in the area east of 110°E, for the 25 experiments configuring with different nudging parameters. It is shown that although the simulated evolution of the intensity index differs for different parameter configuration in detail, the basic feature of the evolution for each experiment is not substantially different. The correlation coefficients for the time series of intensity index of WPSH between observation and simulation experiment from NP01 to NP25 is 0.8168, 0.7964, 0.8495, 0.7813, 0.8038, 0.8098, 0.8504, 0.8365, 0.8270, 0.8455, 0.8106, 0.8411, 0.7873, 0.8227, 0.8615, 0.7975, 0.8331, 0.8554, 0.9027, 0.8239, 0.8382, 0.8350, 0.8957, 0.8641 and 0.8080, respectively. Here again, the NP19 obtains the best performance for the temporal variation of the

intensity index of WPSH, meanwhile, the simulated intensity index shows its variation in well agreement with the observed one before 12:00 GMT of August 14, and the weak degree of the simulated WPSH is smallest after August 17 among all 25 experiments.

Furthermore, the sharply variation of the intensity index on August 17 can not be captured also for all 25 experiments with different configuration of nudging parameters, and the simulated intensity index transition appears on August 16. In addition, all the experiments show their higher intensity index before 12:00 GMT on August 14, and lower intensity index after 00:00 GMT on August 15 than that of the observation. Therefore, it could be concluded that no experiment with different configuration of nudging parameters could solve the problem of turning of the Winnie ahead of time fundamentally. But an appropriate configuration can be effective insuring the simulated track more being close to the observed one.

From the simulated pattern of the precipitation rate averaged between August 12 to August 19, one can see that although an appropriate nudging parameter configuration could partly improve the precipitation pattern simulation, it does not make the simulation being consistency with the observation entirely, which implies that the description of the precipitation physics in the model is still vital in simulating the precipitation pattern (figures are not shown).

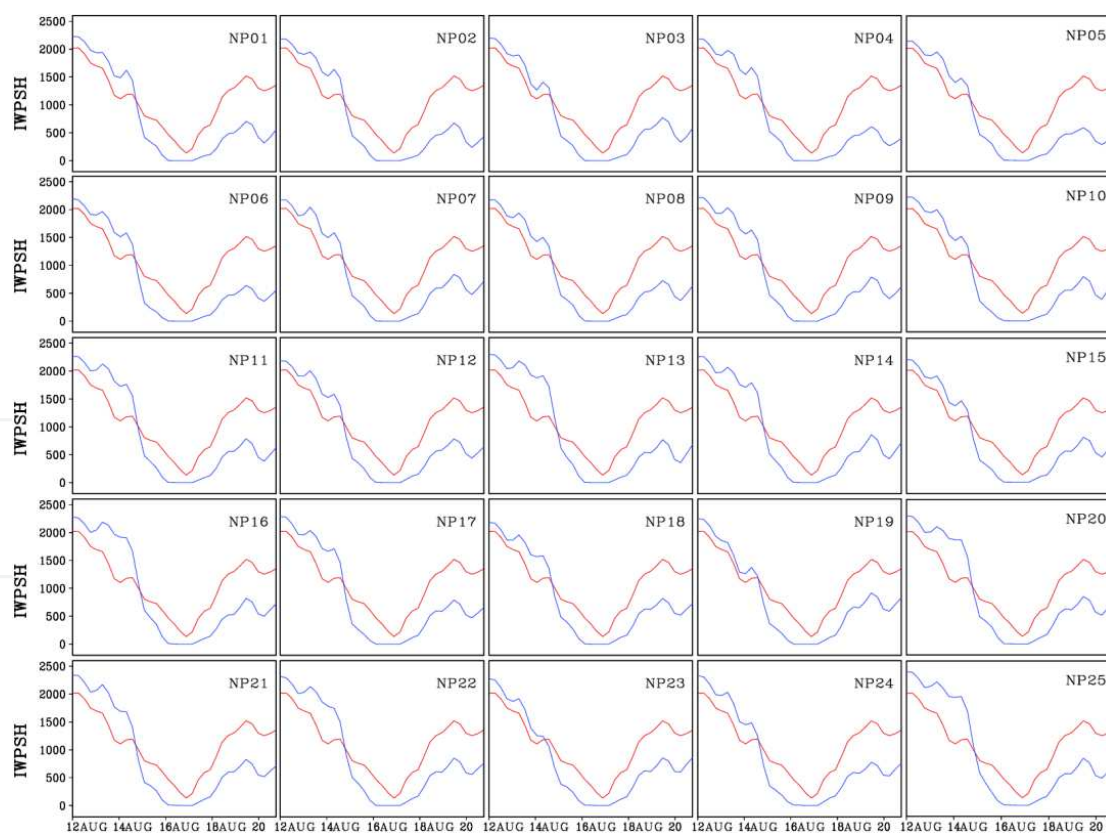


Figure 6. Temporal variations of the observed (solid line) and simulated (dotted line) intensity indices of the western Pacific subtropical high from 00:00 GMT on August 12 to 12:00 GMT on August 20, 1997, for 25 experiments with different configurations of nudging parameters.

To verify the importance of TC on the regional circulation simulation, we depicted the observed and NP19-simulated daily geopotential height at 500 hPa on August 12 and August 16, respectively (Figure 7). It can be seen that the mean circulation over the model domain at 500 hPa on August 12 was reproduced well, for the well-simulated position of Winnie (Figure 7a and 7b). However, the discrepancy between the simulated and observed circulation south to 35°N is much greater for about 5 degree longitudes error in position and 120 gpm error in the intensity of Winnie on August 16 (Figure 7c and 7d). The correlation coefficients between observations and simulations for the region east to 100°E and south to 35°N is 0.9694 and 0.7315, respectively. Therefore, the evolution of 500 hPa geopotential height, as well as the intensity of WPSH, is closely related to the TC track, and the simulated TC track error is the primary cause for the failure in simulating east Asian climate in summer [8].

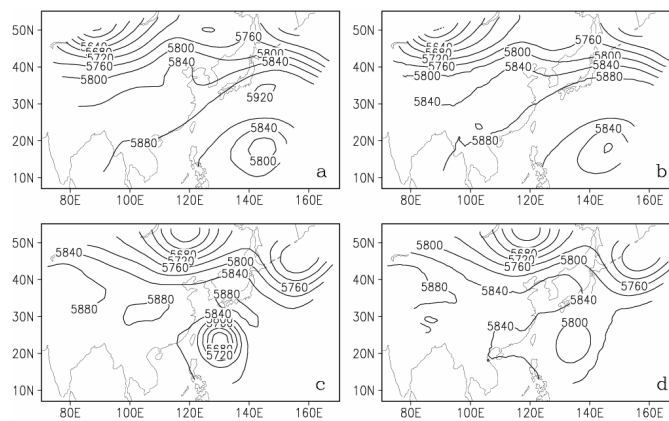


Figure 7. Observed (a, c) and NP19-simulated (b, d) daily geopotential height at 500 hPa on August 12 (a, b) and August 16 (c, d), respectively.

3. Impacts of tropical cyclones on the regional climate over East Asia

It is well known that during summer, WPSH is the predominant large-scale circulation system over the WNP. In most cases, this circulation system regulates the tracks of the TCs. However, the TCs in turn influence the WPSH as well. When a stronger TC turns northeastward over the WNP, it usually causes the WPSH to split [8, 38]. For operational prediction, the impacts of circulation systems, particularly the WPSH, on the tracks of TCs have been studied in detail. However, the quantitative effect of TCs on the regional circulation remains unknown.

Due to the limited observational data available, it is difficult to assess the quantitative effects of TCs on regional circulation systems, particularly on the state of regional circulation without TCs. The RCM is an effective tool that can be used to address this issue. It was noted that the climate in a regional model is determined by a dynamical equilibrium between two factors, i.e., the information provided by the lateral boundary condition and the internal model physics and dynamics [12]. This suggests that the performance of the regional model is mostly dependent on the lateral boundary condition [39, 40]. From this view point, the effects of TCs

on regional circulation systems can be evaluated in terms of the removal of TCs at the lateral boundaries of the model. Therefore, the circulation systems over the model domain would be unaffected by the TCs. In this section, as a case study, RegCM3 is used to determine the extent to which the regional climate is affected by the TCs. This was done by comparing the simulation results at the climate scale with and without TCs at the lateral boundaries of the model's driven fields. The simulation begins at 0000 GMT on July 15 and ends at 1800 GMT on August 31, 1997. During the week of August 17–23 in the simulation period, China suffered huge economic losses due to the damage caused by the violent TC Winnie (1997).

Two experiments were performed, one was the control run (CR) as described above, and the other was the sensitivity run (SR). The SR was conducted by removing the TCs from the 6h interval large-scale driven fields for the same period as that of the CR. This strategy is in agreement with the removal technique of the large-scale TC circulation from the first-guess fields before the bogus TC is inserted into the initial fields, commonly used for the numerical simulation or prediction of TCs [41]. In our approach, we modified the vorticity, geostrophic vorticity and divergence. Then, we solve for the change in the nondivergent stream function, geopotential and velocity potential, and compute the modified velocity field, temperature field and the corresponding geopotential height field. The details of the strategy employed for the removal of TCs from large-scale driven fields can be found in [41].

Figure 8 shows the monthly geopotential height and wind vector of the observations, CR and SR at 200 hPa, 500 hPa and 850 hPa in August 1997. It is observed that the CR performs well for the regional circulation in the lower troposphere over East Asia, while the East Asian summer monsoon predominates the southeastern coast of China and the adjacent WNP; further, a cyclonic circulation interrupts the southwestern summer monsoon over south China (bottom panels in Figures 8a and 8b). The simulated ridge line of WPSH at 500 hPa is at 30°N; this is consistent with the observations (middle panels in Figures 8a and 8b). At 200 hPa, the mean circulation pattern and the South Asia High (SAH) are also reproduced well (top panels in Figures 8a and 8b). However, at 850 hPa, the simulated WPSH is slightly weaker, whereas the lower depression system over the west part of northeastern China is stronger than the observed one, which is partially caused by the TC Winnie passed through Bohai Sea and landed again at Yinkou, Liaoning province, and activated over northeast China.

It is noteworthy that the mean circulation in the lower troposphere in August 1997 is somewhat different from the normal summer monsoon pattern while the southwest summer monsoon flow prevails over south China [13]. The cyclonic circulation at 850 hPa, which interrupted the southwest summer monsoon over south China in August 1997 in the mean chart, was mainly caused by the landfall of TCs, particularly that of the violent TC Winnie on 19 August and its sweep over eastern China in the subsequent days.

In the case of the SR, the simulated WPSH in the lower troposphere intensifies and extends westward significantly. Moreover, the summer monsoon in the lower troposphere with a stronger southerly component from the South China Sea and the Bay of Bengal is predominant over the southeast mainland of China. Meanwhile, the simulated intensity of the lower depression system recovered for TC Winnie is no longer active and finally filling up over northeastern China (shown in the middle and bottom panels in Figures 8c). The simulated

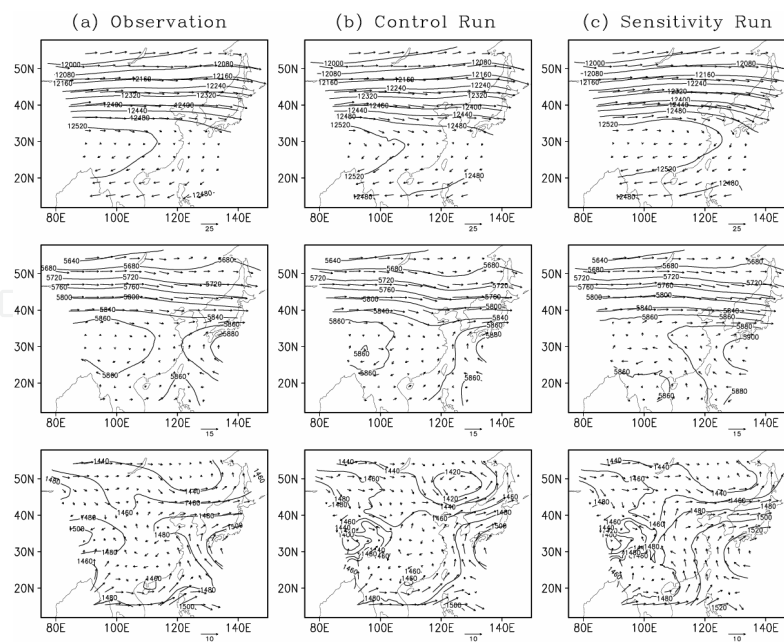


Figure 8. Monthly geopotential height (contour lines) and wind (vector arrows) of the observation (a), CR (b) and SR (c) at 200 hPa (top panel), 500 hPa (middle panel) and 850 hPa (bottom panel) in August 1997.

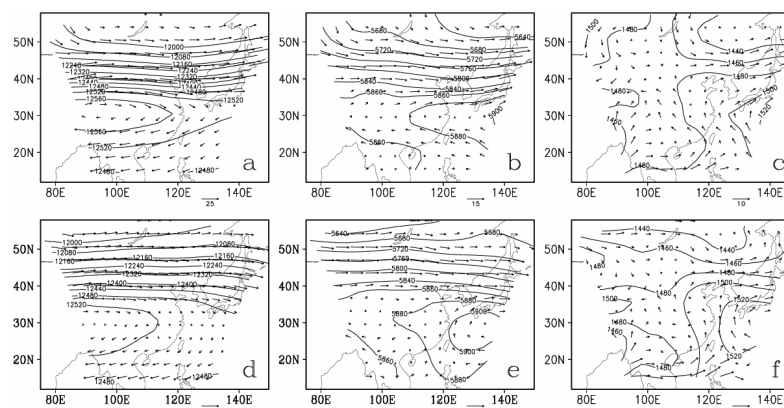


Figure 9. Monthly geopotential height (contour lines) and wind (vector arrows) at 200 hPa (a), 500 hPa (b) and 850 hPa (c) in August 2003.

SAH at 200 hPa is also intensified. However, it extends eastward distinctly, thereby confirming that the WPSH and SAH act in the opposite directions, as noted by Wu et al. [38]. The simulated mean circulation pattern for SR can be verified by the observations. As an example, Figure 9 shows the monthly circulation at 200 hPa, 500 hPa and 850 hPa in August 2003, when TCs over the WNP are observed to be less than usual in this month. It also exhibits a similar pattern for the mean circulation for SR, while the SAH is intensified and extends eastward (Figure 9a); further, the WPSH is also intensified, but it extends westward (Figure 9b), and the southerly monsoon flow prevails over Central and Southern China in the lower troposphere (Figure 9c).

The difference in monthly circulations between SR and CR are shown in Figure 10. It clearly shows an anticyclonic circulation in the entire troposphere over eastern China and the adjacent

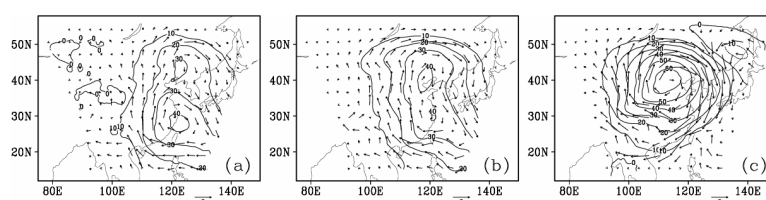


Figure 10. Monthly differences in the geopotential height (contour lines) and wind (vector arrows) between SR and CR at 850 hPa (a), 500 hPa (b) and 200 hPa (c).

WNP. Since TC Winnie was the most violent one in 1997, it significantly influences the difference circulation chart and it exhibits an anticyclonic difference circulation in the middle and lower troposphere and a circular anticyclonic difference circulation at 200 hPa. Moreover, the axis of anticyclonic difference circulation in the vertical is inclined westward above 500 hPa centred at approximately 120°E in the lower troposphere and over the bend of the Yellow River (40°N, 112°E) at 200 hPa.

In order to consider the impacts of TCs on the strength of the WPSH, the intensity index of the WPSH (IWPSH) defined in section 2 is employed here to assess the effects of the TCs on the strength of the WPSH quantitatively. Figure 11 shows the temporal variations of IWPSH in the observation, CR and SR. Four major intensification processes are observed on around August 2, 11, 22 and 30, and three weakening processes are observed on around August 7, 17 and 25. When the activities of the TCs in this period are compared, it is found that each weakening process is attributed to the presence of the following TC over the WNP: Tina, Winnie and Amber, respectively. As shown in Figure 12, these TCs occurred over the WNP during three weakening process respectively and they occupied the position where the WPSH was originally located, resulting in the lower IWPSH. However, the three intensification processes (on August 2, 22 and 30, respectively) are attributed to the presence of the following TCs over the southern coastal area of China and to the west of the WPSH: Victor, Zita and Amber (as shown in Figure 13a, 13c and 13d). These are beneficial to the strengthening of the WPSH over the ocean. Another intensification process (on around August 11) occurred during the intermittent period of TC over the WNP (Figure 13b). This reduction in intensity when the TCs are active over the WNP demonstrates the influence of TCs on the WPSH. Here, it could be inferred that the effect of monsoon latent heating on the strength of subtropical anticyclones, as emphasized by Hoskins [42] and Liu et al. [43], may play a secondary role in the evolution of WPSH and it will be effective only if the TCs are not active over the WNP. Meanwhile, the latent heat release in the cloud wall around the centre of the TCs over southeastern China may have the same effect as that of monsoon latent heating, which will generate a secondary vertical circulation with an ascending branch in the cloud wall and a descending one in the WPSH. This could be the reason why the WPSH is generally intensified after a TC landfall occurs over China. A specific example is TC Amber, which weakened the WPSH when it was over the WNP, but intensified the WPSH after its landfall over China. In fact, TC Winnie also exhibited the same effect before and after its landfall; it contributed to the intensification process of the WPSH before August 21 when it was over east China.

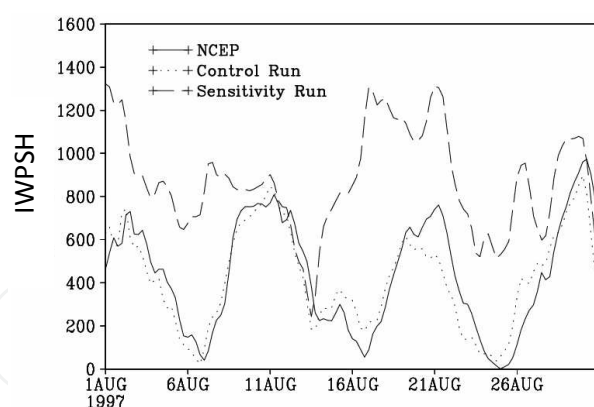


Figure 11. Temporal variation in the intensity index of the WPSH for the observation (solid line), CR (dotted line) and SR (dashed line).

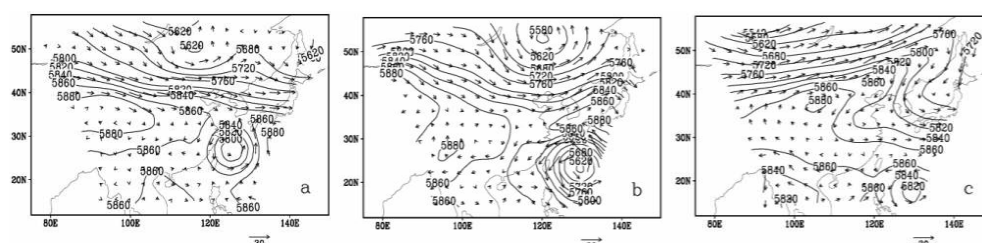


Figure 12. Geopotential height (contour lines) and wind (vector arrows) at 500 hPa on August 7 (a), 17 (b) and 25 (c).

The evolution of the IWPSH for CR shows that the model can reproduce the temporal variation of the WPSH intensity, which demonstrates that the model performs well for the variation in circulation over WNP as well as for the activities of TCs. However, in SR, the simulated evolution of the IWPSH is different from that in the observed one and CR. The most distinct feature is that the three intensification processes (on August 2, 22 and 30) are magnified except for the one on around August 11, which is not directly related to TC. On the other hand, an abnormal intensification process is observed during August 14–22 for the WPSH simulation when TC Winnie is removed from the large-scale forcing fields at the eastern lateral boundary of the model. It should be noted that the mechanisms of the observed and SR-simulated intensification processes of WPSH in those periods are different, i.e., the effects of the TCs are included in the observation but they are removed in the SR simulation. Moreover, it is revealed that the model cannot reproduce the intensification of the WPSH on around August 11, because it is not related to the activity of the TC over WNP.

Generally, TCs over the WNP or China result in substantial precipitation over central and eastern China, which can mitigate the torridity and drought in East Asia when WPSH dominates over there. However, the TCs will interrupt the extension of the East Asian summer monsoon on the weather and climate scales in the lower troposphere, as shown in Figure 8a and 8b. This will eliminate the transportation of water vapour from the Indian Ocean and South China Sea towards eastern China. Figure 14 shows the monthly differences of the precipitable water vapour (PWV) and the percentage rate below 500 hPa between SR and CR. As expected,

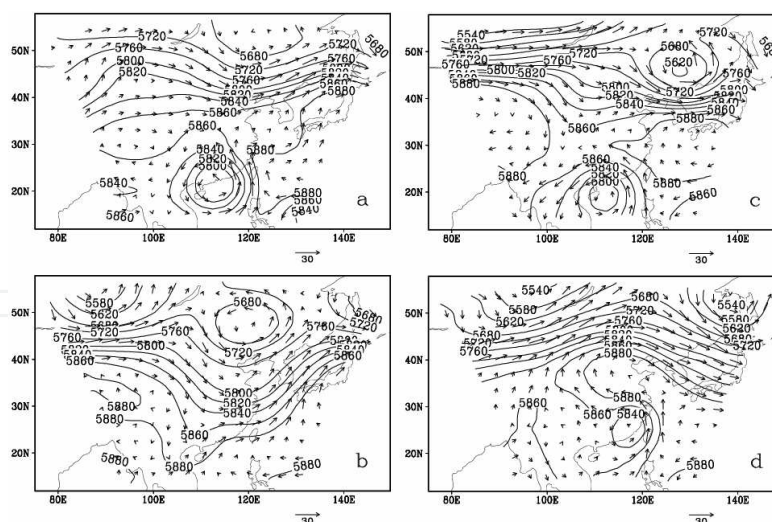
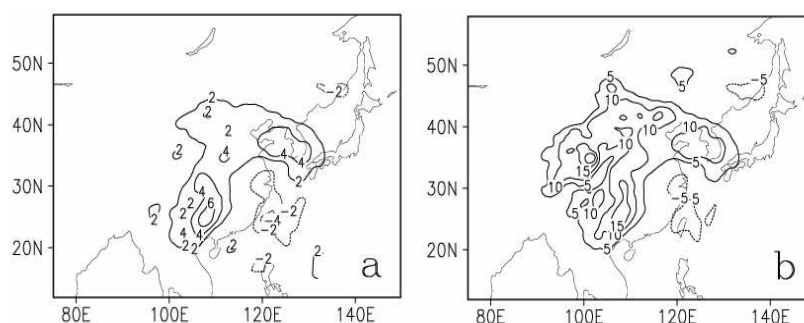


Figure 13. Geopotential height (contourlines) and wind (vector arrows) at 500 hPa on August 2 (a), 11 (b), 22 (c) and 30 (d).



in terms of weakening the WPSH when TCs are over the WNP and interrupting the summer monsoon when TCs make landfall over China. If there were no TCs, the atmosphere over southeast China and northeast China would become drier while that over southwest China and north China would become wetter.

The configuration of nudging parameters for the model buffer zone can significantly affect the TC track simulation. Although the best configuration of nudging parameters does not completely eliminate the error in simulating the track, it can largely reduce the errors. Different parameter configuration would generate RMSE in the track simulation by more than two times. Therefore, the appropriate nudging parameter configuration, which maintains the equilibrium between Newtonian term and Laplace diffusion term of the prognostic equations in buffer zone, is crucial for improving the TC track simulation. Neither strong nudging experiment nor weak nudging experiment is beneficial for simulation of the TC track.

To some extent, the error in the simulation of the TC track is related to that of the intensity of WPSH. The weaker simulated WPSH would be the cause of the turning of TCs ahead of time, which will result in great error of track simulations against track observations. Therefore, improvement only with the RCM lateral boundary scheme does not fundamentally eliminate errors in the simulation of the TC tracks. The key challenges in eliminating the errors are to determine how to solve the problem of simulated weaker WPSH, as well as the appropriate presentation of the interaction between TCs and WPSH.

Moreover, to compare the impact of resolution on the track simulation, experiments at a horizontal grid spacing of 30 km for the different buffer zone size were also performed. It seems a more reasonable track can be obtained from the simulation at a higher resolution, but the TC is not landed as reality for all the experiments, and the simulated intensity is usually much weaker than observed one (figures are not shown). It should be pointed out that the improvement of track for the simulation at a higher resolution may come from the positioning of TC partially, therefore, the discrepancy of track can not be eliminated totally for the simulation at higher resolution, and meanwhile, one cannot expect the much higher resolution for the climate models, though it has been demonstrated that the model would perform well at high resolution [40] and its performance is also related to the domain choice [44] and buffer zone size [45].

It has been known that the model physics plays a fundamental role in TC simulation, though it is as yet unclear whether and to what degree the simulated TC track, structure, intensification, and intensity can be affected by using different physics parameterization schemes [46]. For example, the development of TC is sensitive to the transportation of sensible heat, latent heat and momentum in the underlying surface [47], thus the planetary boundary layer scheme will be important in TC simulation. With the MRI mesoscale nonhydrostatic model, it was found that the precipitation structure induced by typhoon Flo is dependent to the microphysics scheme of the model to a great extent [48], which will in turn reflect the track and intensity of TC through feedback and interaction mechanism. In addition, the simulated tracks of TCs are affected by the detailed microphysics transport in the cumulus parameterization scheme [49].

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