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Numerical Simulation of the 1999 Yangtze River Valley Heavy Rainfall Including Sensitivity Experiments with Different SSTA

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ABSTRACT

With the IAP/LASG GOALS model, the heavy rainfall of the summer of 1999 in the Yangtze River valley is simulated with observational sea surface temperature (SST). Comparing the simulations of 1999 with the corresponding ones of 1998 and the sensitivity experiments with different sea surface temperature anomalies (SSTA) at different ocean regions, the relationships between the floods in the Yangtze River valley and the SSTA in the Pacific and Indian Oceans are studied. The results show that the positive SSTA in the tropical Indian Ocean are a major contributor to the heavy rainfall and may be a very important index to predict the heavy rainfall over the Yangtze River valley in the summer. The simulations also show that the relationships between the SSTA in the tropical eastern Pacific and the heavy rainfall in the Yangtze River valley are very complicated, and the heavy rainfall in the Yangtze River valley can occur in both a decaying and an intensifying El Niño event and also in a La Niña event. However, the different SSTA of different periods in the above three cases play different parts.

Key words: Yangtze River valley, heavy rainfall, sea surface temperature anomaly, numerical simulation

1. Introduction

Following the summer floods of 1998 in the Yangtze River valley, additional floods occurred there in June, July, and August (JJA) of 1999. The second highest water level was recorded in the mid-lower reaches of the Yangtze River and a severe flood occurred in the Taihu Lake valley (National Climate Center, 1999a).

In general, it is thought that sea surface temperature anomalies (SSTA) are the major contributors to climate anomalies in East Asia (Chen, 1977; Gui et al., 1978; Huang and Wu, 1989; Deng et al., 1989; Mao and Wu, 2000). These studies have indicated that the SSTA of the equatorial eastern Pacific, the equatorial western Pacific, the northwest Pacific, and the Indian Ocean have some correlations with the summer rainfall over the Yangtze River valley, but the conclusions from the different studies vary widely.

It is very interesting to note that there are very large differences between the SSTA in 1998 and 1999, and these very different SSTA both caused severe floods in the Yangtze River valley. There have been several papers that have analyzed the climatic background of the 1998 summer floods and show that the El Niño event during 1997–1998 may be an important cause for the floods (Tao et al., 1998; Huang et al., 1998). However, the features of the following La Niña event remained during 1999 (National Climate Center, 1999a). In the month of March 1999, several research groups provided their predictions: there would be more precipitation in North China and less precipitation in the mid-lower reaches of the Yangtze River in the following summer (National Climate Center, 1999b). The cold episode in the central and eastern equatorial Pacific from the preceding winter to the following summer of 1999 might be one of the main reasons to predict the following summer precipitation pattern in China. So the summer floods of 1999 that occurred in the Yangtze River valley were not expected for these groups at that time. A recent study (Sun and Gao, 2000) indicated that the averages of the SSTA index in the Niño 3 region for the five most serious heavy rainfall years and the five most serious drought years in the mid-lower reaches of the Yangtze River in summer are 0.49 and 0.08, respectively, which seems

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to again support the suggested prediction suggestion above. However, Chen et al. (2001) made some studies on the cause of the 1999 summer floods in the Yangtze River valley and indicated that the intensification of the La Niña event in the preceding winter maybe accounts for the southward excursion of the main rain belt and drought in the north of China. In these two cases, it seems that both the decaying El Niño event and intensifying La Niña event might cause the summer floods in the Yangtze River valley. Why do the very different SSTA cause the almost serious floods in the same areas? It seems that it is necessary to further study the relationships between the summer rainfall in the Yangtze River valley and the SSTA in different ocean regions, especially in the central and eastern equatorial Pacific.

Guo et al. (2002) simulated the observed precipitation pattern in the Yangtze River valley in the summer of 1998 using observed sea surface temperatures (SST) with the IAP/LASG GOALS model. The experiments with the observed SST in different ocean areas and different periods show that the SSTA of the equatorial eastern Pacific, the equatorial western Pacific, the northwest Pacific, and the Indian Ocean all have some positive contributions to the heavy rainfall over the Yangtze River Valley and the positive SSTA in the Indian Ocean are a major contributor to the floods. Can the IAP/LASG GOALS model simulate the 1999 summer heavy rainfall in the Yangtze River valley with the observed SST of 1999? Are there any differences between the relationships of summer floods and SSTA, especially in different ocean regions and different periods, in these two years?

In this paper, we first show the precipitation simulations of the summer of 1999 using the IAP/LASG GOALS model with the observed SST and compare the simulations of the summer precipitation of 1998 and 1999 with different SST. Then we make some sensitivity experiments in different ocean regions and different periods. We want to give a clearer understanding of the relationships between the summer floods in the Yangtze River valley and SSTA in different ocean areas.

2. Model and experimental design

The model and the basic experimental design used in this paper are the same as those in Guo et al. (2002). The model is the atmospheric component of the IAP/LASG GOALS model, which is a nine-layer spectral R15 AGCM (Wu et al., 1996, 1997).

The model is integrated for ten years, forced by the observed climatic SST of 1990–1997. The average of the last five years is regarded as a model climate, referred to as the control run. Then the model is integrated with the observed SST of 1999 from 1 January to 31 August and initialized from five different atmospheric conditions (1 January of the sixth, seventh, eighth, ninth, and tenth model year). We do an ensemble of integration and obtain the seasonal mean results for June, July, and August. We call this basic experiment E00. We will compare the differences between E00 and the control run with observations and verify the model's ability to reproduce the observed climatic anomalies in 1999.

The same as that in Guo et al. (2002), a set of experiments is performed to investigate the impact of SSTA in different oceanic regions on the floods. Four regions are chosen: 01–the tropical eastern Pacific (180°E–82.5°W, 11.3°S–11.3°N), 02–the northwest Pacific (120°–180°E, 20.3°–42.8°N), 03–the tropical western Pacific (120°–150°E, 15.8°S–15.8°N), and 04–the tropical Indian Ocean (52.5°–112.5°E, 20.3°S–20.3°N). We note that the selected four regions in this paper are very close to the corresponding key ocean areas selected via EOF analysis by Zhang and Qian (2001). In each experiment for one region, the observed 1999 SST is used within the selected region and the climatic SST is used out of the region. In this way we are able to set different regional ocean experiments: E01, E02, E03, and E04. Comparing them with each other and with E00, it is easy to discuss the impacts of the SSTA of different oceanic regions on the floods.

In order to investigate the effects of the SSTA of different periods on the floods, another two sets of experiments, F and G, are designed. In the F experiments, the observed 1999 SST is used from January to May and the climatic SST is used for JJA in the model integration. In the G experiments, the climatic SST is used from January to May and the observed 1999 SST is used for JJA. Of course, we can do different period SSTA experiments for different regional oceans.

Table 1 lists all the experiments. All of the experiments in the different oceanic regions and of different periods are the ensemble of five different initial integrations from January to August. The five initial atmospheric conditions in the runs are the same as those in E00. The JJA seasonal mean of precipitation is calculated for each experiment. All figures in the paper show only the differences between the experiments and the control run unless stated otherwise.

3. Simulation of the heavy rainfall in summer 1999

3.1 *Differences in SSTA between 1998 and 1999*

As described above, SSTA is situated in the decaying stage of an El Niño event in 1998 and the features

Table 1. The basic experiment E00 and experiments of different regional oceans and different periods with observed 1999 SST.

The period with observed 1999 SST	All oceans	Tropical eastern Pacific	Northwestern Pacific	Tropical western Pacific	Tropical Indian Ocean
Jan–Aug	E00	E01	E02	E03	E04
Jan–May	F00	F01	F02	F03	F04
Jun–Aug	G00	G01	G02	G03	G04

Table 2. The average SSTA of different regional oceans and different periods (°C).

SSTA Jan–May/JJA	Tropical eastern Pacific (01)	Northwestern Pacific (02)	Tropical western Pacific (03)	Tropical Indian Ocean (04)
1998	0.9/–0.1	0.7/0.9	0.2/0.8	0.7/0.5
1999	–0.7/–0.9	1.0/0.8	0.7/0.2	0.1/–0.1

of the La Niña event remain during 1999 (figure omitted). The maximum differences are located in the equatorial eastern Pacific. The average SSTA from January to May 1998 are still in a very strong El Niño phase with a maximum positive SSTA center of more than 3°C in the equatorial eastern Pacific. However, in January 1999, the negative SSTA below –1.0°C dominate all the equatorial central and eastern Pacific, with the minimum anomalies below –2.5°C, and the cold episode remains during spring and summer. It is interesting to note that the JJA seasonal mean SSTA in 1998 in the Niño 3 and Niño 4 regions are negative with a minimum of less than –2°C. This means that there are negative SSTA in the Niño 3 and Niño 4 regions in the summers of both 1998 and 1999 summer. There are also large differences in the Indian Ocean for 1998 and 1999. From the preceding winter to summer of 1998, the positive SSTA control the main parts of the Indian Ocean, while from April to July 1999 the negative SSTA control the North Indian Ocean. Although the trend of SSTA variation in the tropical western Pacific is opposite in 1998 and 1999, the positive SSTA mainly control this region from winter to summer in these two years. There is no large difference in SSTA in the northwest Pacific for these two years. Table 2 shows the average SSTA from January to May and for summer in 1998 and 1999 in the selected regions.

3.2 *Basic experiment and different period experiments*

Figure 1a shows the simulated precipitation anomalies (%) of JJA 1999 for the basic experiment E00. The simulated anomaly precipitation center in the mid-upper reaches of the Yangtze River valley is more than 100% and there is a negative anomaly precipitation center in the mid-upper reaches of the Yellow River valley. Compared with observation, the simulated heavy rainfall center in the Yangtze River valley is shifted northwestward. Considering the low resolution of the model (which has an equivalent grid spacing of roughly 7.5° (lat)×4.5° (long)), we may still say that the model can reproduce the observed heavy rainfall in the Yangtze River valley with the observed SST with an acceptable error. The main weakness of the simulation is that the simulated drought area in North China is much smaller and weaker. Reviewing the 500-hPa geopotential height field, we find that there are simulated negative anomalies in Mongolia, instead of the observed positive anomaly center there (figure omitted), which leads to the shift of the simulated rainfall area.

Figure 1 also shows the simulated precipitation anomaly charts of JJA 1999 for the experiments F00 and G00 and the corresponding charts of JJA 1998 for E00, F00, G00. Carefully reviewing these figures, we can see that there still exist the obvious differences between the simulations of 1999 and 1998, though there is a very strong precipitation anomaly center in the Yangtze River valley in both experiments E00 of 1999 and 1998. The main difference is that the SSTA in the preceding winter and spring seasons have much more influence on the heavy rainfall of JJA 1999, while the heavy rainfall in the summer of 1998 are more controlled by the simultaneous summertime SSTA.

3.3 *Different regional oceans and different period experiments*

The experiments of SSTA in different oceanic regions and different periods are show in Figs. 2–4.

Firstly, we can see that the simulated precipitation anomaly center in the Yangtze River valley in 1999 E01 (Fig. 2a) has a more correct position than that in 1999 E00 (Fig. 1a). Comparing experiment 1999 E01 with experiments 1999 E03 and 1999 E04 (see Figs. 3a

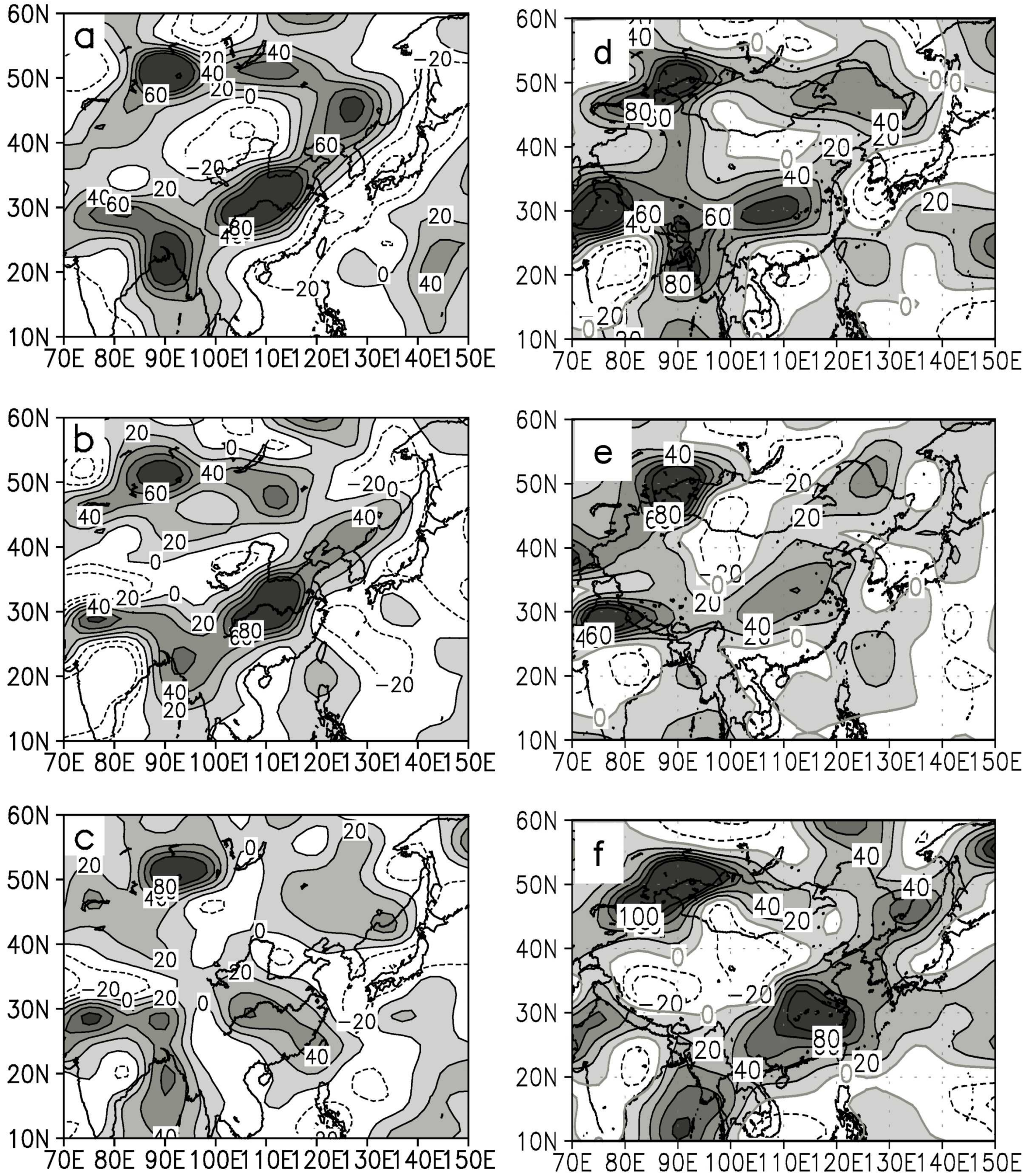

Fig. 1. Simulated precipitation anomalies (%) in JJA 1999 and 1998: (a) in 1999 E00, (b) in 1999 F00, and (c) in 1999 G00; (d) in 1998 E00, (e) in 1998 F00, and (f) in 1998 G00.

and 4a), and with experiment 1999 E02 (figure omitted), the simulated precipitation anomaly center in the Yangtze River valley in 1999 E01 is much stronger than those of E02, E03, and E04 of 1999. This means that the SSTA in the tropical eastern Pacific have a much greater contribution to the heavy rainfall in the Yangtze River valley in the 1999 simulation than the SSTA of other regions, which is different from the 1998 simulation: there the SSTA in the tropical Indian Ocean have the largest contribution to the heavy rainfall in the Yangtze River valley. Secondly, it is interesting to note that the simulated precipitation anomaly center in the Yangtze River valley in 1999 E01 (Fig. 2a) is much stronger than those in F01 and G01 of 1999 (Figs. 2b, c). This means that the SSTA from the preceding winter to summer of 1999 in the tropical eastern Pacific all have an important influence on the heavy rainfall in the Yangtze River valley, which is also different from the 1998 simulation: there the heavy rainfall in the summer is more controlled by the simultaneous summertime SSTA (Figs. 2d–f). However, in the simulations of 1998 and 1999, at least there

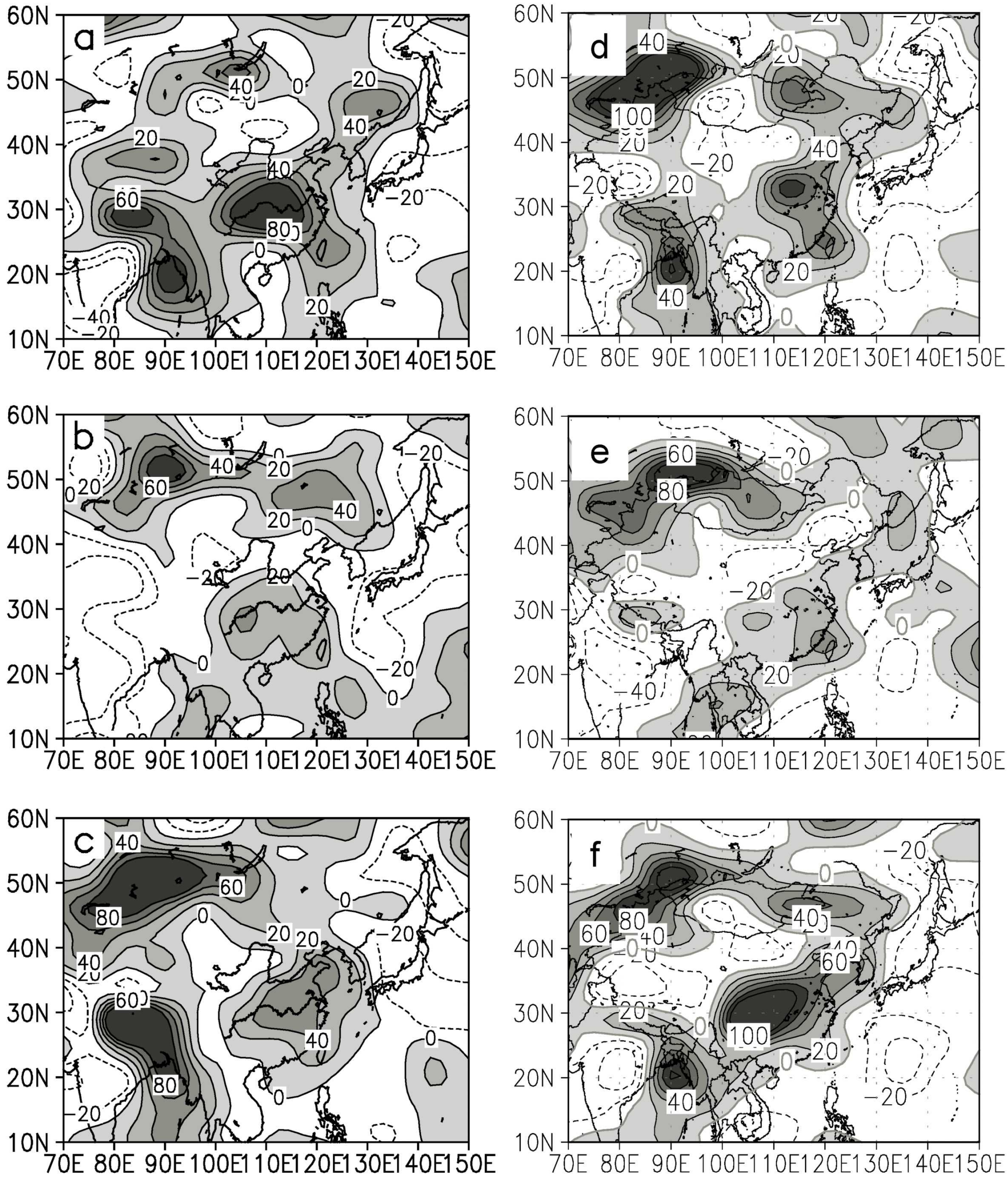

Fig. 2. Same as in Fig. 1, but for region 01.

is the common point that the negative SSTA in the tropical eastern Pacific, especially in the summer season, are a very important factor to the heavy rainfall in the Yangtze River valley.

In Fig. 3 the largest differences between the experiments for region 03 in 1999 and 1998 exist in Figs. 3c and 3f. There is a very strong precipitation anomaly center in the Yangtze River valley simulated in 1999 G03 (Fig. 3c). However, in the simulation of 1998 G03, a weaker precipitation anomaly center is located in the north of the Yangtze River valley (Fig. 3f). Taking notice of the differences between the SSTA of 1999 and 1998, it seems that weak positive SSTA in the tropical western Pacific in summer are beneficial to the heavy rainfall in the Yangtze River valley, while strong positive SSTA in the tropical western Pacific in summertime lead the rain belt to move northward. Comparing the 1999 E03 and 1999 G03 experiments, we can see that the heavy rainfall in the summer is controlled not only by the simultaneous summertime SSTA in the tropical western Pacific, but also by the SSTA there from the preceding winter to spring.

There are obvious differences between the 1998 and

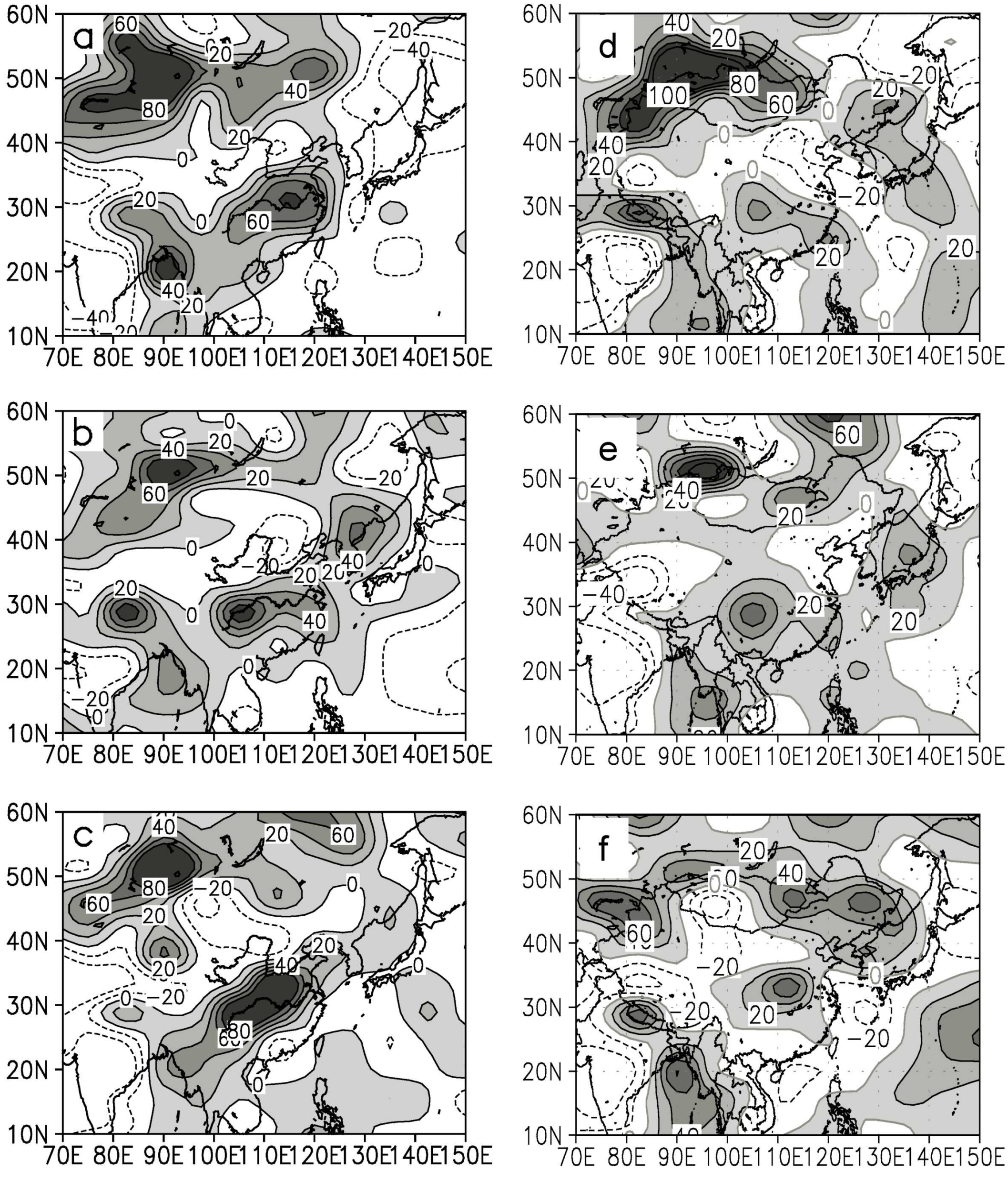

Fig. 3. Same as in Fig. 1, but for region 03.

1999 simulations for the experiments of region 04 (Fig. 4). As mentioned before, the floods in the Yangtze River valley in the summer of 1998 are mainly controlled by the simultaneous summertime SSTA in the tropical Indian Ocean (Figs. 4d–f). However, there is a much weaker precipitation anomaly center in 1999 E04 than in 1998 E04. The largest differences between the 1999 and 1998 simulations also exist in the G04 experiments of the two years (Figs. 4c, f). In consideration of the differences in SSTA in the tropical Indian Ocean between the summers of 1998 and 1999, we may draw the same conclusion as in Guo et al. (2002): warmer SST in the Indian Ocean are beneficial to heavy rainfall over the Yangtze River valley, while lower SST may move the rain belt northward.

As to the experiments of region 02, there are no large differences between the 1999 and 1998 simulations (figures omitted).

4. Sensitivity experiments

In the simulation experiments of 1998 and 1999 we can find the different influences of the SSTA of different regional oceans and different periods on the heavy

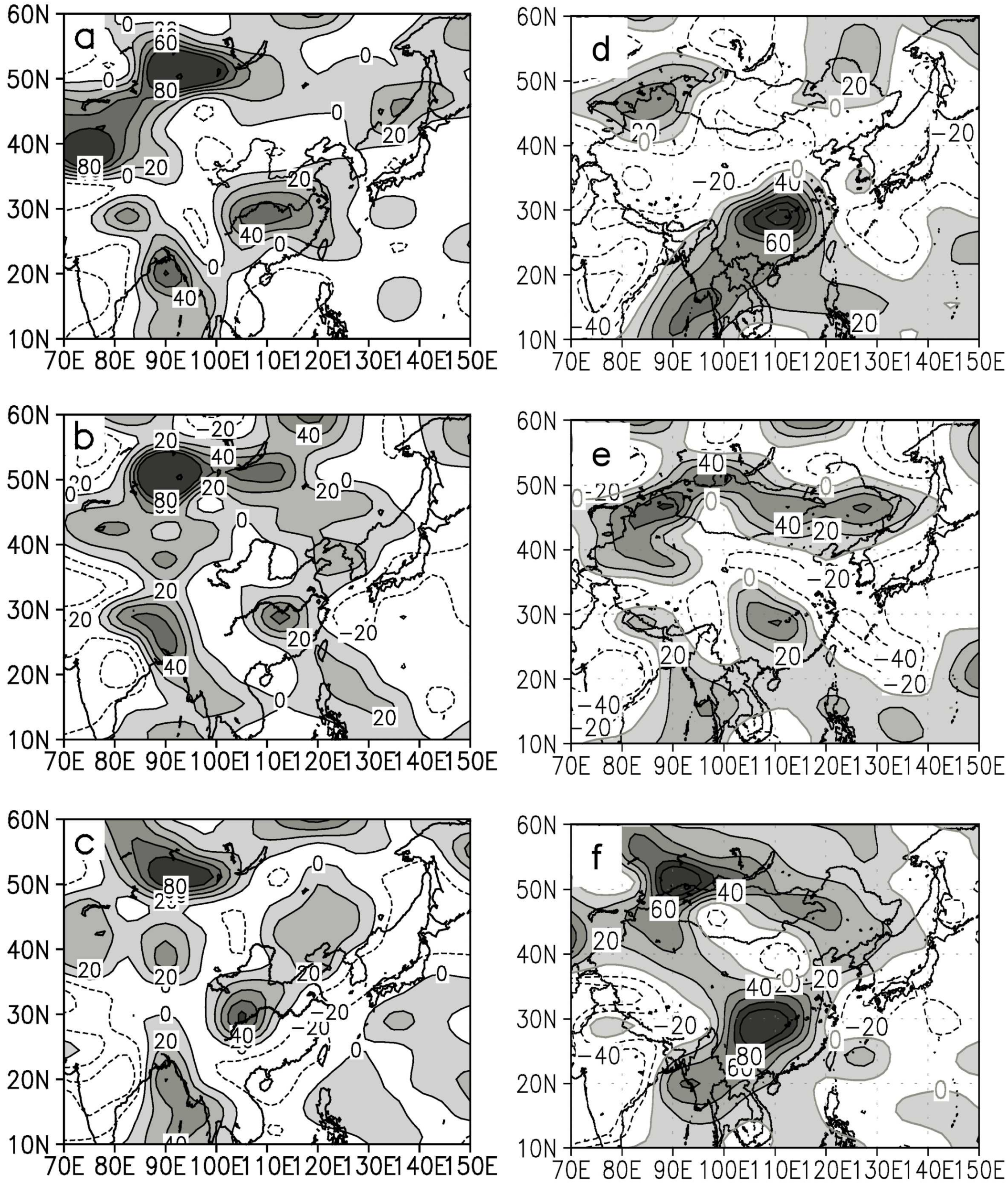

Fig. 4. Same as in Fig. 1, but for region 04.

Table 3. The average SSTA of different regional oceans and different periods (°C) in the sensitivity experiments.

SSTA Jan–May/JJA	Tropical eastern Pacific (01)	Northwestern Pacific (02)	Tropical western Pacific (03)	Tropical Indian Ocean (04)
Sensitivity experiment	0.7/1.0	–1.0/–0.8	0.7/–0.5	–0.7/–0.5

rainfalls over the Yangtze River valley in the summer. We note that the SSTA of these two years are only related to the anomaly situations occurring in a decaying El Niño and a La Niña event. What will happen in the other situations of SSTA? In order to answer this question, we design a set of sensitivity experiments (ST). The SSTA of different regional oceans and different periods used in the sensitivity experiments are given

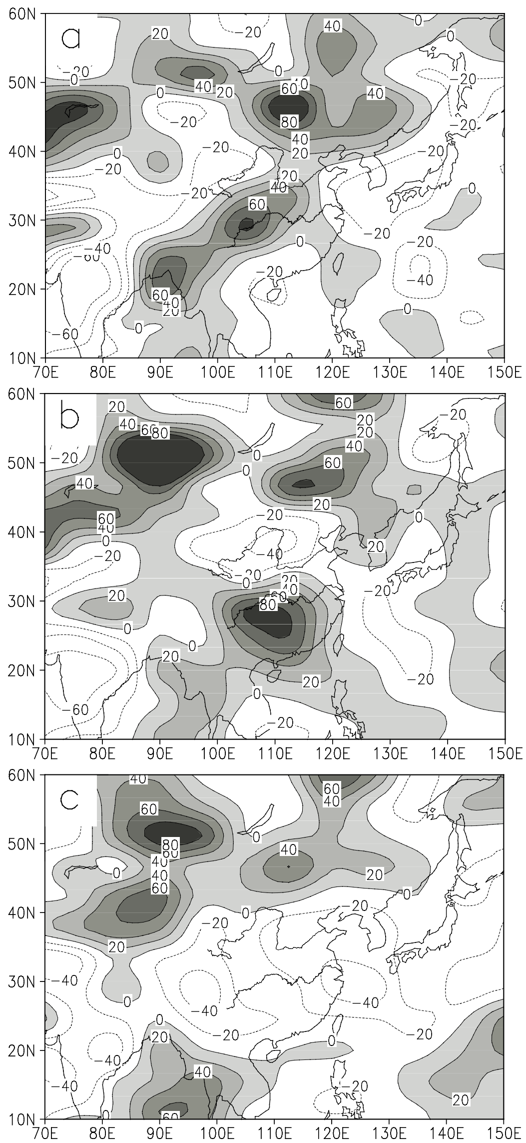

Fig. 5. Simulated precipitation anomalies (%) in JJA in the sensitivity experiment for region 01: (a) in STE01, (b) in STF01, and (c) in STG01.

in Table 3. We want to further investigate the influences of the negative SSTA in the northwest Pacific, tropical western Pacific, and tropical Indian Ocean, and the positive SSTA in tropical eastern Pacific on the heavy rainfall over the Yangtze River valley in summer.

The results of the sensitivity experiments are shown in Figs. 5–8. In the sensitivity experiments for the tropical eastern Pacific we can find that the positive SSTA from winter to summer can also cause a stronger precipitation anomaly in the upper reaches of the Yangtze River valley in summer (Fig. 5a). This means that there indeed exists the possibility for heavy rainfall to occur in the Yangtze River valley in a developing El Niño event. We further note that only the positive SSTA from the preceding winter to spring have the key contribution to the heavy rainfall (Fig. 5b), which the positive SSTA in summer play an opposing role in the heavy rainfall in the Yangtze River valley in summer (Fig. 5c).

Comparing the sensitivity experiments for the tropical western Pacific (see Fig. 6) with the corresponding simulations of 1999 and 1998 (Fig. 3), in general, there are no obvious differences between the sensitivity experiments and the 1999 experiments for region 03, but we can see that a difference exits between the experiments of STG03 (Fig. 6c) and 1998 G03 (Fig. 3f). From these two figures it is easy to arrive at a conclusion that negative SSTA in the tropical western Pacific in summer are also a factor contributing to the heavy rainfall in the Yangtze River valley. Comparing Fig. 6a with 6b and 6c, it seems that the heavy rainfall in the Yangtze River valley in experiment STE03 (Fig. 6a) is more controlled by the negative SSTA in the tropical western Pacific in summer than the SSTA of the preceding winter and spring, which is different from the corresponding experiments of 1999 in region 03 (see Figs. 3a–c).

There are very large differences between the experiments of STE04 (Fig. 7a) and 1998 E04 (Fig. 4d). In experiment STE04, there is much less precipitation in most parts of eastern China, especially in the mid-lower reaches of the Yangtze River valley and the lower reaches of the Yellow River valley. Among all of the simulated experiments of 1998, 1999, and the sensitivity experiments, STE04 shows the most drought in the Yangtze River valley. We also note that there are obvious differences between STE04 and STF04 and STG04 (Figs. 7b, 7c). This means that the negative SSTA from the preceding winter and spring to summer in the tropical Indian Ocean all contribute to the drought in the Yangtze River valley in summer. Comparing STF04 and STG04 with 1998 F04 and 1998 G04 (Figs. 4e, 4f), it can be seen that the negative SSTA from the preceding winter and spring in the tropical Indian Ocean are beneficial to move the summer rain belt northward. Comparing STF04 with experiment XG04 of 1998 (see Fig. 9a, Guo et al., 2002), it seems that the stronger the negative SSTA are, the more northward the rain belt shifts. We note that the negative SSTA used in the experiment XG04 of 1998 are about double the SSTA in experiment STG04.

As for the sensitivity experiments for region 02 (figure omitted), it is very strange that there are no obvious differences between the simulated precipitation anomalies in JJA of STE02 and 1999 E02 in China to a 99% confidence level, even though the SSTA in re-

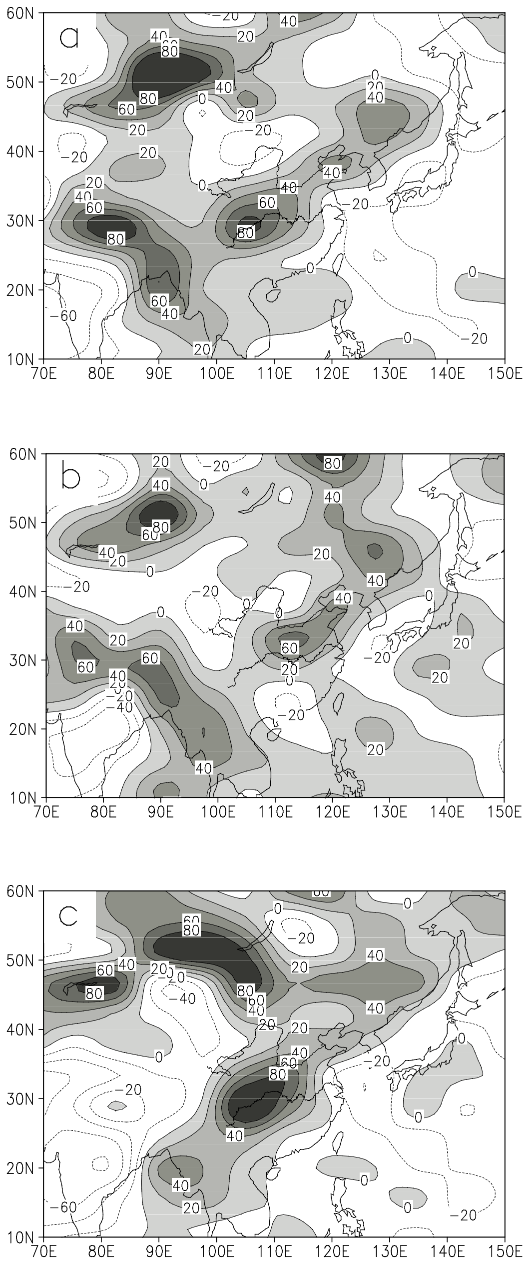

Fig. 6. Same as in Fig.5, but for region 03: (a) in STE03, (b) in STF03, and (c) in STG03.

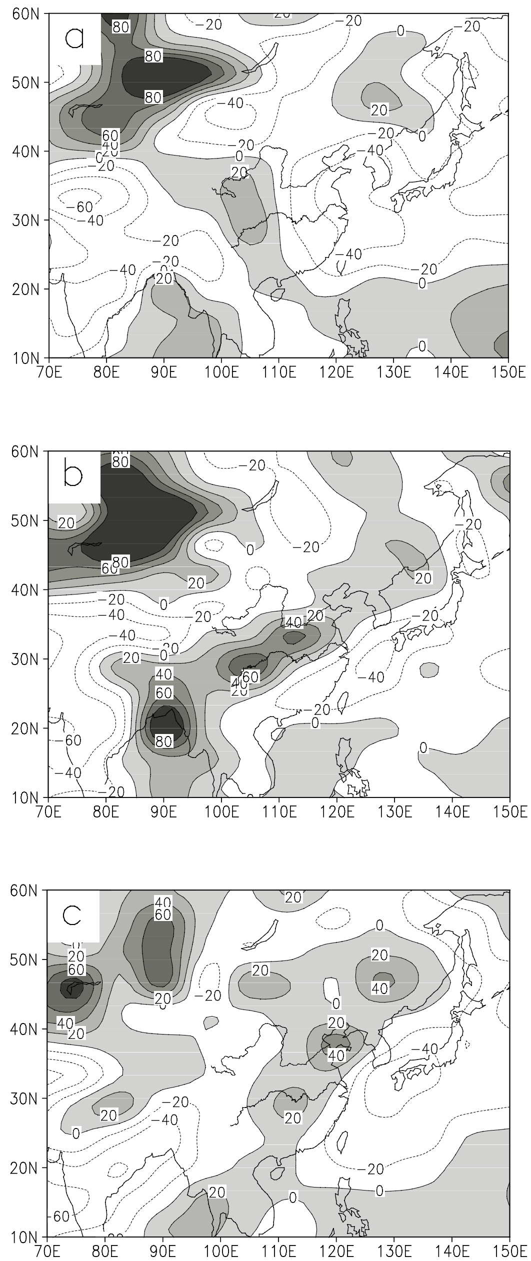

Fig. 7. Same as in Fig.5, but for region 04: (a) in STE04, (b) in STF04, and (c) in STG04.

gion 02 used in these two experiments are opposite. The above results are different from some recent diagnostic studies which indicated that there is a positive correlation between the SST of the Kuroshio area and the summer rainfall over the Yangtze River valley (Li and Ding, 2002; Chen and Wu, 1998). How do we explain the simulated results? One reason may be that the selected key ocean areas are different from each other. Region 02 is much larger than the so-called Kuroshio areas used in Li and Ding (2002) and Chen and Wu (1998). It is interesting to note that Zhang and Qian (2001) indicated that the variation of SSTA in the northwest Pacific has a positive correlation with the precipitation anomalies over the Yangtze River valley only in autumn; there the key ocean area is close to region 02 in the paper. It seems that we need a finer model to study the effect of SSTA in this region.

5. Summary and discussion

The IAP/LASG GOALS model is able to simulate the observed precipitation pattern in East China in the summer of 1998, especially the heavy rainfall over the Yangtze River valley using the observed SST in 1998. The model is also able to simulate the heavy rainfall over the Yangtze River valley in the summer of 1999 using the observed SST of 1999, which is very different from the SST in 1998. This means that the model has a good ability to simulate the heavy rainfall over the Yangtze River valley in the summer, which provides a good basis to study the relationships between the heavy rainfall over the Yangtze River valley and the SSTA of different regional oceans and different periods.

According to the analyses of the simulation experiments of 1998 and 1999 and the sensitivity experiments, we can draw the following conclusions.

(1) The positive SSTA in the tropical Indian Ocean, especially the SSTA in summertime, are a major contributor to the heavy rainfall over the Yangtze River valley in summer, and the negative SSTA in the tropical Indian Ocean move the summer rain belt northward. The negative SSTA from the preceding winter and spring to summer in the tropical Indian Ocean will lead to a drought in the Yangtze River valley in summer. The simulations of this paper show that the very strong positive SSTA in the tropical Indian Ocean are the first important factor in the heavy rainfall over the Yangtze River valley in the summer of 1998. So we have good reason to say that the SSTA in the tropical Indian Ocean may be a very important index to predict flooding and drought over the Yangtze River valley in summer.

(2) The SSTA in the tropical eastern Pacific, which are the second most important factor in the 1998 flooding and the first most important factor in the 1999 flooding, are another major factor in the heavy rainfall in the Yangtze River valley in summer. The simulations show that the relationships between the SSTA in the tropical eastern Pacific and the heavy rainfall in the Yangtze River valley are very complicated. The heavy rainfall in the Yangtze River valley can occur in both a decaying and intensifying El Niño event and can also occur in a La Niña event. The observations seem to support the above conclusion, e.g., the floods of 1983 and 1998 occur in a decaying El Niño event, and the floods of 1991 occur in an intensifying El Niño event, and the floods of 1999 occur in a La Niña event. However, the simulations show that the different SSTA of different periods in the above three cases play different parts. In a decaying El Niño event, the negative SSTA in the tropical eastern Pacific in summer are a major factor in the heavy rainfall in the Yangtze River valley. In an intensifying El Niño event, the positive SSTA of the preceding winter and spring in the tropical eastern Pacific play a key part in the heavy rainfall. In a La Niña event, the negative SSTA from the preceding winter and spring to summer in the tropical eastern Pacific all have an influence on the heavy rainfall in the Yangtze River valley in summer.

(3) The negative or weak positive SSTA in the tropical western Pacific in summer are beneficial to the heavy rainfall in the Yangtze River valley, while the strong positive SSTA in the tropical western Pacific move the rain belt northward. It is interesting to note that this conclusion from the numerical simulation is consistent with some diagnostic studies (Huang and Wu, 1989; Huang and Sun, 1994), but not consistent with others (e.g., Sun and Gao, 2000). Perhaps this means that the SSTA in the tropical western Pacific are one of the factors to influence the heavy rainfall in the Yangtze River valley, but are not the most important factor, which is supported by the simulations in this paper.

It is necessary to perform more numerical simulations for other flood and drought years in the Yangtze River valley to verify the above conclusions. It is also necessary to study the process and mechanism of the influence of the SSTA of the different oceanic regions and different periods on the East Asian climate.

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