NUMERICAL EXPERIMENTS OF THE EFFECTS OF SEA SURFACE TEMPERATURE ANOMALIES OVER THE PACIFIC ON PRECIPITATION IN 1991 *

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ABSTRACT

A zonal domain, primitive equation model is used in this paper to study the influences of the main sea surface temperature anomaly (SSTA) areas over the Pacific on precipitation in 1991. Some numerical experiments are made and the mechanisms of the influences are discussed. The results show that the influences of the SSTA are mainly confined within the tropical and the subtropical regions. The direct effect of the SSTA is to change the exchanges of the sensible heat and the water vapour between the air and the sea, through the consequent changes of temperature and the flow fields and the feedback process of condensation, the SSTA finally affects precipitation.

Key words: sea surface temperature anomaly (SSTA), changes in precipitation, numerical modeling

I. INTRODUCTION

The importance of the effects of SSTA on the regional and the global climate has been proved by many observational and diagnostic studies (Zhang et al. 1991; Yuan et al. 1991). In order to depict the mechanisms of such effects, many investigators conducted numerical experiments. Recently, Rowell et al. (1989; 1992) used the 11–layer UK GCM and the real SSTA to simulate the relationships of the SSTA with the precipitation changes in Sahel and obtained some meaningful results.

In the summer monsoon period of 1991, the precipitation in the Changjiang River and the Huaihe River valleys was highly above the normal, while it was below the normal in South China. Over Southeast Asia, the South Asia and even over some places of North America there are also apparent anomalies in precipitation according to the information and data from climate and Data Division of National Meteorological Centre of China.

Wang et al. (1995) have conducted some numerical experiments to study the causes of the floods taking place in July, 1991 over the Changjiang River and the Huaihe River valleys in

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China. In their experiments they did not adopt regular areas of SSTA. To the contrary, they constructed the areas and the values of the SSTA used in their model according to the real observed distribution of the SSTA over the western Pacific in that July. Their results showed that a slender and small negative SSTA area along the coast of the western Pacific was an important factor for the floods, while the single effect of the larger positive SSTA area over the western Pacific made the precipitation decreasing.

In this paper, the more realistic distribution of the SSTA over the Pacific is used to further study the precipitation anomalies over East China in July, 1991. At the same time, the influences of the Pacific SSTA on the changes of precipitation over Southeast Asia, South Asia and other regions with evident changes of precipitation are also discussed. The mechanisms of the SSTA effects are analysed as well.

II. THE MODEL AND THE EXPERIMENTAL SCHEMES

The model we used is a P–σ incorporated coordinate system primitive equation model with 6 layers in vertical. There are 5 layers in the atmosphere, the lowest layer with thickness of 50 hPa taken as the atmospheric boundary layer. The sixth layer is in soil or water with a thickness of 40 cm or 50 m, respectively, which is adopted to compute the temperatures at the ground surface, in the soil and at the sea surface. The dynamic frame and the model physics of the atmospheric model as well as soil model can refer to Qian's paper (1985).

The model domain covers a zonal area between 30°S and 70°N. The spherical network system is used with a grid size of 5 lat. × 5 long.; the time step is 15 min. and the time integration scheme is the one hour Euler backward and 5 hours leapfrog interactive method.

By use of the above described model two numerical experiments are made. In the first experiment the initial fields are the multiyearly averaged July monthly zonal mean geopotential height fields. The sea surface temperature (SST) field is the mean observational one of July. The initial solar declination is set on June 25. The time integration is up to 35 d and the July mean climate state is gotten by averaging the last 30 d results added together in every hour. The second experiment is just the same as the first one but with the difference that, from the sixth model day, the mean SST field, which is changing as the time integration goes, is changed to a modified SST field by overlapping the SSTA similar to that of July, 1991 over the Pacific to the mean SST field. For the convenience of description, the two experiments are designated by CNL and STA , respectively, and their designations and specifications are listed in Table 1.

Table 1. Designations and Specifications of Two Experiments

Designations	Experiments	Initial meteorological fields	Initial SST fields	Integration time (d)
CNL	control exp.	multiyearly averaged July zonal mean	multiyearly July monthly mean	35
STA	anomaly exp.	same	same but adding SSTA	35

As mentioned above, the SSTAs in STA experiment are given by reference to the realistic SSTA field in July, 1991. Figures 1a and 1b are the realistic SSTA field in July, 1991 and the

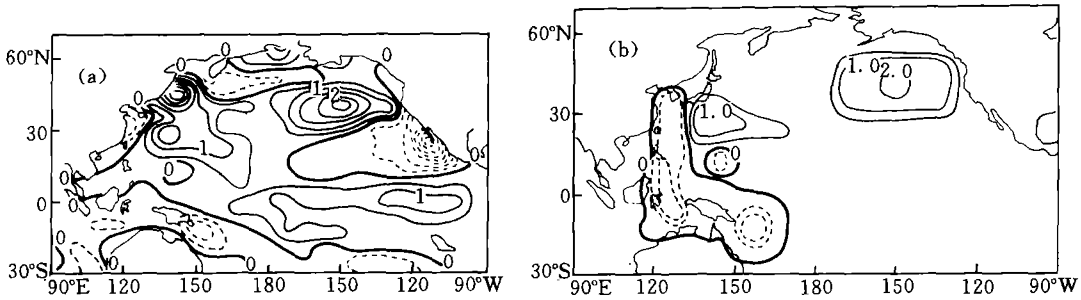

Fig. 1. The realistic SSTA in July, 1991 (a) and the model SSTA in STA experiment (b).

model SSTA field, respectively. It can be seen that the large positive area of SSTA in the northern Pacific, the large positive SSTA area with smaller values in the western Pacific and the negative SSTA area with a very irregular shape in the equatorial western Pacific in Fig. 1a are all reflected in Fig.1b. There are still some areas of SSTA in Fig.1a not shown in Fig.1b. Such a treatment in Fig.1b is due to the fact that those SSTA areas may not have essential influences on precipitations of July 1991.

It may also be seen from Figs.1a and 1b that the SSTA field used in STA experiment has not only the similar shape to the realistic one but also the same values.

III. THE EFFECT OF SSTA ON PRECIPITATION ANOMALY

The authors have pointed out from the previous experiments that if there are only the positive SSTA areas in the western Pacific, the precipitation over the Changjiang River and the Huaihe River valleys of China will decrease, and only when negative SSTA areas exist on the west side of the positive SSTA areas and to the South, does the precipitation over the valleys increase. The mechanism of such different effects was also discussed (see Wang et al. 1995). In this study the areas and the values of the SSTA are completely the same as those in the previous study over the western Pacific. The difference is that the positive SSTA with vast area over the northern Pacific is included in this study, too. It makes the SSTA field more similar to the observational SSTA in July, 1991. If the precipitation anomalies over the Changjiang River and the Huaihe River valleys and other regions in the world, especially over the regions surrounding the Pacific Ocean are closely related to the SSTA over the Pacific Ocean, then generally speaking, the simulated anomalies of precipitation should be somewhat improved in STA experiment in this study.

Figure 2a is the distribution of the percentage of precipitation deviations in China in July, 1991. Figure 2b is the differences of precipitation between STA and CNL experiments (STA minus CNL). From Fig. 2a it can be seen that the positive deviations of precipitation are located over the Changjiang River and the Huaihe River valleys, the north part of the North China and Northeast China, while negative deviations over South China and the south part of East China. Another area with positive deviations of precipitation is located over the east part of the Qinghai–Xizang Plateau, while surrounding this positive area there are areas with negative deviations of precipitation. By comparison of Fig. 2b and Fig. 2a it is found that they are basically in agreement with each other in general patterns, especially, on the east and the west sides of the

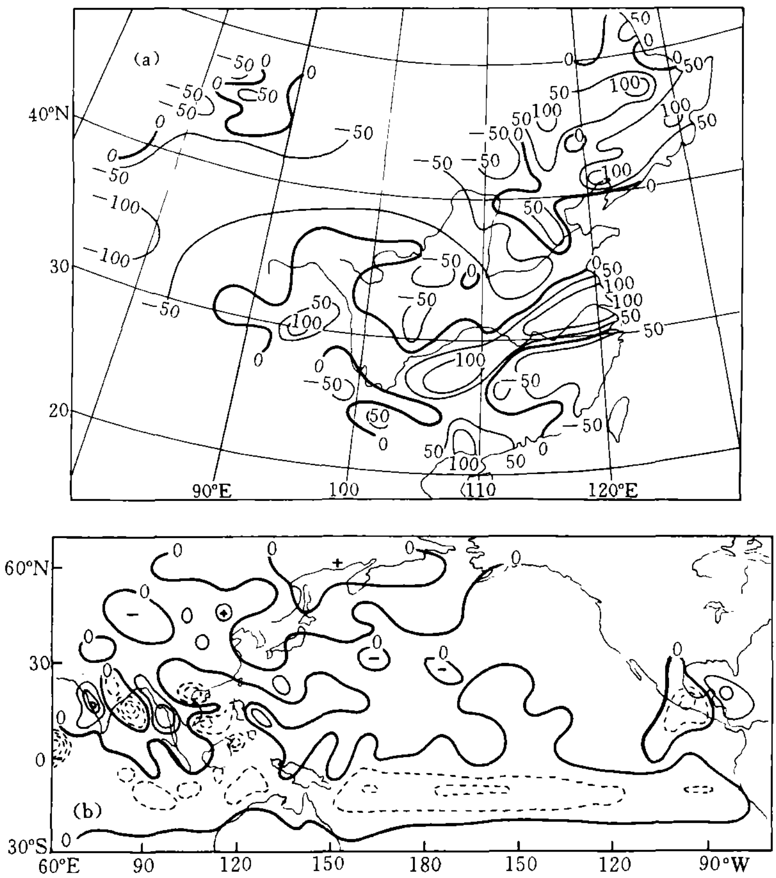

Fig. 2. The deviation percentage of precipitation in China in July, 1991 (a) and the simulated differences of precipitation (mm / d) between STA and CNL (b).

plateau where the differences of precipitation are similar to the observations. However, in the simulation map the north boundaries of the negative differences over South China and the south part of East China shift somewhat southward; the values of the positive deviations of precipitation over the Changjiang River and Huaihe River valleys and the Northeast China are less; the narrow and long area with negative deviations over the Huanghe River valley is not produced by the simulation. By comparison with the results of Wang's previous simulation (Wang et al. 1995) it is found that over most areas of China, the differences of precipitation are similar; however the simulations over the Qinghai–Xizang Plateau and its vicinities are better improved.

From Fig. 2b we can again find that over the tropical region of the Northern Hemisphere, the precipitation changes due to the SSTA in the Pacific are most evident, especially, near the coast lines. At the mid and the high latitudes north of 30°N the changes are not evident. So the tropical regions are the most sensitive regions in response to SSTA. The case is just the the same over the Pacific, for example, the precipitation changes are more evident over the equatorial eastern Pacific and the tropical western Pacific, though the SSTA area over the North Pacific is largest and most intense and the precipitation changes there are small. Over the Pacific there is not very good correlation between the precipitation changes and the SSTA, though over the western Pacific the positive (negative) SSTA areas are roughly corresponding with the positive (negative) deviations of precipitation and the spatial scales of the precipitation anomalies are smaller than that of the SSTA. Therefore, the responses of the precipitation to the SSTA are very complex.

Duo to the lack of the data of the precipitation changes in the other regions of the model domain beyond China, what we can only do is to compare the modeled results with the precipitation anomalies listed in "the Climate Monitoring Bulletin" of July, 1991 (published by the Climate Data Division of National Meteorological Centre of China). From Fig. 2b it can be seen that the precipitation over the north and east parts of India decreased, while that over the west part increased, which are in agreement with the Bulletin descriptions. Over the Gulf of Mexico the precipitation also increased and in agreement with the Bulletin. Compared with the simulation in Wang's previous paper (1995), it is found that the precipitation changes over India are evidently better simulated, while that over the Gulf of Mexico is basically the same.

From the above discussions we can conclude that the more realistic distribution of the SSTA indeed may obtain good simulation results in better agreement with observations. After a detailed comparison with Wang's previous simulation (1995) we find that the positive SSTAs over the northern Pacific have no direct evident influences on the precipitation changes in the very area and surrounding areas of the Pacific Ocean though they do affect the precipitation over the Indian Ocean and its coastal regions. It seems that such effects are realized by the teleconnection mechanism in the inner atmosphere.

IV. THE MECHANISM OF THE SSTA EFFECTS

In order to clarify the mechanism of the SSTA effects on precipitation, we analysed the differences of precipitation and the vertical motions at the 300 hPa level between the two experiments. We found astonishing similarity between the two kinds of differences and close relationship between the vertical motions at the 300 hPa level and the cumulus convective rainfall. Taking into account that the precipitation changes mostly appear in the tropical regions that we have pointed out in the previous section, we may conclude that the SSTA influences the precipitation through their effects on the convective activities.

Figure 3a is the differences of the vertical motions (10^{-1}mm / s) at the 300 hPa level between the STA and the CNL experiments. By comparison of Fig. 3a and Fig. 2b, it is found that the areas with increasing vertical motions are corresponding to the areas with increasing precipitation and vice versa. For instance, there is a couple of positive and negative deviation areas of precipitation in the border area between North America and South America, and correspondingly in Fig. 3a there is a couple of positive and negative difference areas of vertical motions just in that area. In China, India and Southeast Asia the two kinds of differences match each other very well, too.

According to the continuity equation of the dynamic equation set, the vertical motions are related to the divergence or convergence fields of the horizontal flows. By using the continuity equation in the pressure coordinate system and assuming $\mathbf{V}_1$ and $\mathbf{V}_2$ be the horizontal velocities and ω_1 and ω_2 the vertical components of velocity in the pressure coordinate of the CNL and the STA experiments, respectively, then we have

$$\Delta\omega = \omega_1 - \omega_2 = -\int_0^P \nabla \cdot (\mathbf{V}_1 - \mathbf{V}_2) dP, \tag{1}$$

where $\Delta\omega$ is the difference of the vertical velocities between the two experiments. The above expression can be rewritten as

$$\Delta\omega = -\int_0^P \nabla \cdot \mathbf{V}' dP, \tag{2}$$

where the difference $\mathbf{V}_1 - \mathbf{V}_2$ is represented by the differential vector $\mathbf{V}'$. In both Eqs. (1) and (2), the assumption of $\omega = 0$ at $p = 0$ is used. From Eq. (2), it is seen that when there is divergence of $\mathbf{V}'$ in the upper atmosphere and convergence in the lower atmosphere, and the convergence is less than the divergence, then $\Delta\omega < 0$, that is, the vertical motion will increase.

Figures 3b and 3c are the differential wind vectors between STA and CNL in the boundary layer and at the 300 hPa level respectively. From them we can see that there is an evident cyclonically differential circulation over the positive SSTA area in the Pacific Ocean at the lower levels of the atmosphere because of the direct effects of the SSTA and the flow has convergence. Over the negative SSTA area, there is an anticyclonically differential circulation; however, it is not strong due to the smaller area and the irregularity of the negative SSTA and the divergence is weak as well. At the upper levels of the atmosphere, the anticyclonically differential circulation corresponding to the positive SSTA over the northern Pacific has no centre, but combines with the anticyclonically differential circulation over the western Pacific to form a whole body. Therefore, the response of the lower atmosphere to the SSTA is more evident than that of the upper atmosphere, and the scale of the response is equivalent to the scale of the SSTA field. The circulation changes over the other regions in Figs. 3b and 3c can be considered as those induced by the changes of circulations over the Pacific regions. By comparison of Figs. 3a, 3b and 3c we find that the changing centres of the vertical motions are usually located over the well matched areas of the upper level divergence and the lower level convergence.

How do the SSTA fields influence the upper and the lower level horizontal flow fields? We have pointed out that the most direct effect of the SST field is to change the sensible and the latent heat fluxes at the sea surface. Figure 3d is the differences of the sensible heating rates (K / d) in the boundary layer of the STA experiment minus the CNL. It is found from the map that the positive and the negative SSTA areas (see Fig. 1b) are corresponding to the positive and negative differences of sensible heating rates. The changes of the sensible heating rates over the equatorial Pacific are induced and the changes over the Asian continent and the Mid Africa are also induced, because the atmosphere is a continuous medium and changes in certain areas can not be confined locally to those areas themselves.

From the comparison of Fig. 3d and Fig. 3b, it is seen that in the areas with increasing sensible heating rates, the low level temperature rises up; the pressure drops down; the low pressure circulation forms and vice versa. Changes of the upper level flow fields (Fig. 3c) are mainly the induced changes; therefore, they have no direct correspondent relationships with the SSTA.

The SSTAs change not only the sensible heat flux but also the latent heat flux. The changes of the sensible heat flux can directly alter the temperatures of the atmospheric boundary layer. Analysis of the temperature differences between the two experiments at the 850 hPa level shows that there are usually positive differences of temperature over the regions with positive SSTA and vice versa (figures omitted). The latent heat flux can not directly change the atmospheric

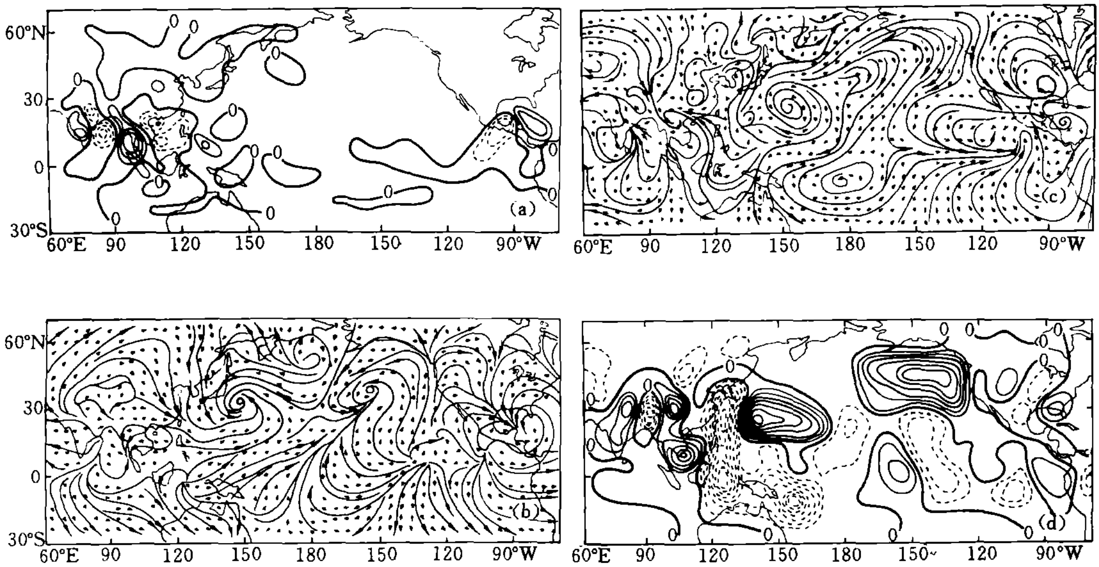

Fig. 3. The differences between STA and CNL (STA−CNL) of (a) vertical motions (10^{-1}mm / s) at the 300 hPa level, (b) wind vectors in the boundary layer, (c) wind vectors at the 300 hPa level and (d) sensible heating rates (K / d) in the boundary layer.

temperature, can heat the air only when it is transformed into the heat energy through the atmospheric vertical motion and the condensation. Therefore, it is reasonable to consider the sensible heat as the active quantity and the latent heat as the passive one. However, when condensation takes place, the latent heat is transformed into heat energy and influences the atmosphere, there is interactive feedback processes in the atmosphere.

From the above discussion, it is seen that over the positive (negative) SSTA areas the sensible heat fluxes increase (decrease), which induces the lower level temperatures to rise up (drop down), the convergence (divergence) and the low (high) pressure circulation to be enhanced; consequently, the atmospheric vertical motions and the vertical stabilities change. Over the positive SSTA areas the latent heat fluxes increase and the moisture from the ocean to the air increases. The moisture is transferred to the surrounding areas and the upper atmosphere by horizontal and vertical motions. Under certain suitable conditions, condensation takes place and heat is released to heat the atmosphere. Then the state of atmospheric circulation is changed and so is the characteristic of the distribution of precipitation. Therefore, the SSTAs can affect the the changes of precipitation in the continental and the farther areas through the changes of atmospheric circulation state. This is just the mechanism of the effects of SST.

V. CONCLUSIONS

Numerical experiments in this study indicate that the SSTAs over the Pacific Ocean do have close relations with the anomalies of precipitation over China, South Asia, Southeast Asia, America and so on. However, the main areas affected by the SSTA are located in the tropical and the subtropical regions. The precipitation at mid and high latitudes is influenced very little by the SSTA. Over the western Pacific, the positive and the negative SSTA areas fairly match the areas with the positive and the negative differences of precipitation, respectively; however, over the northern Pacific there is no evident correlation. The SSTA first changes the sensible heating rates and the moistening rates in the low atmosphere, therefore; the temperature and the moisture of the low atmosphere are altered; then the horizontal and the vertical motions of atmosphere change and so do the convective activities and the precipitation due to cumulus condensation. After condensation takes place, the released latent heat can be used to heat the atmosphere and then the horizontal and the vertical motions, and the precipitation distribution are further changed, thus forms a complex mechanism of feedback.

Therefore, the areas and the values of the SSTA are not required to be very large. The changes of the sensible heat are not large either; however, they are the trigger mechanism. The small values of the changes of sensible heat can induce the changes of latent heat with larger areas and values, in the meantime, make the atmospheric circulations change anomalously, and the anomaly of atmospheric circulations will induce the changes of precipitation, which dominate the changes of the atmospheric heating fields. Then a complex mechanism of interaction forms between the anomalies of the atmospheric heating field and the circulation.

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