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Can the climate background of western North Pacific typhoon activity be predicted by climate model?

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Based on the observation and reanalysis data through 1948—2004, the vertical shear of zonal wind, outgoing longwave radiation, and divergence fields in the lower and upper troposphere during summer are revealed to correlate significantly with the concurrent western North Pacific (WNP) typhoon frequency, and they therefore can be regarded as predictors for the WNP typhoon activity anomaly. After that, the 34-year (1970—2003) ensemble hindcast experiments are performed by the nine-level atmospheric general circulation model developed at the Institute of Atmospheric Physics Under the Chinese Academy of Sciences (IAP9L-AGCM), aiming to investigate the numerical predictability of the summer vertical shear of zonal wind and divergence field in the lower troposphere. It is found that the temporal correlation coefficients between the hindcast and observation are 0.70 and 0.62 for the vertical shear of zonal wind and divergence field, respectively. This suggests that the model possesses a large potential skill for predicting the large-scale climate background closely related to the WNP typhoon activity, and the model is therefore capable of performing the real-time numerical prediction of the WNP typhoon activity anomaly to some extent.

the western North Pacific typhoon frequency, IAP9L-AGCM, ensemble hindcast, predictability

Typhoon is a kind of severe weather system occurring over the tropical ocean and always makes strong influences on human activities, production, life, and societal property by virtue of its complex characteristics and broad-scale impacts. According to the pertinent statistics, the western North Pacific (hereinafter as WNP) is the ocean where the frequency of typhoon activity is the highest worldwide. Correspondingly, special geographical orientation determines that China is one of the countries which are most frequently influenced by typhoon activity. As such, making the real-time prediction of the WNP typhoon activity is of great importance and has become a key issue of the rainy-season climate prediction in China.

The genesis and subsequent evolution of typhoon depend on a variety of thermal and dynamical conditions. Many studies have been conducted to explore the potential rule of the genesis, evolution, and the relevant climate background characteristics of typhoon[1−7], so as to find out effective approach or method to predict typhoon activity. Therein, it has been indicated in many researches that the WNP typhoon activity correlates well with ocean status. For example, Lander[8], Saunders et al.[9], and Camargo and Sobel[10] reported a close relationship between the WNP typhoon frequency and El Niño event. Besides, significant correlation between the thermal conditions in the equatorial East Pacific and the typhoon frequency in the western Pacific was revealed by Pan[11] and Dong and Qi[12], and according to this relationship Jiang and Sha[13] evaluated the possibility to make the statistic prediction of the interannual variation

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of the tropical cyclone activity over the West Pacific in terms of the equatorial East Pacific sea surface temperature (SST). More recently, close relationships between the WNP typhoon frequency and the North Pacific oscillation, the area index of sea ice over the North Pacific, and even the circulation anomaly over the east side of Australia and Antarctic oscillation were also found[14−17]. These investigations provide valuable information for detecting the WNP typhoon activity anomaly and are helpful for us to figure out operational prediction approach or method for typhoon activity and then to minimize typhoon-related damages.

In the literature of the seasonal prediction for typhoon activity, the statistic method is first utilized. For example, Gray et al.[18] investigated the potential predictability of the Atlantic basin tropical cyclone activity in view of many climate factors and evaluated the influence of initial prediction date on prediction skill. Chan et al.[19] established a prediction scheme for seasonal tropical cyclone activity over the WNP by incorporating many ENSO-related predictors, such as Southern Oscillation index, the Australian monsoon intensity, and the intensity of the subtropical high over the South Pacific. Although some advances have been made in the climate prediction of typhoon activity by use of statistic method, the internal atmospheric variability and atmospheric dynamics processes are excluded from this kind of methodology. Therefore, numerical prediction approach is also necessary.

In the previous studies concerning the numerical prediction of typhoon, atmospheric general circulation model (AGCM) is used more widely than coupled atmosphere-ocean model by virtue of the current limitation of SST predictability[20]. At present, a relatively direct approach is to count the number of tropical cyclone-like systems that the model simulates. For example, Vitart et al.[21] examined the predictability of the number of tropical storms over different ocean basins by using an AGCM, leading to the conclusion that the potential predictability is particularly strong over the WNP and eastern North Pacific, and to a lesser extent over the western North Atlantic. However, it is well known that tropical cyclone belongs to weather system, and the spatial scale of the key convective activity processes related to the genesis and evolution of tropical cyclone is mostly less than 50 km. Clearly, AGCMs currently being used, with comparatively coarse horizontal resolution and unconquerable system error, can represent neither the characteristics of tropical cyclone nor the interaction between tropical cyclone and its background fields as they occur in nature. As thus, making best use of the prediction result of the large-scale atmospheric general circulation factors that are closely related to typhoon activity and possess large numerical predictability to make the further prediction of typhoon activity is a possible numerical approach. Following such idea, Thorncroft and Pytharoulis[22] investigated the predictability of the Atlantic tropical cyclone activity purely based on the vertical shear of zonal wind predicted by an AGCM forced by observational or persistent SST anomaly. Wang et al.[23] attempted to perform the real-time prediction of the WNP typhoon activity anomaly by analyzing several climate factors, as predicted by an AGCM, that correlate closely with the WNP typhoon frequency. As a further step, here the authors firstly figure out the major climate factors that can be regarded as the predictors of the WNP typhoon activity. The potential numerical predictability of the WNP typhoon activity anomaly is then evaluated according to the numerical predictability of these climate factors. It is finally shown that this approach is feasible to make the real-time numerical prediction of the WNP typhoon activity.

1 Data and experimental design

The climate elements examined here include the vertical shear of zonal wind (VSZW), outgoing longwave radiation (OLR), and divergence fields in the lower and upper troposphere. The data of wind field, OLR, and SST are from the U.S. National Centers for Environmental Prediction and National Center for Atmosphere Research. The initial dataset used in the IAP9L-AGCM hindcast experiment includes geopotential height, air pressure, wind, relative humidity, and air temperature at 17 vertical levels, and near-ground geopotential height, air pressure, wind, air temperature, and relative humidity. The observed typhoon frequency data are from the U.S. Joint Typhoon Warning Center[24,25].

In an attempt to evaluate the numerical predictability of the climate background of the WNP typhoon activity, 34-year (1970—2003) ensemble hindcast experiments are performed by the nine-level atmospheric general circulation model developed at the Institute of Atmospheric Physics Under the Chinese Academy of Sciences (IAP9L-AGCM)[26−28]. Taking into account that the prediction for rainy season climate is launched in March and that the WNP typhoon activity is centralized through June to October, the ensemble hindcast experiments for every year are respectively started from seven initial atmospheric fields on 22—28 February and then run through to the end of October. The hindcast result for each year is expressed as the ensemble average of the seven integrations, and the summer mean denotes the average of June to October (JJASO). For each year, the climate anomaly as predicted by the IAP9L-AGCM is calculated by subtracting the model climatology from the hindcast result. The model climatology used here is the JJASO average of a 30-year control run.

The IAP9L-AGCM is a global grid-point model with 4°×5° horizontal resolution and nine unequally spaced levels in the vertical direction with the top at 10 hPa. The model's fidelity of climate simulation and its potential predictability of short-term climate have been previously described or evaluated in detail[29,30]. By virtue of the IAP9L-AGCM's good performance for short-term climate prediction, the model has been used to perform the real-time extra-seasonal and extra-annual climate prediction in China since 2002 and has reproduced relatively accurate climate predictions for rainy season precipitation anomaly, winter climate anomaly, and spring dust weather anomaly for many times so far[31,32].

2 Analysis of the correlation between the WNP typhoon frequency and large-scale atmospheric general circulation factors

The VSZW is an important factor that influences the genesis and evolution of typhoon and its intensity can be used to estimate the frequency of typhoon activity. Figure 1 displays the geographical distribution of the correlation coefficient between the VSZW intensity, calculated from the wind difference between 200 and 925 hPa, and the WNP typhoon frequency averaged from June to October through 1948 to 2004. Significantly negative correlation coefficients appear clearly in the main development region (MDR) of typhoon. In other words, the WNP typhoon frequency tends to become more (less) when the VSZW intensity within the range of 155E°—170°W and 8°—17°N is weaker (stronger), which is in line with Wang et al.'s[23]. Monthly and summer mean correlation coefficients averaged within the dashed rectangle areas shown in Figure 1 are further illustrated in Figure 2. It can be found that the summer prediction skill of the WNP typhoon frequency is larger than monthly one, which is closely related to the climate predictability of the IAP9L-AGCM that the prediction skill of seasonal climate is usually larger than monthly one[30]. These results corroborate that the VSZW intensity is indeed a valuable predictor of the WNP typhoon activity, and the real-time prediction skill of the WNP typhoon activity can, to a large extent, be improved if the VSZW intensity can be well predicted in advance with numerical model. Aiming to examine the extent to which the WNP typhoon frequency depends on the VSZW intensity, their interannual variations are plotted in Figure 3. Overall, the variations of the VSZW intensity and the WNP typhoon frequency are almost opposite in phase through the whole period, except for several individual years such as 1972, 1985, 1991, and 1992. Further investigation reveals that these years are either ENSO years or the years when the strong SST anomaly occurs in the equatorial middle-east Pacific in summer (figure omitted), which suggests that besides the VSZW intensity

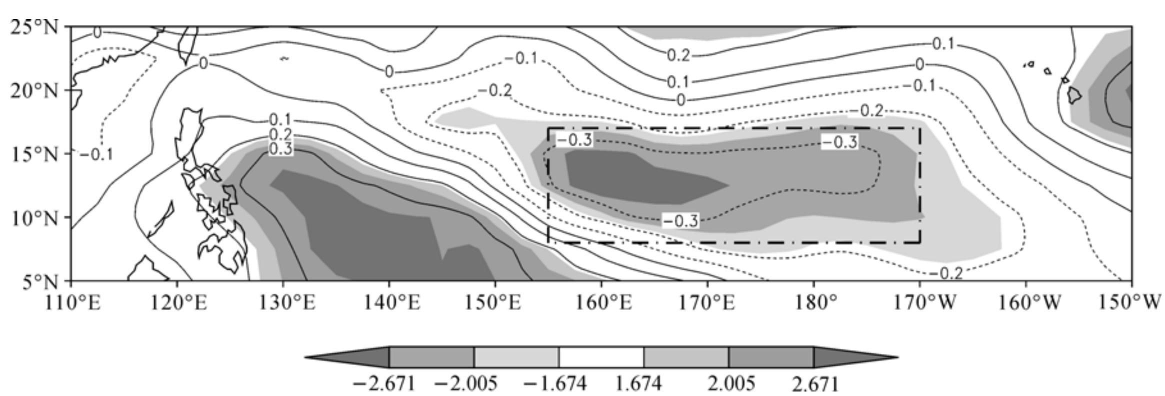

Figure 1 The geographical distribution of the correlation coefficient between summer WNP typhoon frequency and the concurrent VSZW intensity through 1948 to 2004. The dashed rectangle denotes the areas with large negative correlation coefficients, and the shaded areas from light to dark correspond to 90%, 95%, and 99% significance level, respectively.

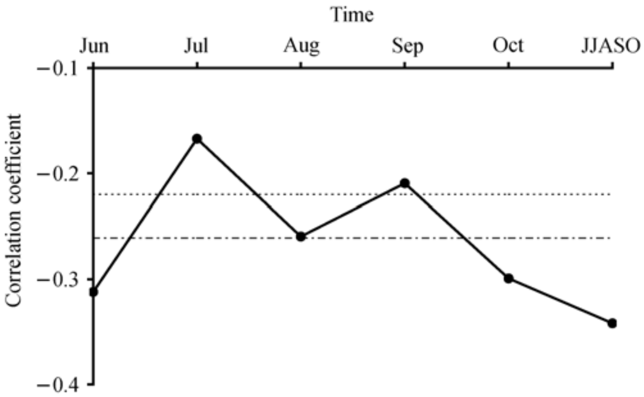

Figure 2 Spatial correlation coefficients between monthly and summer WNP typhoon frequency and the concurrent VSZW intensity averaged within the rectangle areas shown in Figure 1 through June to October. The dotted and dotted-solid lines correspond to 90% and 95% significance level, respectively.

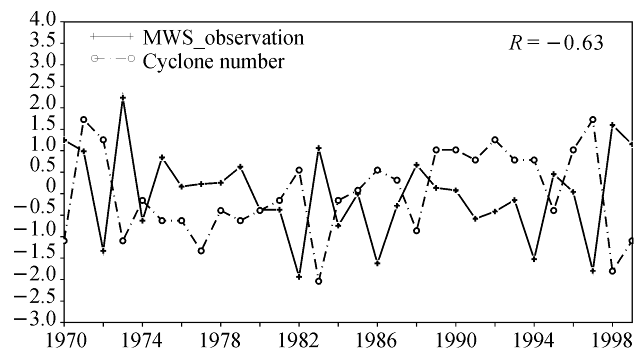

Figure 3 Normalized interannual variation of summer WNP typhoon frequency and the concurrent VSZW intensity averaged within the rectangle areas shown in Figure 1.

there are other climate conditions such as SST contributing to the WNP typhoon activity.

Analysis of OLR, denoting atmospheric convective activity, reveals that it correlates negatively with the WNP typhoon frequency in the MDR of typhoon within the range of 145°—180°E and 0°—16°N significantly. Compared to the dashed rectangle areas shown in Figure 1, the key areas for OLR are somewhat westward and extend equatorward (Figure 4). In addition, when the WNP typhoon frequency is above normal, there are significant convergence (divergence) anomalies in the lower (upper) troposphere, centralizing within 145°—180°E and 2°—14°N (145°—180°E and 12°—25°N) (Figure 5). On the contrary, divergence fields in the lower and upper troposphere are featured with the completely opposite configuration when the WNP typhoon frequency is below normal (figure omitted).

The above analysis indicates that the VSZW, OLR, and divergence fields in the lower and upper troposphere are valuable predictors of the WNP typhoon activity. Moreover, the areas with significant correlation coefficients between the WNP typhoon frequency and these climate factors are located in low latitudes where the model possesses relatively larger climate prediction skill. Therefore, it is certainly a reasonable approach to make prediction of the WNP typhoon activity anomaly by predicting these large-scale climate background fields in advance with climate model. Whereas, whether this scientific idea can be realized is determined by the numerical predictability of these climate factors.

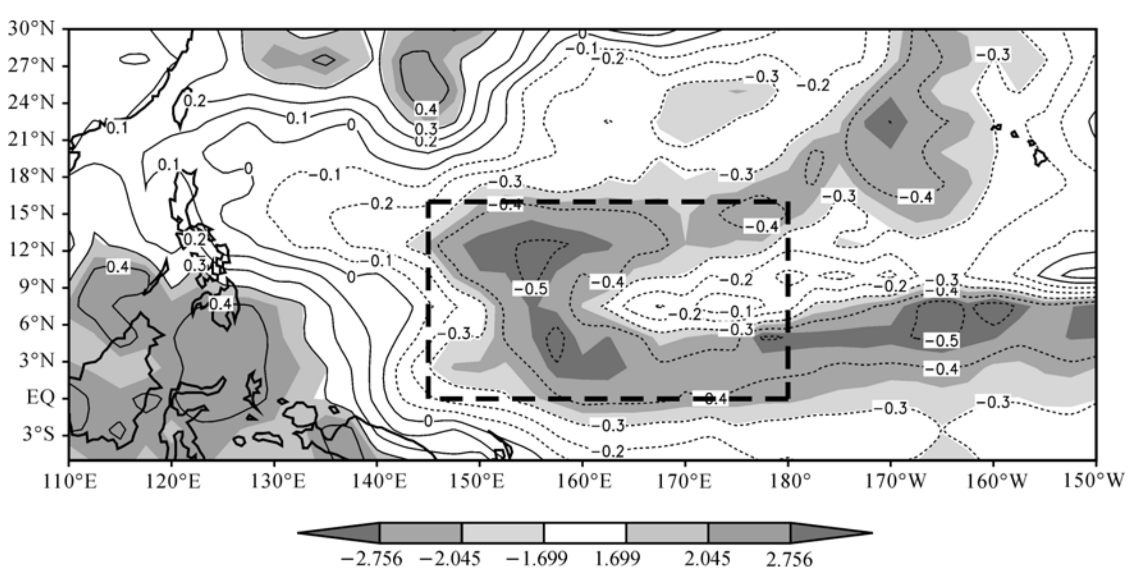

Figure 4 The geographical distribution of the correlation coefficient between summer WNP typhoon frequency and the concurrent OLR through 1975 to 2004 (the dashed rectangle and the shaded areas denote the same as Figure 1.).

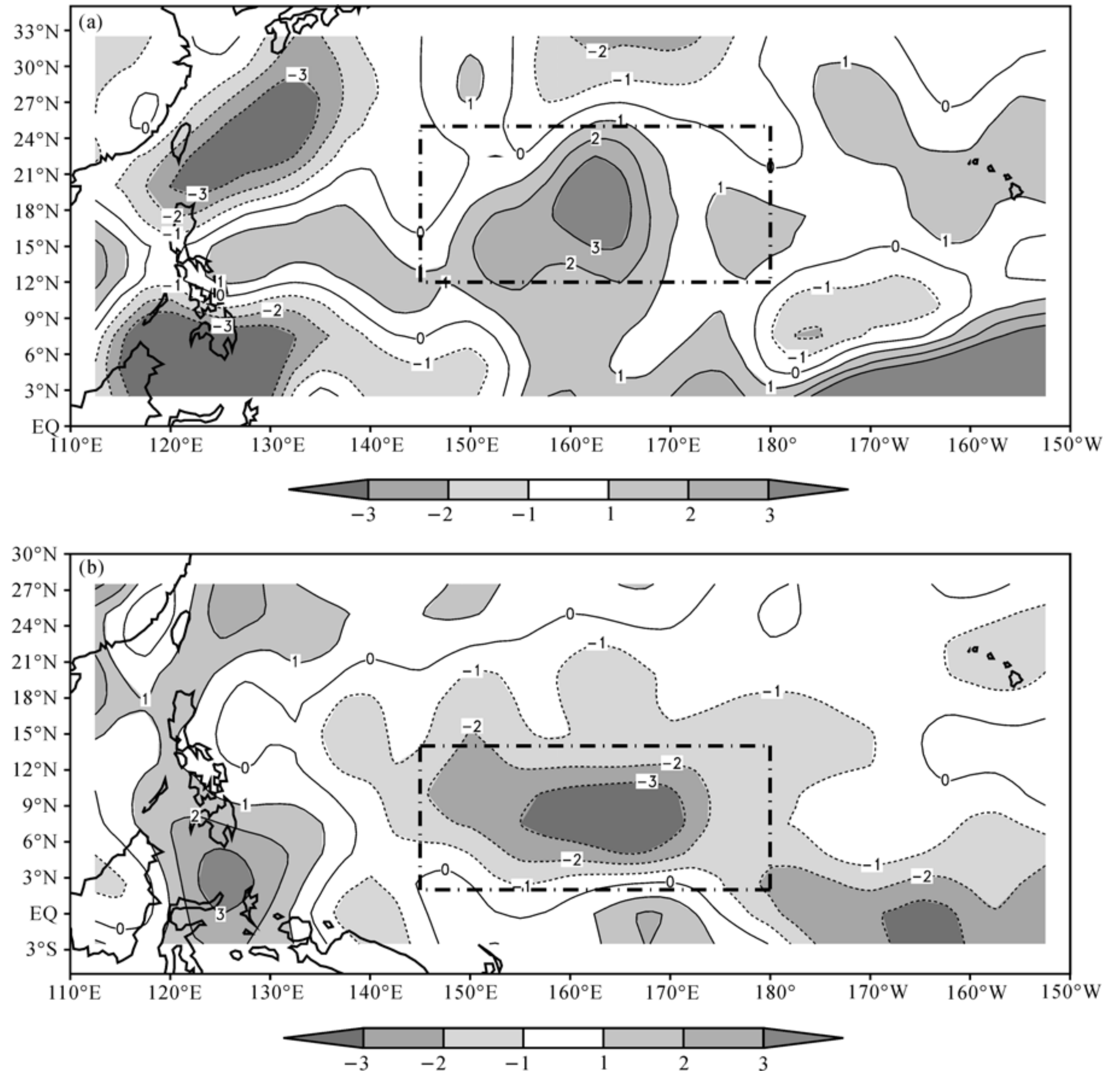

Figure 5 Divergence fields at 200 hPa (a) and 925 hPa (b) when summer WNP typhoon frequency is above normal (unit: 1E7; the dashed rectangle denotes the areas with large anomaly.).

3 Analysis of the numerical predictability of the climate background fields behind the WNP typhoon activity

Figure 6 shows that the IAP9L-AGCM hindcasted VSZW correlates positively with the observation significantly in the dashed rectangle areas shown in Figure 1 where the correlation coefficients enlarge from 0.40 in the northwest to more than 0.70 in the southeast, suggesting a large potential prediction skill the IAP9L-AGCM holds for the VSZW. Furthermore, the interannual variations of the hindcasted and observed VSZW intensity averaged within the key areas through 1970—2003 indicate that, except for several individual years, the model results agree well with the observation in phase through the whole period and in the detailed values in some years, and the corresponding correlation coefficient between them is 0.45 (Figure 7). It should be noted here that the simulated magnitude is somewhat smaller as a whole. Actually, this weakness is well known in the current numerical climate prediction field and usually can be partly overcome by applying model-dependent correction system[33], which will be explored in our future research. On the whole, Figure 7 further corroborates the IAP9L-AGCM's capability to predict the VSZW intensity and hence supports the feasibility of making numerical prediction of the WNP typhoon frequency to a large extent.

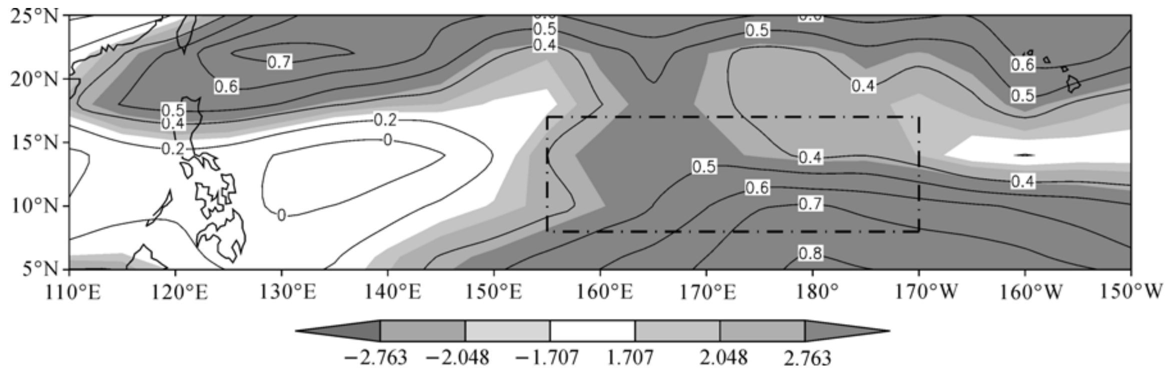

Figure 6 The geographical distribution of the temporal correlation coefficient of VSZW between the hindcast experiment and observation through 1970 to 1999 (the dashed rectangle corresponds to Figure 1, and the shaded areas denote the same as Figure 1.).

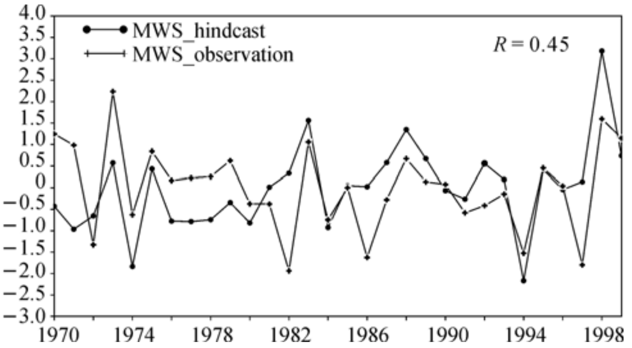

Figure 7 Normalized interannual variation of summer VSZW intensity averaged within the dashed rectangle areas shown in Figure 1.

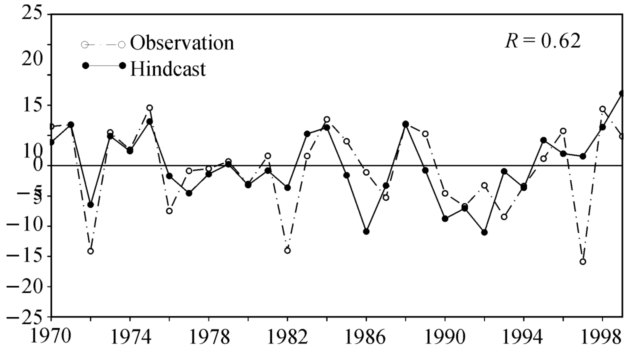

Figure 8 Interannual variation of divergence at 925 hPa averaged within the dashed rectangle areas shown in Figure 5(b) (unit: 1E7).

Meanwhile, the hindcasted interannual variation of the divergence at 925 hPa averaged within the dashed rectangle areas shown in Figure 5(b) accords well with the observation both in phase and magnitude, and the corresponding correlation coefficient is 0.62 (Figure 8). This means that the IAP9L-AGCM possesses large potential predictability for this factor and it therefore can be taken as another predictor of the WNP typhoon activity in the real-time prediction. It should be noted that the prediction skill of the divergence filed at 925 hPa averaged within the dashed rectangle areas shown in figure 5b is relatively larger before the 1990s when the correlation coefficient between the hindcast and the observation reaches up to 0.72. The reason for this interdecadal difference in predictability will be further explored in the next step. Moreover, a common characteristic is found in Figures 7 and 8. That is the IAP9L-AGCM seems to exhibit relatively larger (smaller) prediction skill for summer climate when El Niño event is in phase of decay (development). Aiming at this point, an especial attention is paid to the IAP9L-AGCM's potential predictability of summer climate based on its 30-year (1970—1999) ensemble hindcast experiments. It is revealed that the potential predictability of summer climate is relatively smaller during the years when the El Niño event occurs, whereas it is larger during the years when the El Niño event occurs in the last years (figure omitted). The mechanism behind the result remains unclear so far and will be addressed in the future.

All of the above indicate that some large-scale climate background fields closely related to the genesis and evolution of the WNP typhoon can be predicted by the IAP9L-AGCM to some extent, and they therefore can be used as the predictors of the WNP typhoon activity. Here, we take 1994 and 1998 as examples of the years when the WNP typhoon frequency is above and below normal, respectively. As for summer 1994, the VSZW intensity as hindcasted by the IAP9L-AGCM is below normal and anomalous convergence field appears in the lower troposphere (Figure 9), both of which are exactly in favor of the genesis and development of the WNP typhoon. On the contrary, in summer 1998 the VSZW intensity is above normal and anomalous divergence field appears in the lower troposphere (Figure 10), both of which inhibit the WNP typhoon activity. Thus it can be judged that if the SST can be accurately predicted,

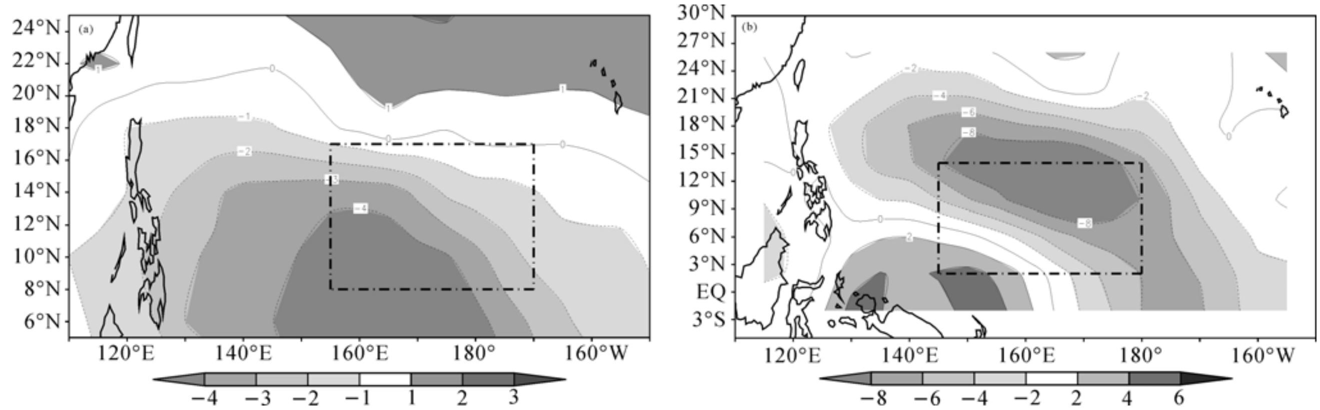

Figure 9 The geographical distribution of the anomalous vertical shear of zonal wind (a) and divergence at 925 hPa (b) in the MDR of the WNP typhoon in summer 1994 as hindcasted by the IAP9L-AGCM (unit: 1E7; the dashed rectangle areas in Figures (a) and (b) correspond to those shown in Figures 1 and 5(b), respectively.).

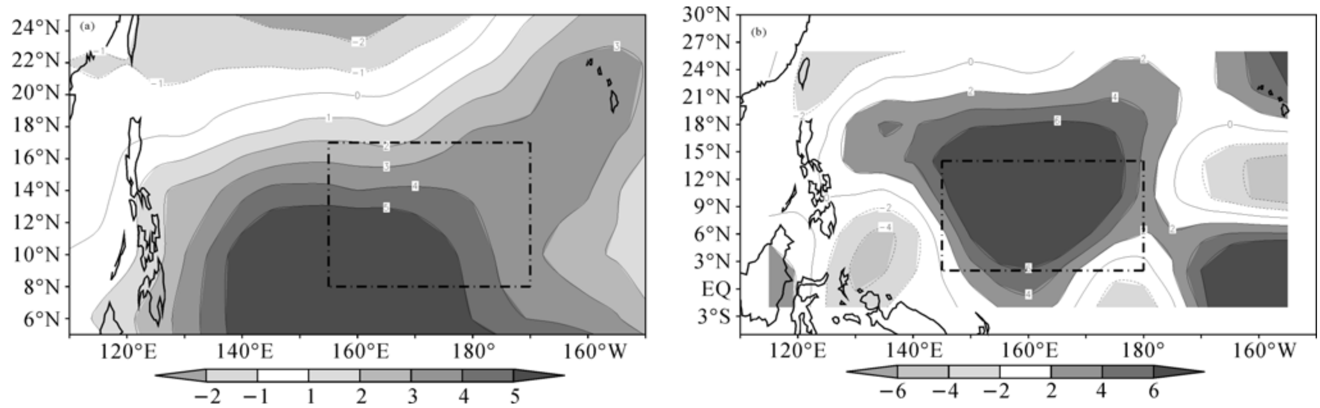

Figure 10 Same as Figure 9, but for 1998.

the valuable real-time prediction of the WNP typhoon activity can be made by the IAP9L-AGCM via the VSZW intensity and divergence field in the lower troposphere.

4 Conclusion and discussion

In an attempt to investigate the numerical predictability of the WNP typhoon activity in summer, the correlation coefficients between the WNP typhoon frequency and the synchronous VSZW, OLR, and divergence fields in the lower and upper troposphere are firstly analyzed. Statistically significant relationships are found in the MDR of the WNP typhoon, which give prominence to the role of the three factors as indicators of the WNP typhoon activity. After that, the 34-year (1970—2003) ensemble hindcast experiments are performed by the IAP9L-AGCM, and the numerical potential predictability of these three climate factors is then evaluated. On the whole, the prediction skill is large and relatively persistent for both the VSZW intensity and divergence field in the lower troposphere. This means that the numerical prediction of these two climate factors can be routinely monitored to give guidance for making the real-time prediction of the WNP typhoon activity one seasonal ahead.

Clearly, the dynamical mechanisms behind the genesis and evolution of typhoon are quite complicated, and typhoon activity results from a broad variety of climate and weather factors. These have been embodied in the present analysis to some extent. Additionally, there are still deficiencies embedded in the state-of-the-art models, such as the inadequacies in the parametrization of physical processes and relatively coarse horizontal resolution. Therefore, it is greatly difficult to obtain the precise numerical prediction of routine climate elements, let alone making the accurate prediction of the climate factors influencing typhoon genesis and evolution. As such, it is especially important to search for operational approach or method to predict complicated typhoon-type weather processes. Moreover, it should be reminded that the numerical experiment is performed by an AGCM here, and the effect of the SST is consequently prohibited. However, it has been pointed out that both the SST in the equatorial middle-east Pacific and the sea temperature in the WNP subsurface have significant influences on the tropical cyclone[34,35]. Therefore, the fully coupled ocean-atmosphere model should be emphasized in this filed.

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