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Influence of the Mascarene High and Australian High on the Summer Monsoon in East Asia: Ensemble Simulation

XUE Feng* (薛 峰), JIANG Dabang (姜大膀), LANG Xianmei (郎咸梅), and WANG Huijun (王会军)

LASG,Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

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ABSTRACT

By using a nine-level atmospheric general circulation model developed at the Institute of Atmospheric Physics (IAP 9L AGCM), two sets of numerical experiments are carried out to investigate the influence of the Mascarene high (MH) and Australian high (AH) over the southern subtropics upon the East Asian summer monsoon circulation and summer precipitation in East Asia. The use of ensemble statistics is adopted to reduce the simulation errors. The result shows that with the intensification of MH, the Somali low-level jet is significantly enhanced together with the summer monsoon circulation in the tropical Asia and western Pacific region. Furthermore, the anticyclonic anomaly in the tropical western Pacific to the east of the Philippines may induce a weak East-Asia-Pacific teleconnection pattern. In the meantime, geopotential height in the Tropics is enhanced while it is reduced over most regions of mid-high latitudes, thus the northwestern Pacific subtropical high at 500 hPa extends southwestward, resulting in more rainfall in southern China and less rainfall in northern China. A similar anomaly pattern of the atmospheric circulation systems is found in the experiment of the intensification of AH. On the other hand, because the cross-equatorial currents associated with AH are much weaker than the Somali jet, the anomaly magnitude caused by the intensification of AH is generally weak, and the influence of AH on summer rainfall in China seems to be localized in southern China. Comparison between the two sets of experiments indicates that MH plays a crucial role in the interactions of general atmospheric circulation between the two hemispheres.

Key words: mascarene high, Australian high, East Asian summer monsoon

1. Introduction

Since Findlater (1969) found the existence of the Somali low-level jet anchoring off eastern Africa and revealed its relations with the Indian summer monsoon, the concept of interactions of general circulation of the atmosphere between the two hemispheres has been widely accepted. In fact, Chinese meteorologists, early before Findlater's(1969) study, realized the importance of the cross-equatorial current from Australia in the development of synoptic systems in the tropical western Pacific and East Asia. Previously, Li (1956) noted that the typhoon genesis over the tropical western Pacific can be triggered by the activity of cold air over Australia. Later, Tao et al. (1962) found that the alternative changes between zonal and meridional circulation in East Asia are closely related to those in Australia during the boreal summer: with the development of meridional circulation in Australia, the cross-equatorial current in the lower troposphere intensifies, then the meridional circulation in the low latitudes of East Asia prevails. As weather satellite data and data from other sources became available, the role of the Australian high (AH) in the establishment and development of summer monsoon circulation in East Asia was further demonstrated (Zhao and Wang, 1979; Wang and Zhao, 1987; Tao and Chen, 1987; etc.). Besides AH, the importance of the Mascarene high (MH, also called the Indian Ocean subtropical high) was emphasized by Huang and Tang (1987, 1989), who found that the development of MH usually takes place earlier than that of AH and the other components of the East Asian summer monsoon regime, so that MH plays a leading role in the interactions between the two hemispheres. More recently, our studies have shown that the establishment of the winter circulation over regions occupied by MH and AH occurs earlier (around middle April) than that of the Asian summer monsoon circulation (Xue et al., 2002). On the interannual timescale, our studies further revealed that the intensities of MH

*E-mail: fxue@lasg.iap.ac.cn

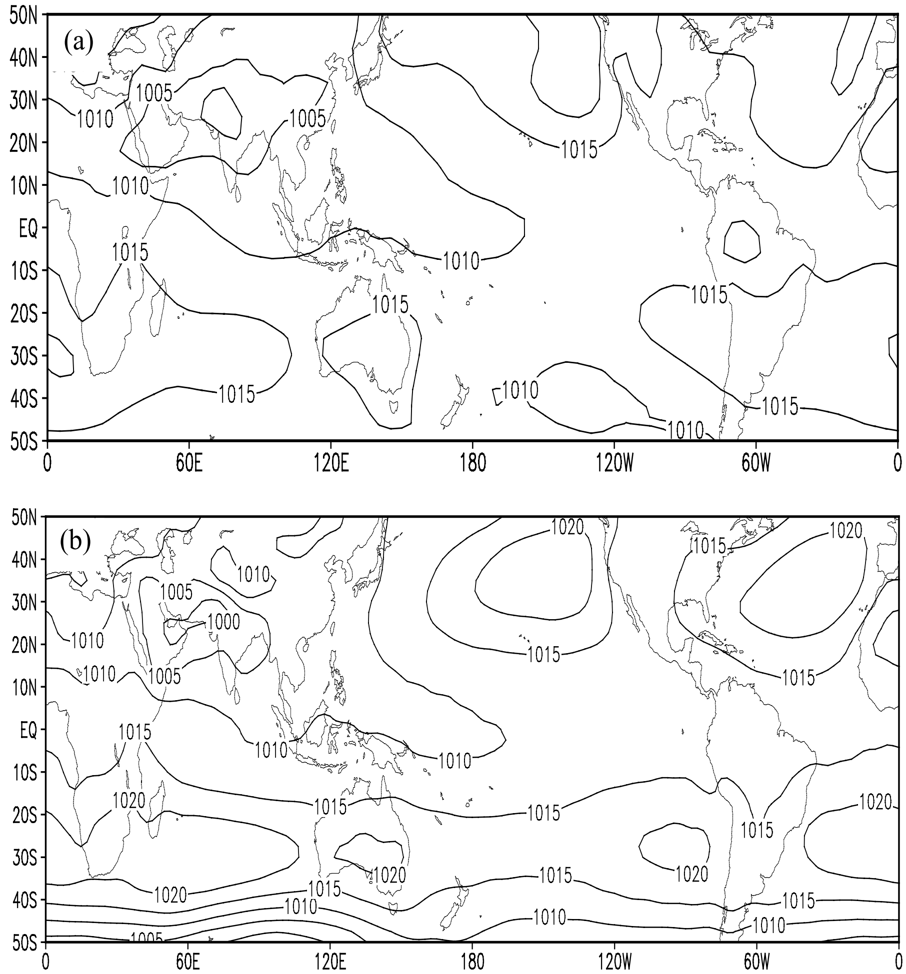

Fig. 1. Geographical distribution of sea level pressure in JJA (hPa), (a) simulation, (b) climatological mean during 1958–1997 based on NCEP/NCAR reanalysis data.

and AH are closely related to summer monsoon rainfall over East Asia (Xue et al., 2003). Based on these studies, it can be concluded that the winter circulation in the Southern Hemisphere, especially AH and MH, plays an important role in the East Asian summer monsoon (EASM).

In addition to observational studies, atmospheric general circulation models (AGCM) have also been used to simulate the interactions between the two hemispheres. As a major channel connecting the two hemispheres, the Somali low-level jet was reproduced in a p-sigma AGCM (Qian et al., 1987). Based on a numerical experiment of intensified MH, Yang and Huang (1989) showed that the intensification of MH leads to an anomalous East-Asia-Pacific teleconnection pattern, thus affecting the activities of the summer monsoon in East Asia. He et al. (1991) simulated the northward advance of EASM due to cold air activities over Australia. In spite of the usefulness of these results, the aforementioned studies were based on a short period of integration and focused on intraseasonal or seasonal timescales. On the interannual timescale, however, it is evident that longer integrations are essential to study this issue. Based on our previous observational study (Xue et al., 2003), we carry out two sets of numerical experiments with a nine-level atmospheric GCM developed at the Institute of Atmospheric Physics (IAP 9L AGCM) in an attempt to further elucidate the influence of MH and AH on EASM.

2. Model validation and experiment design

The IAP 9L AGCM is a global grid-point model including the troposphere and stratosphere, with a resolution of 4° latitude by 5° longitude and nine unequal sigma levels in the vertical direction. Compared with most other models, this model possesses some unique

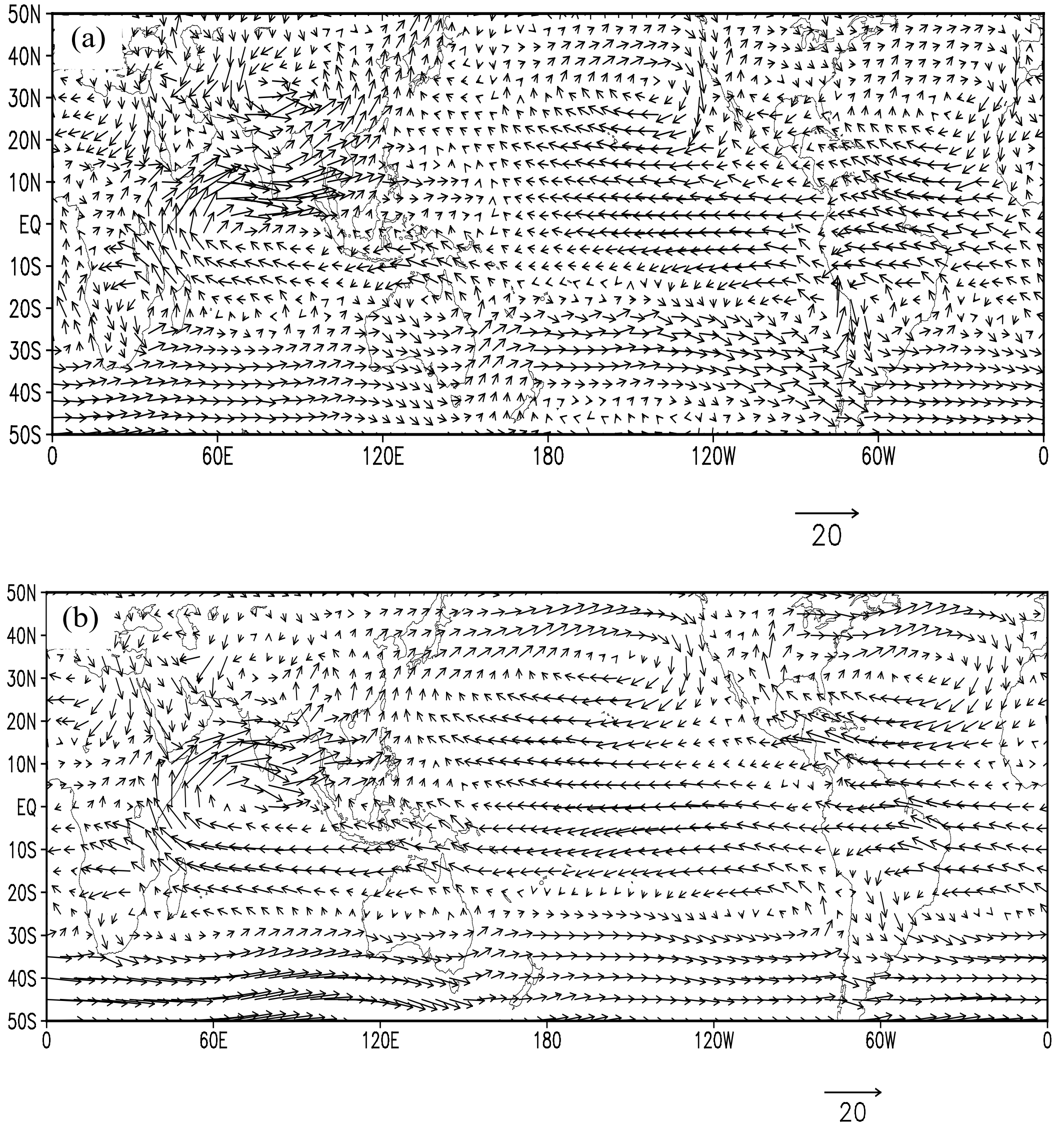

Fig. 2. The same as Fig. 1, except for 850-hPa wind field (m s^{-1}).

features such as the subtraction of a standard stratification in a dynamical frame and the compactness in mathematical formulation and numerical computation (Bi, 1993; Liang, 1996). The model generally simulates a realistic distribution of the present climate (Bi, 1993).

Ensemble simulation is adopted in this study because in so doing, errors in numerical experiments can be greatly reduced (Zeng et al., 1997). The model's boundary condition is taken as the climatological mean sea surface temperature and sea ice coverage during 1979–1996. The model is run for 20 years, and the result based on the 20-year integration is referred to as the control experiment (CTL–EXP).

To gain confidence in simulating the influence of MH and AH on EASM, it is a prerequisite to validate the model's performance in simulating the atmospheric circulation systems related to EASM. For this purpose, sea level pressure, horizontal wind at 850 hPa, geopotential height at 500 hPa, and rainfall over East Asia and the western Pacific region during boreal summer (June-July-August, JJA) are selected for comparison between CTL-EXP and observations. Figure 1 shows sea level pressure in JJA for the 20-year mean simulation and climatological mean during 1958-1997 based on NCEP/NCAR reanalysis data (Kalnay et al., 1996). The model generally simulates the high pressure belt in the subtropics of the Southern Hemisphere including MH and AH with about 5 hPa underestimation; the Indian low and North Pacific subtropical high are also

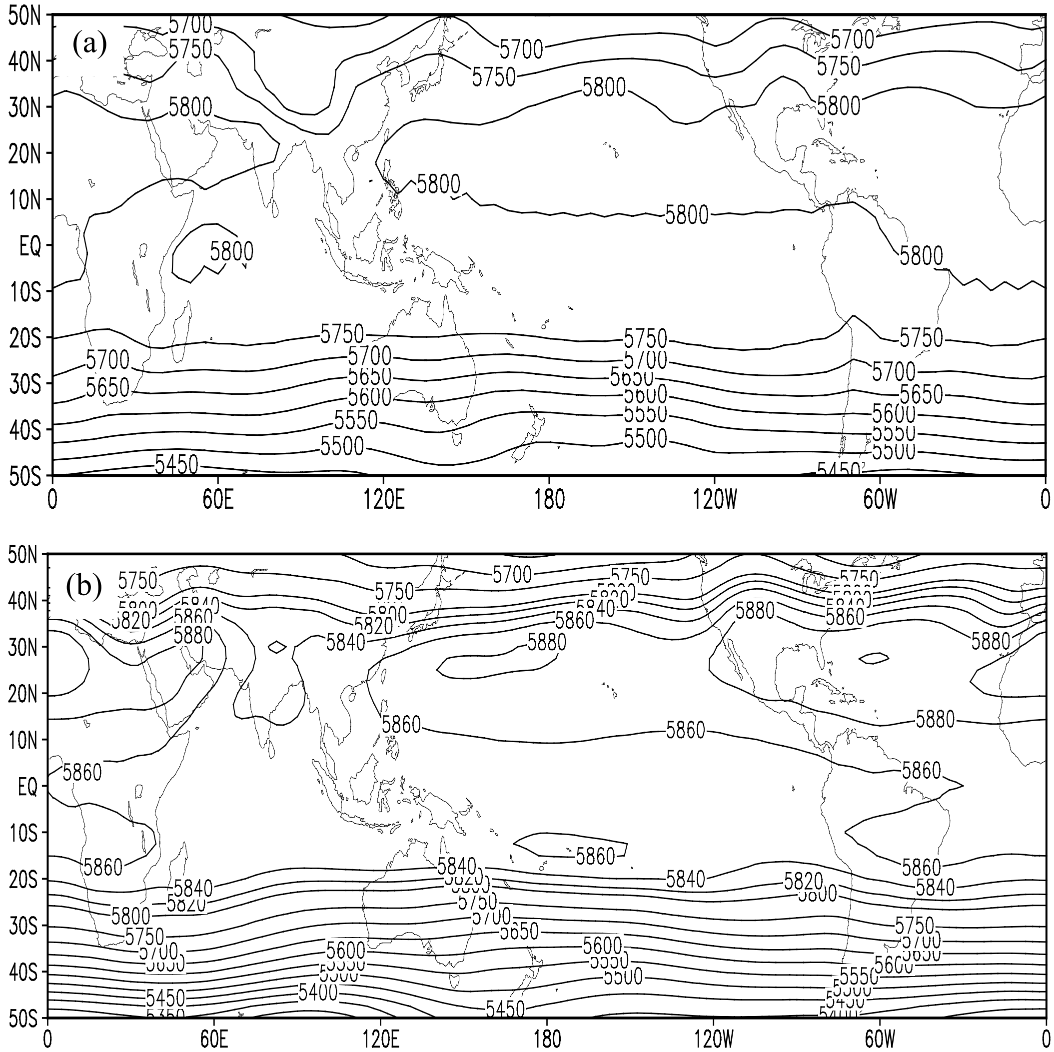

Fig. 3. The same as Fig. 1, except for 500-hPa geopotential height (gpm). In (b), for comparison, the contour interval is 20 gpm when the geopotential height is larger than 5800 gpm.

reproduced, but the latter is positioned more poleward than its observational counterpart.

As shown in Fig. 2, the model simulates the anticyclonic circulation in the southern subtropics and the cross-equatorial currents associated with MH and AH, i. e., the Somali low-level jet and the cross-equatorial current near the Indonesian Archipelago, with the former much stronger than the latter in both simulation and observation. In the Northern Hemisphere, the tropical summer monsoon circulation (i.e., the tropical westerlies) over South Asia and Southeast Asia is well captured by the model while a stronger southwest monsoon circulation over the East Asian continent and a weaker anticyclonic circulation in North Pacific are found in the simulation.

The model simulates the large-scale characteristics of the 500-hPa geopotential height in JJA including major ridges and troughs in the Northern Hemisphere (Fig. 3). The values, however, are systematically underestimated except in high latitudes, thus the gradient of geopotential height between high and low latitudes is significantly smaller than that in the observation. Fortunately, the northwestern Pacific subtropical high, which has a notable influence on EASM, is reproduced though the values are underestimated by 60 gpm and the ridge line is located somewhat equatorward.

Figure 4 shows the simulated precipitation rate in

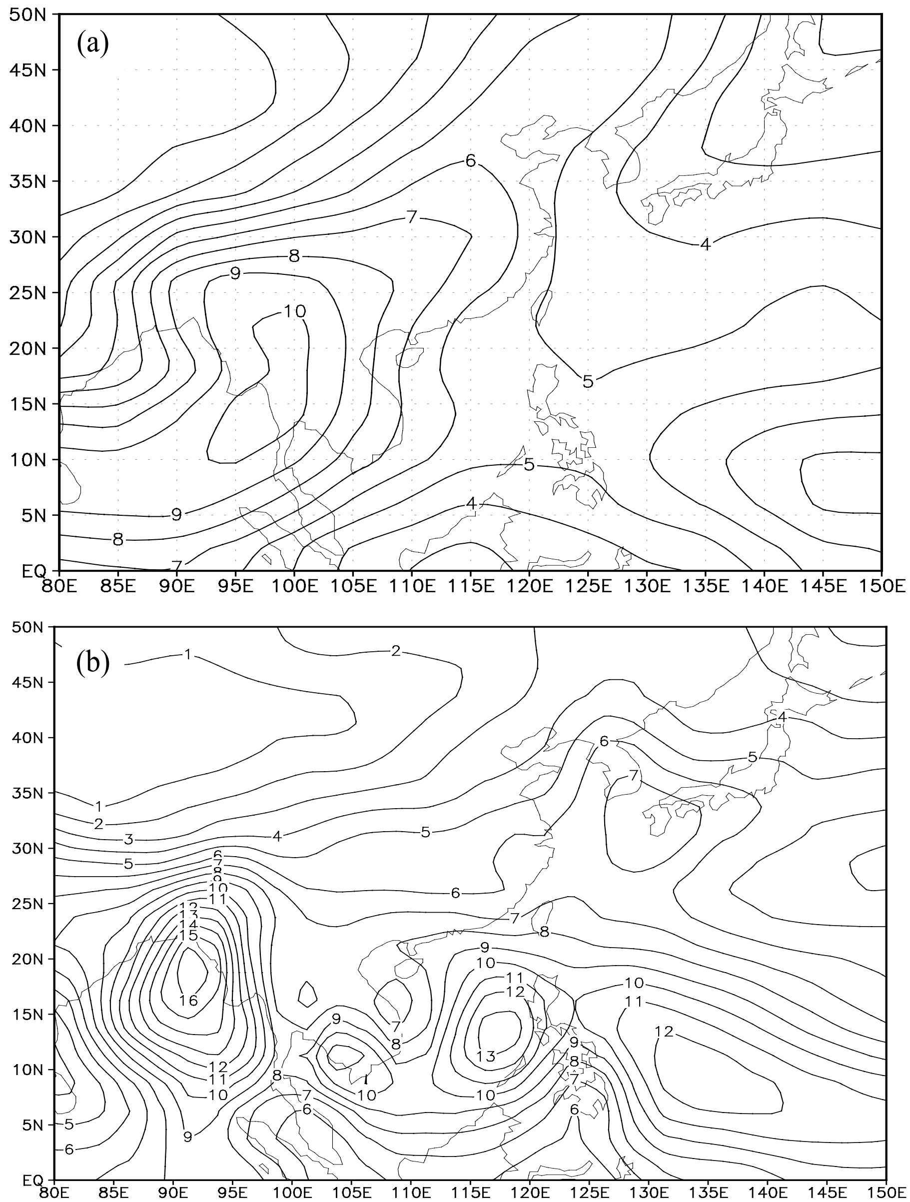

Fig. 4. Precipitation rate in JJA over Asia and the western Pacific region (mm day^{-1}), (a) simulation, (b) climatological mean during 1979–1999 based on the reanalysis data from Xie and Arkin (1997).

JJA over Asia and the western Pacific, together with the climatological mean data during 1979-1999 from Xie and Arkin (1997) for comparison. The model generally simulates the maximum rainfall belt associated with the intertropical convergence zone (ITCZ), extending northwestward from the Bay of Bengal to the western Pacific to the east of the Philippines. In addition, the rainfall center over the Bay of Bengal and Burma and the lesser rainfall belt near the Equator are also reproduced, and the rainfall over the East Asian continent is simulated to a relatively high degree of accuracy. On the other hand, the model fails to simulate some small-scale precipitation centers such as those over the Philippines, the tropical western Pacific, and southern Japan.

In summary, the IAP 9L AGCM simulates the major circulation systems associated with EASM including the MH, AH, Indian low, northwestern Pacific subtropical high, as well as the cross-equatorial currents and the tropical westerlies. The model also simulates the large-scale distribution of summer precipitation over Asia and the western Pacific. Therefore, it is be-

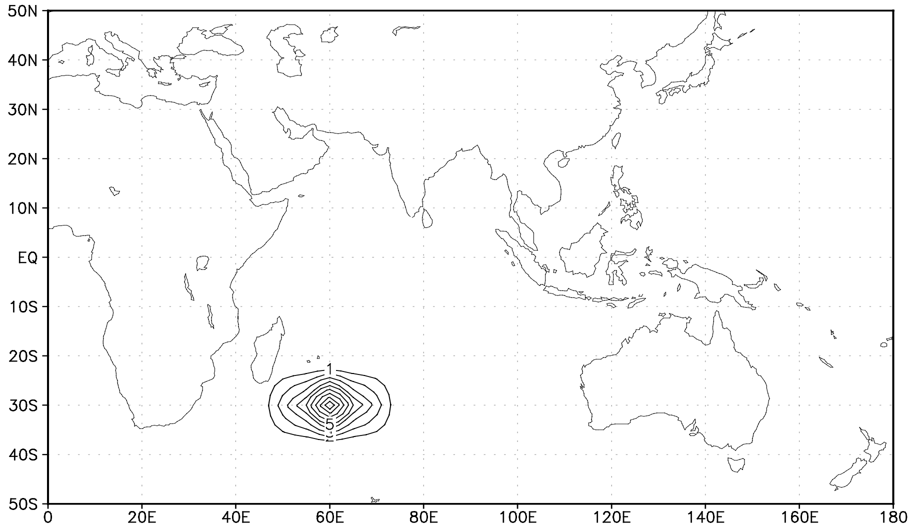

Fig. 5. Distribution of the added sea level pressure anomaly in the experiment of anomalous intentification of the Mascarene high (hPa).

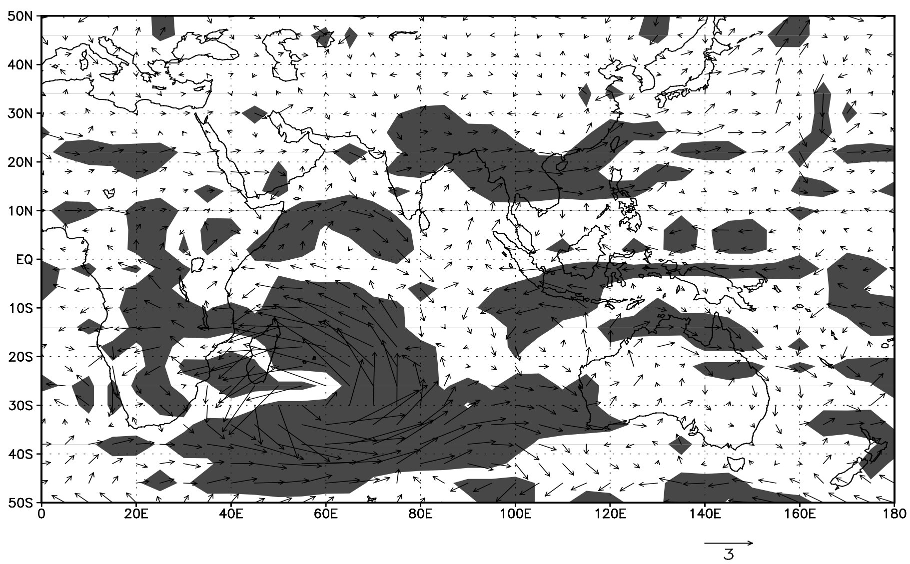

Fig. 6. Difference of 850-hPa wind in JJA between MH-EXP and CTL-EXP (m s^{-1}); regions above the 95% significance level are shaded.

lieved that this model is appropriate to this study.

Based on the distribution of sea level pressure in CTL-EXP (Fig. 1a), MH is centered over (30°S, 60°E). In addition, our previous observational study showed that the maximum intensity change in the center of MH is about 10 hPa (Xue et al., 2003). In the experiment of anomalous intensification of MH (MH-EXP), therefore, the maximum anomaly of 10 hPa is added onto the grid point (30°S, 60°E) and the added anomaly is reduced in turn on the neighboring grid points as shown in Fig. 5. Since the establishment of winter circulation in the southern subtropics occurs in mid April (Xue et al., 2002), in MH-EXP, the above anomaly is directly added once a day beginning from 15 April to 31 August in each year of the 20-year CTL-EXP. Comparison between CTL-EXP and MH-EXP shows that such added anomalies are generally balanced within 2 hours and disappear within 24 hours, so the above experiment scheme is reasonable for maintaining the anomaly of MH. And in a similar manner to the MH-EXP, in the experiment of anomalous intensification of AH (AH-EXP), the same anomaly is added to the Australian region with the center at (30°S, 140°E) (not shown).

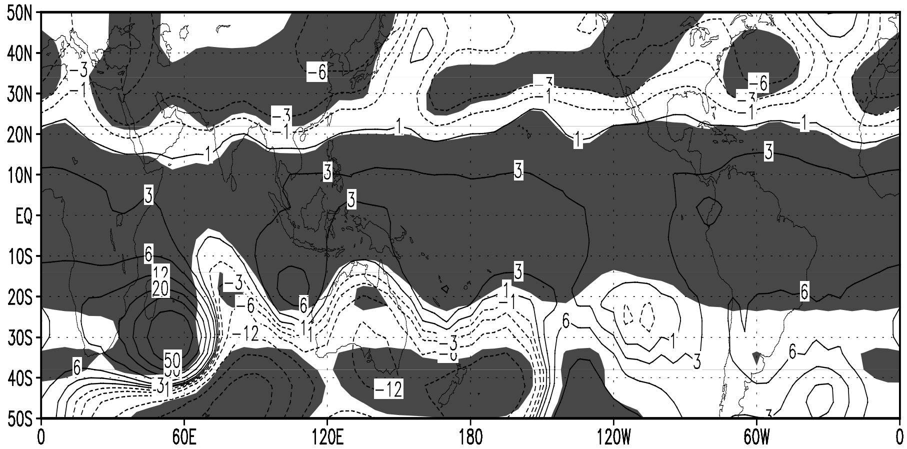

Fig. 7. Difference of 500-hPa geopotential height in JJA between MH-EXP and CTL-EXP (gpm); regions above the 95% significance level are shaded.

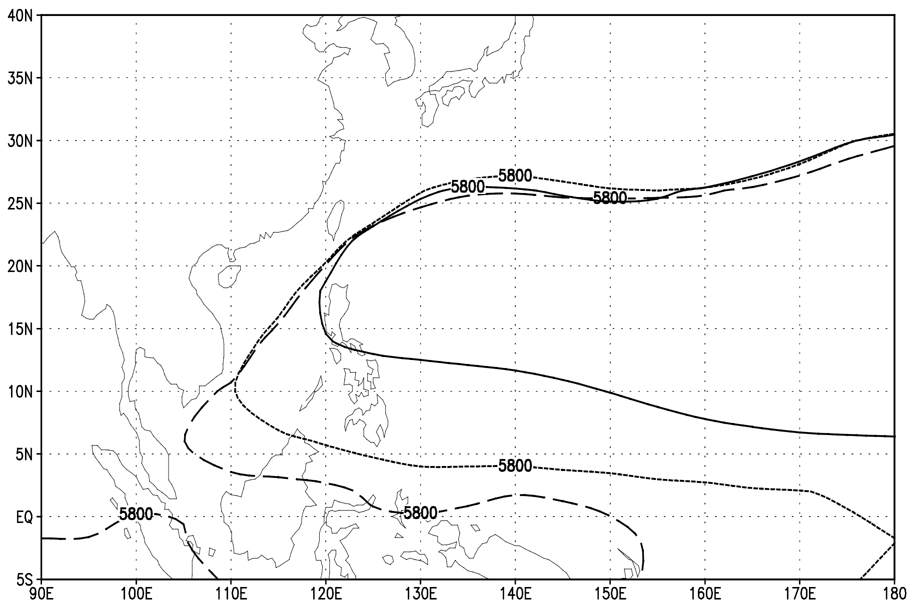

Fig. 8. The simulated isoline of 5880 gpm in JJA for CTL-EXP (solid line), MH-EXP (long dashed line), and AH-EXP (short dashed line), respectively.

3. Analysis of simulation results

In this section, we analyze changes in EASM due to the intensification of MH and AH. Figure 6 shows the 20-year mean difference of 850-hPa wind in JJA between MH-EXP and CTL-EXP in the previous section; regions above the 95% significance level by a *t*-test are shaded. As a result of the intensification of MH, a giant anticyclonic anomaly appears over the Indian Ocean and its neighboring areas, and in the mean time, the Somali low-level jet and the related tropical summer monsoon circulation extending from India to the western Pacific are obviously enhanced. Also evident is the intensification of the anticyclonic anomaly north of Australia and the related tropical easterlies and the cross-equatorial current near Indonesia. In particular, it is noted that an anticyclonic anomaly appears in the warm pool region to the east of the Philippines. The studies by Nitta (1987) and Huang and Sun (1994) have shown that anomalous convective activities owing to the sea surface temperature anomaly in the tropical western Pacific can result in the East-Asian-Pacific teleconnection pattern (or Pacific-Japan pattern), thus affecting the climate anomaly in East Asia. However, the above result clearly reveals that the convective activities above the warm pool region

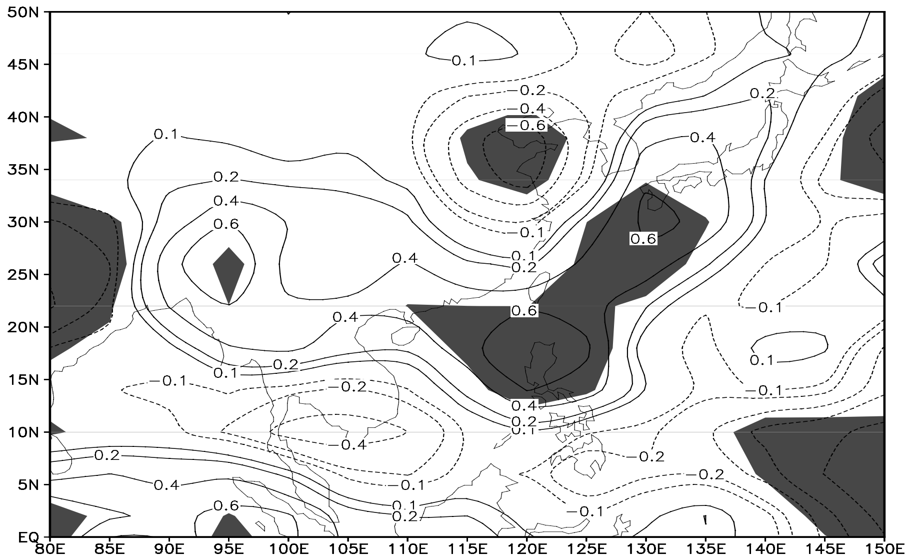

Fig. 9. Difference of precipitation rate in JJA between MH-EXP and CTL-EXP over Asia and the western Pacific (mm day^{-1}); regions above the 95% significance level are shaded.

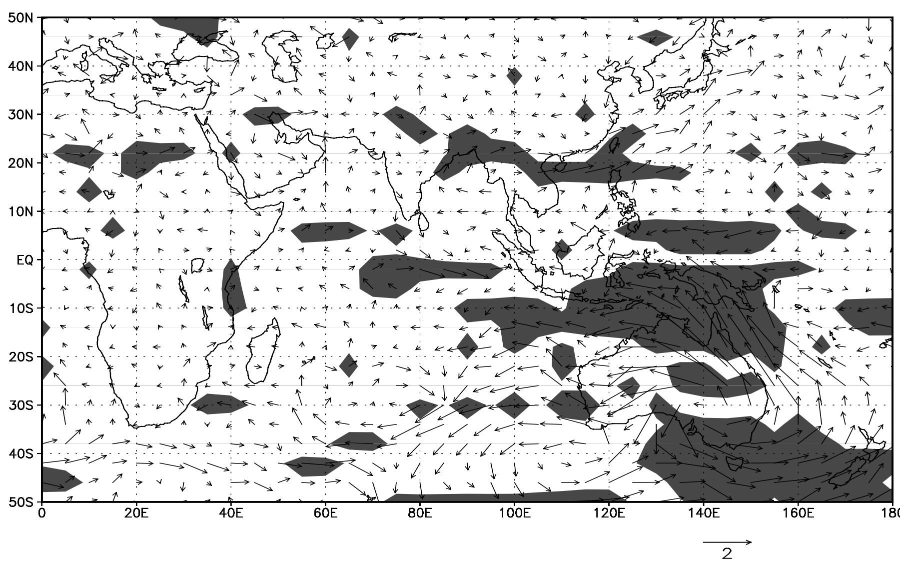

Fig. 10. Difference of 969-hPa wind in JJA between AH-EXP and CTL-EXP (m s^{-1}), regions above the 95% significance level are shaded.

can also be suppressed by the anomalous intensification of MH.

A clear response to the intensification of MH is also found in the 500-hPa geopotentia height, as shown in Fig. 7. Geopotential height in the Tropics is enhanced while it is reduced in most regions of mid-high latitudes in both hemispheres. In particular, one would expect that because of the enhancement of geopotential height in the tropical western Pacific and reduction in the East Asian continent, the northwestern Pacific subtropical high will be situated far more equatorward. A more distinct picture can be seen in Fig. 8, where the simulated 5800-gpm isoline in MH-EXP is more southwestwardly positioned than in CTL-EXP; this result agrees well with the observation by Shi and Zhu (1995). In addition, according to the observational studies (e.g., Ding, 1994; Chen and Zhao, 2000), this pattern can result in above-normal rainfall in southern China and below-normal rainfall in northern China during boreal summer. Figure 9 clearly illustrates that as a result of the intensification of MH, more rainfall

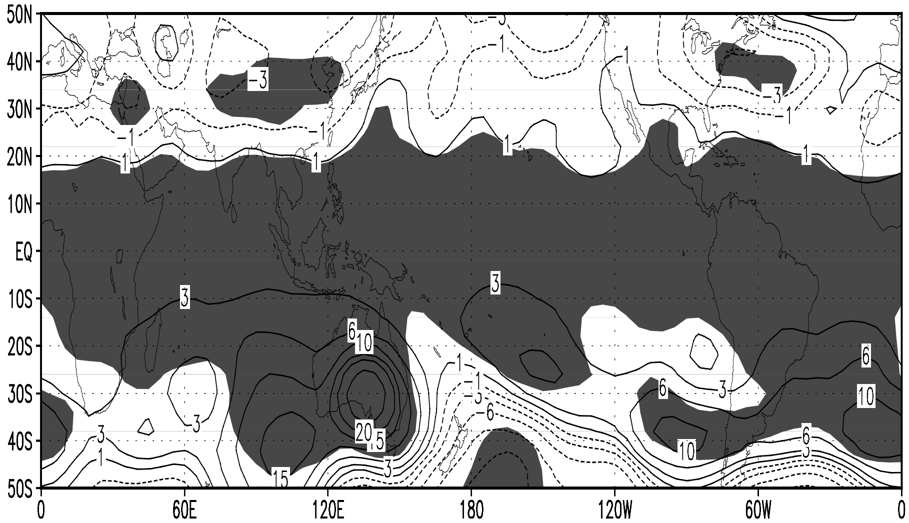

Fig. 11. Difference of 500-hPa geopotential height in JJA between AH-EXP and CTL-EXP (gpm); regions above the 95% significance level are shaded.

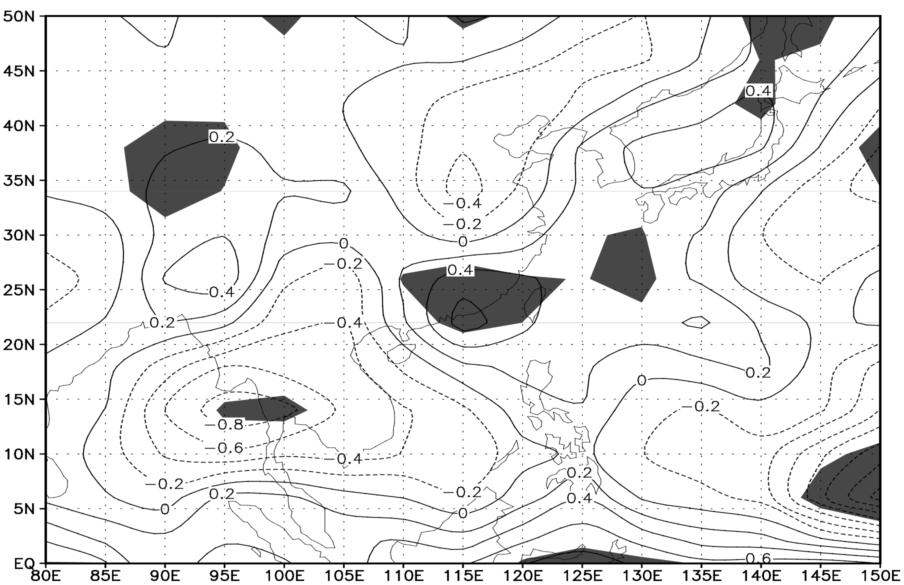

Fig. 12. Difference of precipitation rate in JJA between AH-EXP and CTL-EXP over Asia and the western Pacific (mm day^{-1}); regions above the 95% significance level are shaded.

is found in southern China, Japan, and the adjacent oceanic regions, while less rainfall is found from the Indochina Peninsula to the tropical western Pacific east of the Philippines. In particular,it is noticed that a significantly negative rainfall anomaly appears in northern China.

Similar to that in MH-EXP, an anticyclonic circulation anomaly appears at the surface level over Australia with the intensification of AH, and the cross-equatorial currents near Indonesia are also enhanced (Fig. 10). In addition, the tropical westerlies from the Bay of Bengal to the western Pacific east of Taiwan and the tropical easterlies off the Equator are simultaneously intensified. As a consequence, an anticyclonic anomaly appears in the tropical western Pacific east of the Philippines. The wind anomaly at 850 hPa or 700 hPa is very similar to the one at 969 hPa except that the cross-equatorial currents are not significantly changed (figures not shown).

Figure 11 shows that the difference of geopotential height between AH-EXP and CTL-EXP strongly resembles that in Fig. 7 in large-scale distribution, i.e., there is an enhancement in the Tropics and reduction in mid-high latitudes, but the anomaly magnitude is much weaker than in MH-EXP, especially in the East Asian continent. In agreement with this weaker anomaly, shown in Fig. 8, the southwestward extension of the subtropical high in AH-EXP is not as significant as that in MH-EXP. Figure 12 shows that due to the intensification of AH, there appears more rainfall from southern China to Japan and less rainfall from the Bay of Bengal to the tropical western Pacific to the east of the Philippines. Unlike MH-EXP, however, no significant changes in rainfall are found in northern China. Summarizing the above comparison between MH-EXP and AH-EXP, we can conclude that MH has a more significant influence on the East Asian summer monsoon than AH. This result is reasonable because the Somali jet associated with MH is much stronger than the cross-equatorial currents associated with AH (Fig. 2).

4. Summary and discussion

Based on the 20-year control experiment, it is proved that the IAP 9L AGCM simulates the atmospheric circulation systems associated with EASM and the large-scale distribution of precipitation in East Asia. The model is, therefore, suitable for investigation of the influence of MH or AH on EASM.

The ensemble simulation is used to study changes in the atmospheric circulation and precipitation due to the intensification of MH. The result shows that with the intensification of MH, the Somali low-level jet is obviously enhanced along with the tropical summer monsoon circulation from India to the tropical western Pacific. In particular, convective activities can be suppressed due to the intensification of anticyclonic anomaly in the tropical western Pacific to the east of the Philippines. It is therefore suggested that besides the local effect of sea surface temperature, the East-Asian-Pacific teleconnection pattern can also result from changes in the intensity of MH. Moreover, geopotential height is enhanced in the Tropics while it is reduced over most regions of mid-high latitudes. In this case, the northwestern Pacific subtropical high at 500 hPa extends more southwestward than its normal position, resulting in more rainfall from southern China to Japan and less rainfall from the Bay of Bengal to the tropical western Pacific as well as in northern China.

Similar to MH, due to the intensification of AH, the cross-equatorial currents near the surface level are enhanced along with the tropical summer monsoon circulation. The enhancement of the 500-hPa geopotential height in the Tropics and reduction in mid-high latitudes are also found in AH-EXP, however, the anomaly magnitude is much weaker than in MH-EXP. Therefore, the influence of AH on EASM is weaker than that of MH, and more rainfall is found in southern China with the intensification of AH.

As already pointed out by Huang and Tang (1987) and Xue et al. (2003) from observations, the result in this study further proves that MH plays a crucial role in the interaction between the southern winter circulation and the summer monsoon circulation in the Northern Hemisphere. In particular, it is worth noting that due to the earlier establishment of winter circulation and the persistence of this circulation system during boreal spring though summer in the southern subtropics (Xue et al., 2002), the intensity of MH or AH is of importance in summer rainfall prediction in China. For better prediction of summer precipitation in China, therefore, it is necessary to pay more attention to the revelation of the physical mechanism responsible for the changes in intensity of the two highs.

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REFERENCES

Bi Xunqiang, 1993: IAP 9L AGCM and climate simulation, Ph. D. dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences, 210pp. (in Chinese)

Chen Xingfang and Zhao Zhenguo, 2000: *Studies on Predictions of Precipitation During Flood Period in China and Applications*. China Meteorological Press, Beijing, 241pp. (in Chinese).

Ding Yihui, 1994: *Monsoons over China*, Kluwer Academic Publishers, 420pp.

Findlater, J., 1969: A major low level aircurrent over the Indian Ocean during the northern summer. *Quart. J. Roy. Meteor. Soc.*, **95**, 362–380.

He Jinhai, Li Jun, and Li Yongping, 1991: The influence of processes of cold air activities over Australia on East Asian summer monsoon-A numerical experiment. *Acta Meteorologica Sinica*, **49**, 162–169. (in Chinese)

Huang Ronghui, and Sun Fengying, 1994: Impacts of the thermal state and the convective activities in the tropical western warm pool on the summer climate anomalies in East Asia. *Chinese J. Atmos. Sci.*, **18**, 61–72.

Huang Shisong, and Tang Minming, 1987: On the structure of the summer monsoon regime of East Asia. *Scientia Meteorologica Sinica*, **13**(3), 1–14. (in Chinese)

Huang Shisong, and Tang Minming, 1989: Medium-range oscillation and teleconnection of the atmospheric circulation systems over the Northwest Pacific and South Indian Ocean. *Acta Meteorologica Sinica*, **3**, 571–581.

Kalnay, E. and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Li Xianzhi, 1956: A synthetic theory of formation of typhoons. *Acta Meteorologica Sinica*, **27**, 87–100. (in Chinese)

Liang Xinzhong, 1996: Description of a nine-level grid atmospheric general circulation model. *Advances in Atmospheric Sciences*, **13**, 269–298.

Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation. *J. Meteor. Soc. Japan*, **70**, 243–256.

Qian Yongfu, Wang Qianqian, Dong Yiping, and Gong Yuanfa, 1987: Numerical experiment of Somali low-level jet. *Chinese J. Atmos. Sci.*, **11**, 215–226.

Shi Neng, and Zhu Qiangen, 1995: The climatic features of Australia high and Mascarene high in the Southern Hemisphere and their influence on summer precipitation in eastern China. *Scientia Meteorologica Sinica*, **15**(2), 20–27. (in Chinese)

Tao Shiyan, Xu Shuying, and Guo Qiyun, 1962: Characteristics of zonal and meridional circulation patterns in the tropics and subtropics during boreal summer. *Acta Meteorologica Sinica*, **32**, 91–103. (in Chinese)

Tao, S.-Y., and Chen L. X., 1987: A review of recent research on the East Asian summer monsoon in China. *Monsoon Meteorology*, C. P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 60–92.

Wang Shaowu, and Zhao Zongci, 1987: *Basis of Long-range Weather Forecast*, Shanghai Sci. & Tech. Press, 201pp. (in Chinese)

Xie, P., and P. A. Arkin, 1997: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539–2588.

Xue Feng, Lin Yihua, and Zeng Qingcun, 2002: On the seasonal division of general circulation of the atmosphere and its abrupt change, Part III, Climatological mean. *Chinese J. Atmos. Sci.*, **20**, 243–251.

Xue Feng, Wang Huijun, and He Jinhai, 2003: Interannual variability of Mascarene high and Australian high and their influences on summer rainfall over East Asia. *Chinese Science Bulletin*, **48**, 492–497.

Yang Xiuqun, and Huang Shisong, 1989: The influence of intensity change of Mascarene high on the general circulation of atmosphere—A numerical experiment. *Scientia Meteorologica Sinica*, **9**(2), 125–138. (in Chinese)

Zeng Qingcun, and Coauthors, 1997: Seasonal and extraseasonal predictions of summer monsoon precipitation by GCMs. *Advances in Atmospheric Sciences*, **14**, 163–176.

Zhao Zongci, and Wang Shaowu., 1979: Interactions between general circulation of atmosphere in the two hemispheres and climate. *Acta Meteorologica Sinica*, **37**, 58–68. (in Chinese)