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Anomalies in the Tropics Associated with the Heavy Rainfall in East Asia during the Summer of 1998①

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ABSTRACT

The summer of 1998 was characterised by a severe flood in East Asia. The possible linkages were examined among the anomalies in the tropics that may be associated with the severe flood. The anomalies of 1998 are obtained by removing the climatology, which is the average of the ECMWF (European Centre for Medium Range Weather Forecasts) Re-Analysis (ERA) data over 15 years from 1979 to 1993, from the corresponding fields of 1998, which are obtained from the ECMWF operational analyses.

In comparison to the results of Nitta (1990), it was found that there are considerable similarities in the atmospheric circulation anomalies between the summers of 1998 and 1988, in the tropics as well as in middle-high latitudes. It was shown that the atmospheric convection is slightly suppressed over the tropical western Pacific. In general, the suppressed convection corresponds to a negative anomaly of SST in the warm pool region. In the summers of 1998 and 1988, however, there are positive anomalies of SSTs in the tropical western Pacific, corresponding to the suppressed convection over there. This slightly suppressed convection may not provide a viable forcing mechanism for the severe flood in East Asia. It was postulated that the zonal wind anomalies in the tropics, in addition to the atmospheric convection over the tropical western Pacific, influence the position and intensity of the North Pacific subtropical high.

In both summers of 1998 and 1988, while the stronger convection occurs over the warmer tropical Indian Ocean, the suppressed convection corresponds to the positive anomalies of SSTs in the tropical western Pacific. A possible explanation was given for the broken relationship between SSTs and OLR, (Outgoing Longwave Radiation) by analyzing the large-scale atmospheric circulation anomalies in the tropics.

The heat fluxes at the surface in the warm pool of the tropical western Pacific and tropical Indian Ocean were also examined by using the ERA-15 data. To avoid the inconsistency between the ERA-15 and the operational analyses, the anomalies of the heat fluxes at the surface in the warm pool region in the summer of 1988, instead of the summer of 1998, were examined. The anomalous latent heat flux and the net solar radiation flux are the main reason for the positive anomalies of SSTs in the tropical Indian Ocean and in the tropical western Pacific, respectively. The suppressed convection over the tropical western Pacific allows more solar radiation fluxes downward at the surface, which would increase the SSTs.

Key words: Anomalies in the tropics, Comparison between 1998 and 1988, Surface heat flux

1. Introduction

In the summer of 1998, the Yangtze River basin, including Nenjiang River Valley in Northeast China suffered a severe large-scale flood only next to that in the summer of 1954 in this century. The flood caused approximately the death of 3000 individuals and the direct economic damage of 250 billion RMB yuans (Yan, 1998). This extreme disaster prompted a series of immediate studies on it (e. g., Huang et al., 1998; Tao et al., 1998).

The evolution of the East Asian summer monsoon shows a great variability from year to

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year. Hence, the summer precipitation in the Yangtze River and the Huaihe River Basin, which largely depends on the East Asian summer monsoon, also shows a great interannual variability, and seriously influences the crop yield in that region. Much attention has been paid to the case studies on the extremely anomalous climate in East Asia in summer (e. g., Park and Schubert, 1997; Nitta, 1990), since this extremely anomalous climate causes remarkable damages on the life of people and property.

The influence of the thermal state of the western Pacific warm pool on the interannual variability of the circulation and precipitation over East Asia and the northern Pacific has been extensively studied (Huang and Li, 1987; Huang and Sun, 1992; Nitta, 1987; Kurihara, 1989; Lu and Huang, 1998). The results of these studies show that when the sea surface temperature (SST) in the tropical western Pacific is above normal, the convective activities become stronger over the region and an atmospheric Rossby wave is generated and propagates from the tropics to the extratropics. In these cases, the Yangtze River basin and Japan experience the below–normal rainfall and above–normal temperature in summer. When the SST in the tropical western Pacific is below normal, the Yangtze River basin and Japan experience the above–normal rainfall and below–normal temperature in summer. Lu and Huang (1998) showed that the Rossby wave generated by the SST anomalies in the warm pool influences the interannual variations of the blocking high over the northeastern Asia, summer rainfall in the Yangtze River basin, and the subtropical high over the western North Pacific.

Nitta (1990) investigated the relationship between the unusual summer weather over Japan and the tropical conditions in 1988, and showed that the cool and rainy summer in Japan can be directly explained by the weak convective activity in the tropical western Pacific around the Philippines. His analysis showed that the convection centre corresponding to the rising centre of the Walker circulation was abnormally shifted westward from the normal position over the tropical western Pacific towards the Bay of Bengal. According to the obviously negative SST anomalies in the tropical eastern Pacific and the positive SST anomalies in the Indian Ocean, he speculated that the warmer SST in the Indian Ocean together with the extreme La Niña event might force the convection centre to move westward to the Bay of Bengal.

The effects of the SST anomalies in the tropical Pacific and Indian Ocean on the Indian summer monsoon and the large–scale atmospheric circulation in the tropics have been widely investigated. Palmer et al. (1992) studied the impacts of the observed SST anomalies in individual oceans on the Indian summer monsoon, and found that the tropical (equatorward of 30° latitude) Pacific SST anomalies can account for much of the interannual variation in the Indian rainfall. In comparison to the tropical Pacific, the interannual variability in the Indian Ocean, the tropical Atlantic Ocean, or the extratropical SSTs had a relatively modest influence on the tropical large–scale flow. Ju and Slingo (1995) and Soman and Slingo (1997) suggested that during the El Niño years, the modulation of the Walker circulation, with implied additional subsidence over the Eastern Hemisphere, is the dominant mechanism whereby the Asian summer monsoon is weakened. During the La Niña years, their results suggested that the complementary warm SST anomalies in the western Pacific enhance the tropical convection, and this enhanced convection leads to an early onset and stronger Asian monsoon.

It is widely inferred that the longitudinal gradient of thermal states causes the longitudinal difference of the atmospheric circulation in the tropics. Bjerknes (1969) defined the Walker circulation as a thermal circulation driven by the gradient of sea surface temperature along the equator. Yang et al. (1992) proposed that there is a link between the Asian summer monsoon region and the arid region west to it via the concept of a closed atmospheric circulation cell similar to Walker circulation. These studies attempted to explain the atmospheric circulation by gradients of the thermal states, instead of the in situ responses.

In this study, we will focus on the thermal state over and of the warm pool region, which includes the tropical western Pacific and Indian Ocean. In Section 2, the datasets that are used in this study are described. A brief description of the precipitation and circulation features in East Asia is presented in Section 3. Section 4 shows that the anomalies of SST in the warm pool region and the atmospheric convection above. We analyze the large–scale atmospheric circulation anomaly (in Section 5) and surface heat fluxes (in Section 6) in the tropics, and launch a possible mechanism for the relationship between the convection (inferred by OLR) and SST, especially in the warm pool region of the tropical western Pacific and Indian Ocean. The summary and discussion are given in Section 7.

2. Data

In this study, the ECMWF Re–Analysis (ERA) data averaged for the 15–year period from 1979 to 1993 are used as the climatology, and the anomalies of 1998 are obtained by removing the climatological fields from the corresponding fields of 1998. The data used in the present study include upper air fields on 17 standard pressure levels, and the surface parameters and fluxes as grid point values in a so–called reduced N80 Gaussian grid. This grid has 160 irregularly spaced latitudes approximately 1.125 degrees apart. The longitude points close to the equator are exactly 1.125 degrees apart. However, the intervals increase towards the poles to avoid crowding of grid points. The model sign convention is used, i.e., downward fluxes are positive. The upper air fields and SSTs are analyzed, while the surface fluxes are forecast 24–hour accumulations (from midnight).

Gibson et al. (1997) gave a comprehensive description of the assimilation scheme, forecast model used in ERA. Except for the horizontal resolution, the ERA assimilation scheme is identical to the ECMWF operational system used from April 1995 to January 1996. It comprises T106 spectral resolution in the horizontal with 31 hybrid model levels in the vertical, Optimal Interpolation intermittent statistical analysis with 6–hour cycling and diabatic non–linear normal mode initialisation.

The data of 1998 were produced by using the ECMWF operational analyses, which are different from the ERA data assimilation scheme. The differences are in data assimilation techniques, model algorithms and model resolution. For example, the 4D–Var assimilation system was introduced operationally at ECMWF in November 1997. In June 1998, the following changes were also introduced into ECMWF operations. For the conventional data the main changes are the use of the hourly (instead of six–hour) surface observations from frequently reporting stations, and the use of the radiosonde temperatures at all reported levels in place of geopotential height, winds, and humilities on standard pressure levels. The 10m–wind observation operator was unified for all observation types.

The major problem for use of ERA data and ECMWF operational analysis data may be the analyses on the fluxes at the surface. In Section 6, we will give a more detailed description on the reliability of some relevant surface flux data.

3. *Anomalies of the precipitation and atmospheric circulation in the extratropics*

Fig. 1 shows the precipitation anomalies in East Asia and the western Pacific during the

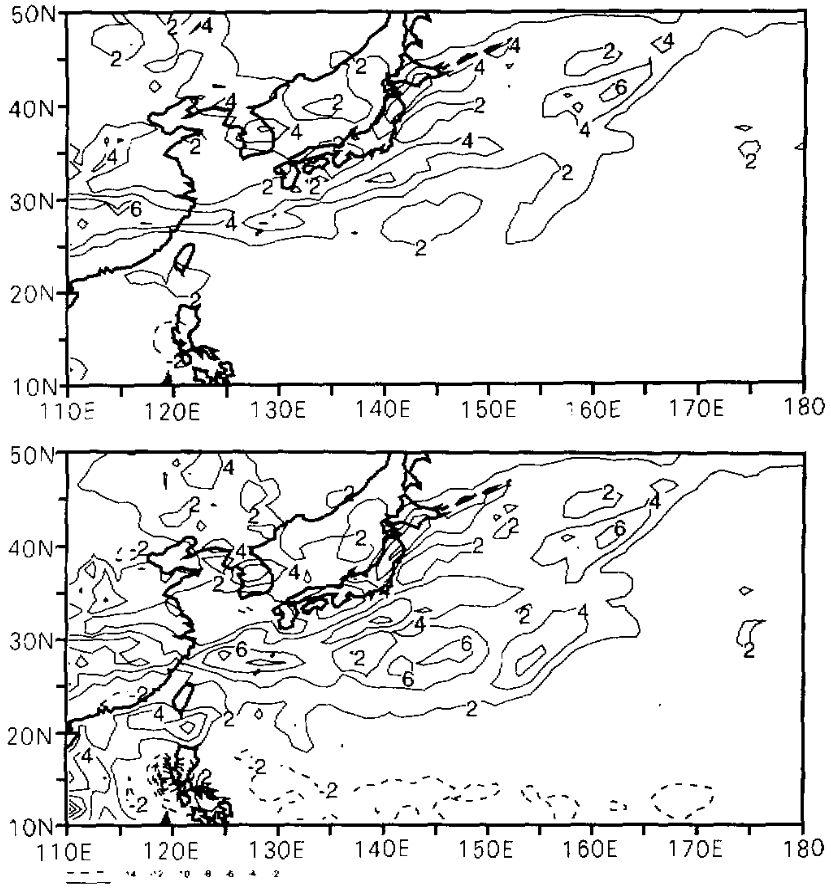

Fig. 1. Precipitation anomalies in East Asia during the summer of 1998. The upper one is the large-scale precipitation anomaly and the lower one is the total precipitation anomaly. Units are in mm / day with contour interval 2 mm / day. Positive contours are shown solid, negative contours dashed, and zero contour is not shown for the sake of clarity.

summer of 1998. The upper one is for the large-scale precipitation anomaly and the lower one for the total precipitation anomaly. Both of them show that there are two areas of positive anomalies, one is along the Yangtze River basin and extends north-eastward to Japan, i.e., along the Meiyu front; another is in Northeast China and Korea. In the lower figure, which shows the total precipitation anomaly (including large-scale precipitation anomaly and convective precipitation anomaly), there is a boarder belt of the positive anomaly along the Meiyu front, and a negative anomaly along 10–15°N. Along this belt of negative anomaly, the strongest negative anomaly is around the Philippines. Except the negative anomaly of precipitation, the distribution and strength of the large-scale precipitation anomaly are considerably similar to those of the total precipitation anomaly, suggesting that the large-scale precipitation anomaly causes the floods in the Yangtze River basin, Northeast China, Korea,

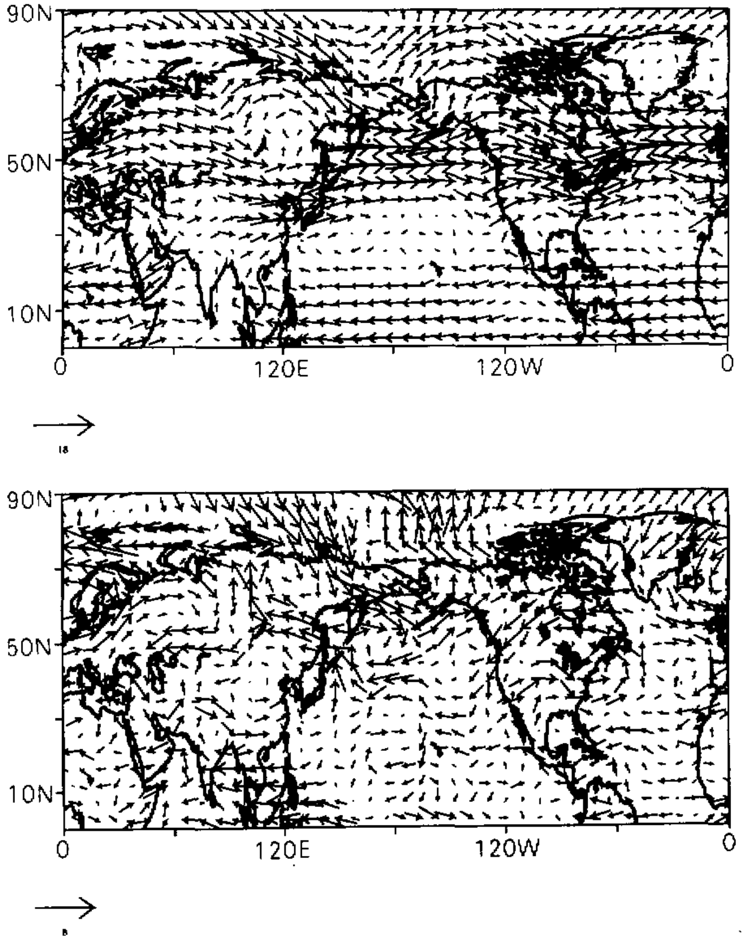

Fig. 2. Mean (upper one) and anomalous (lower one) winds at 500 hPa during the summer of 1998. The wind anomalies are departures from the seasonal average for 15 years from 1979 to 1993.

and Japan.

In the tropical western Pacific, there is a belt of negative total precipitation anomaly, with a strong negative centre around the Philippines. There is, however, only a small region with a weak negative anomaly of the large–scale precipitation around the Philippines. This infers that there would be suppressed convection around the Philippines during the summer.

Since the anomalies in this study are calculated by different databases, as mentioned in Section 2, it is necessary to compare the results in this study to the results obtained by some other ways. We made a comparison with the observed precipitation anomaly in China, e.g., Fig. 1 of Tao et al. (1998), which is obtained by the observation at observation stations in China. The comparison shows that the precipitation anomaly in this study is in a fairly good agreement with the observation, in distribution as well as in strength.

The mean and anomalous winds at 500 hPa (Fig. 2) show the large–scale circulation background for the floods in East Asia during the summer of 1998. The wind anomalies are departures from the seasonal average for 15 years from 1979 to 1993. At the upper figure (mean winds during the summer), there is a strong ridge over the northeastern Asia. In fact, blocking highs occur frequently over the region during the summer of 1998, especially in July and August. Accompanied the ridge over the northeastern Asia, there is a deep trough at the direction of northwest–southeast over Northeast China. Actually, there are much more troughs going through Northeast China during the summer of 1998, causing the severe flood in Northeast China (Tao, personal communication). On the other hand, the subtropical high over the western North Pacific is somewhat intensified and westward shifted obviously to Indo–China Peninsula. The intensification of the subtropical high over the western North Pacific is more obvious in the anomalous winds at the lower levels (see Fig. 6). Over the Yangtze River basin, the cold air from the north along the westward of the trough meets the warm and wet air from the south along the subtropical high, which provides a favourable circulation condition for the prolonged maintenance of the rainy season. Furthermore, the obviously westward shifted subtropical high causes the westward extension of the Meiyu rainbelt into the upper stream of the Yangtze River.

The anomalous winds at 500 hPa (lower one of Fig. 2) show a wave train along the coast of the North Pacific. There is a cyclone–like anomaly over East Asia, Bering Sea, and United States, respectively. There is an anticyclone–like anomaly respectively between these cyclone–like anomalies, i.e., over the northeastern Asia and over the western coast of Canada. This wave train is similar to the teleconnection pattern caused by the thermal conditions over and of the tropical western Pacific (Huang and Li, 1987; Nitta, 1987; Huang and Sun, 1992; Nitta, 1990). This type of distribution of the cyclones and anticyclones is favourable to the above–normal summer precipitation in the East Asian monsoon region.

4. Anomalies of sea surface temperature and atmospheric convection in the tropics

In Section 3, we examined the circulation anomaly in middle latitudes and found that there is a wave train along the coast of the North Pacific. This wave train is proposed by the previous studies (Huang and Li, 1987; Nitta, 1987; Huang and Sun, 1992; Nitta, 1990) to be caused by the thermal conditions over and of the tropical western Pacific. In this section, we will investigate the SST anomalies in the tropical oceans and the convection anomalies above.

It is well known that there is a positive SST anomaly in the Indian Ocean during most El Niño events, while a negative SST anomaly in the western Pacific (e.g., Ju and Slingo, 1995). In the summer of 1998, however, there is an anomalous pattern of the distribution of SST anomalies. Fig. 3 shows the SST anomalies in the tropics during the summer of 1998. The SST anomalies are departures from the seasonal average for 15 years from 1979 to 1993. In the summer of 1998, the weak cold episode (La Niña) conditions maintained, with the negative equatorial SST anomalies observed between 160°E and 120°W. Significantly positive SST anomalies occupied the warm pool region (including the tropical Indian Ocean and the tropical western Pacific), with an approximate maximum magnitude of 1–1.5°C. The SSTs are considerably above normal, since usually the SSTs show a small variability in the warm pool region.

Outgoing longwave radiation (OLR) can describe very well the atmospheric convection in the tropics. During the summer of 1998, the tropical convection is suppressed slightly around the Philippines, and enhanced remarkably over the tropical Indian Ocean, the Bay of Bengal, the South China Sea and Indonesia (Fig. 4). This pattern of OLR anomalies develops

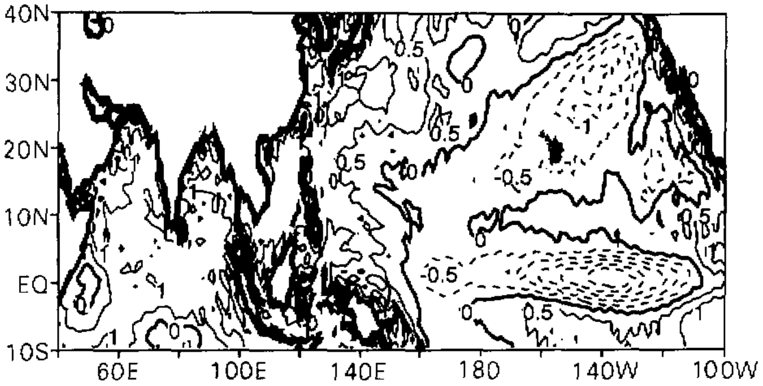

Fig. 3. SST anomalies in the tropical Pacific and Indian Ocean during the summer of 1998. The SST anomalies are departures from the seasonal average for 15 years from 1979 to 1993. The contour interval is 0.5°C.

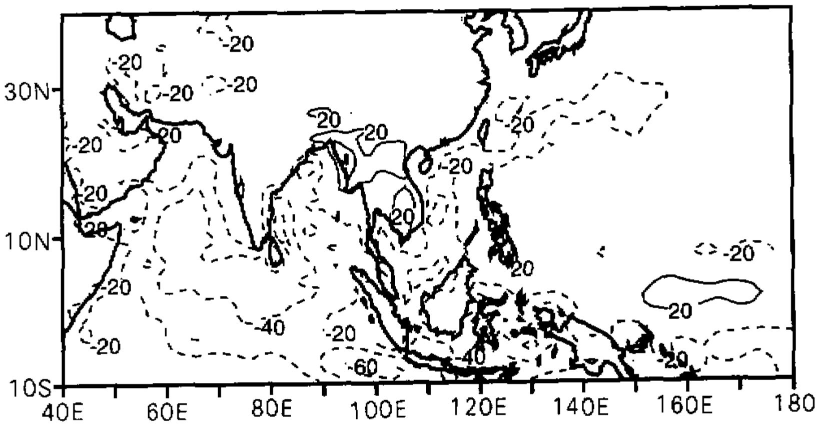

Fig. 4. Anomaly of the outgoing longwave radiation during the summer of 1998 in the tropical western Pacific and Indian Ocean. Units are in W m^{-2} with contour interval 20 W m^{-2}. Positive contours are shown solid, negative contours dashed, and zero contour is not shown for the sake of clarity.

during June and is dominantly persistent for the whole summer (Climate Analysis Centre, 1998). The distribution of the column integrated diabatic heating anomaly (Fig. 5) is very similar to that of OLR anomaly, with significantly greater column integrated diabatic heating to the west of the Philippines and slightly less column integrated diabatic heating to the east of the Philippines.

In the summer of 1998, SSTs are above normal in the Indian Ocean and the Bay of Bengal. At the meantime, the convection and column integrated diabatic heating are also above normal over these regions. Over the tropical western Pacific, however, the convection and diabatic heating are below normal, though SSTs are warmer. Lau et al. (1997) argued

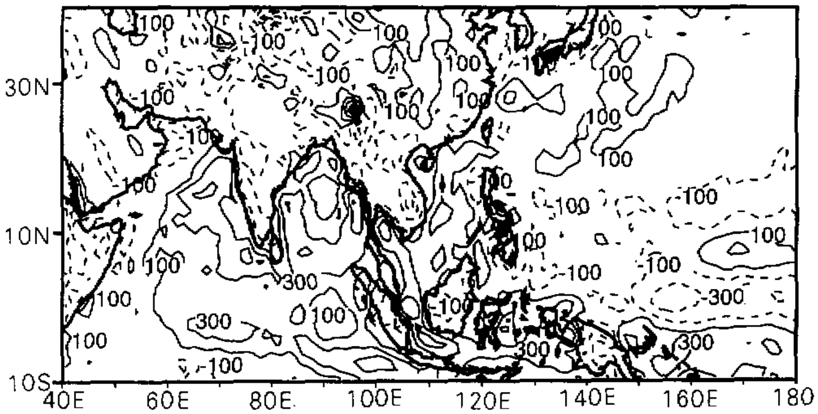

Fig. 5. Anomaly of the column integrated diabatic heating during the summer of 1998 in the tropical western Pacific and Indian Oceans. Units are in W m^{-2} with contour interval 200 W m^{-2}. Positive contours are shown solid, negative contours dashed, and zero contour is not shown for the sake of clarity.

that the warmer SSTs–enhanced convection relationship may be broken down due to the large–scale circulation in the tropics.

5. Anomalies of atmospheric circulation in the tropics

In the tropics (around 10°N), at 850 hPa, there are westerly anomalies over the Indian Ocean and strong easterly anomalies over the western Pacific, the Bay of Bengal and the Arabian Sea. Over the tropical eastern Pacific, the westerly anomalies exist (Fig. 6). At the upper levels (200 hPa), however, the wind anomalies are basically at the opposite directions to those at the lower levels over the above–mentioned regions, except over the Bay of Bengal, India and the Arabian Sea. This fact suggests that there may be upward motion over the Bay of Bengal and the Indian Ocean, downward motion over the central Pacific, where the SSTA is negative, and another upward motion over the western coast of America, where the SSTA is positive. Hence, the tropical SST anomalies appear to drive two large–scale closed circles of anomalous atmospheric circulation in the tropics.

These wind anomalies in the tropics are associated with those in the subtropics. At the lower levels, there is an anticyclonic circulation anomaly in the North Pacific, showing that the North Pacific subtropical high stretches westwards, and is stronger than normal. This type of the North Pacific subtropical high may transfer a larger amount of water vapour into the East Asian summer monsoonal area. At the upper level, an anticyclonic anomaly of winds exists over the Tibetan Plateau, which shows a stronger South Asia High.

A scale analysis of Hoskins (1986) on the thermodynamic energy equation suggests that in the tropics where the Burger number $B = N^2 H^2 / f^2 L^2$ is large, the adiabatic cooling and warming are associated with ascent and descent, respectively, and tend to balance the diabatic warming and cooling. Hence, the distributions of the OLR anomaly (Fig. 4) and diabatic heating anomaly (Fig. 5) suggest that there would be anomalies of ascent and descent, respectively, west and east of the Philippines, which is shown by the vertical distribution of

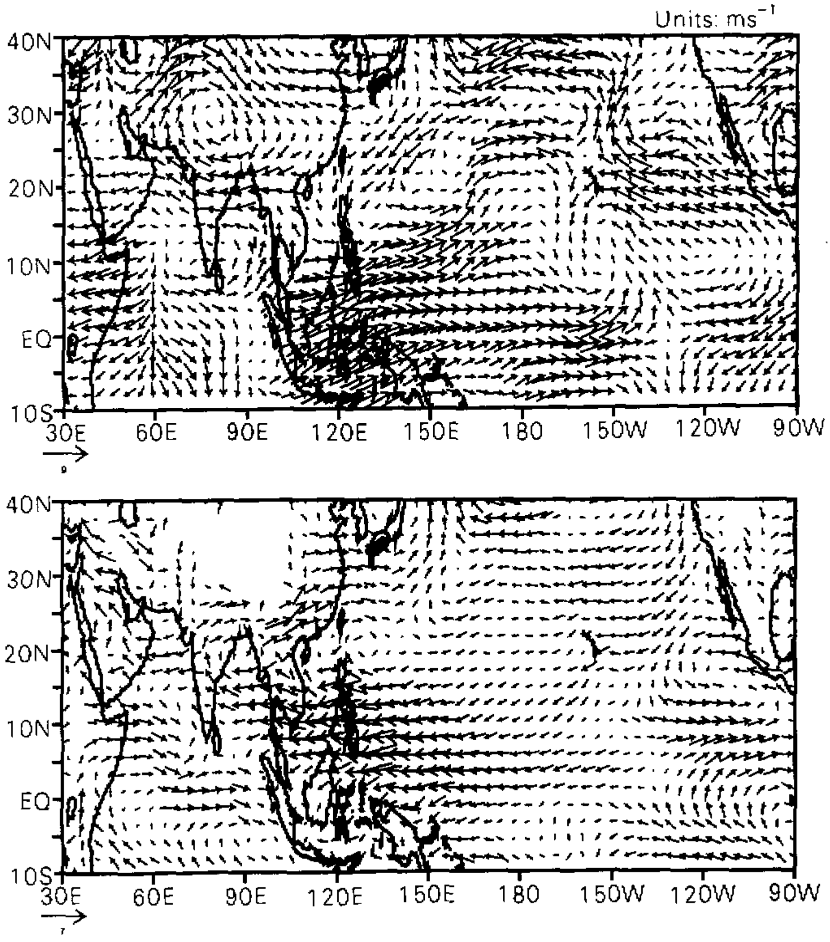

Fig. 6. Horizontal wind anomalies at 200 hPa (upper) and 850 hPa (lower) during the summer of 1998. The domain is (10°S–40°N, 30°E–90°W), which includes the tropical Indian Ocean and tropical Pacific Ocean.

streamfunction anomaly along 10°N (Fig. 7). Fig. 7 also suggests that along 10°N, there are westerly anomalies at the upper levels and easterly anomalies at the lower levels over the Pacific and the Bay of Bengal.

Usually, there is a divergent centre at 200 hPa over the tropical western Pacific, east of the Philippines. This divergent centre is associated with the ascent flow of the Walker circulation in the tropics. However, the centre shifts westward to the Bay of Bengal in the summer of 1998, and the centre of the divergent anomaly is located over the Arabian Sea (Fig. 8). This fact is in good agreement with other fields analyzed above, and is considerably consistent with that in the summer of 1988 (Nitta, 1990).

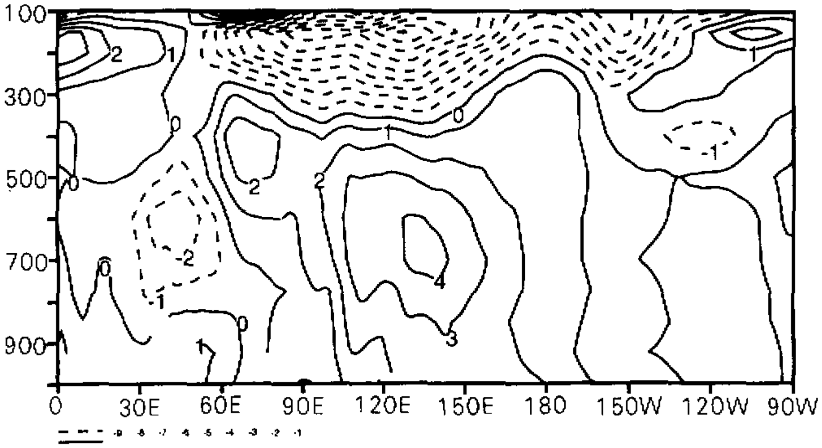

Fig. 7. Streamfunction anomaly along 10°N during the summer of 1998. The contour interval is 1 $\times 10^6\ m^2\ s^{-1}$. Units: in $10^6\ m^2\ s^{-1}$.

6. Anomalies of the surface heat fluxes over the warm pool

The analyzed results in the previous sections suggest that the longitudinal gradient of SST anomalies dominates the large–scale atmospheric circulation anomalies in the tropics. Influenced by the large–scale atmospheric circulation anomalies, the atmospheric convection anomalies may not correspond to the SST anomalies below. A new question arises naturally–what is the reason for the positive SST anomalies both in the tropical Indian Ocean and in the tropical western Pacific at the same time, which in general show a tendency of the out–phase variations? The interaction between atmosphere and sea should be concerned to answer this question.

It is well known that most La Niña events are associated with a negative SST anomaly in the Indian Ocean. During the La Niña events, the Indian summer monsoon circulation is stronger. Due to the stronger circulation, there may be more evaporation (or latent heat flux) and a negative SST anomaly in the Indian Ocean. During the summers of 1998 and 1988, however, there is a positive SST anomaly in the Indian Ocean while a significantly negative SST anomaly exists in the central / eastern Pacific. The relationships among the SSTs in the tropical eastern Pacific, the western Pacific, and the Indian Oceans are too complicated to be simply described. Thus, we will focus on the surface heat fluxes in an attempt to understand better the reason for the positive SST anomalies in the tropical western Pacific and Indian Ocean.

In the warm pool region (including the tropical Indian Ocean and tropical western Pacific), the horizontal gradients of temperature are small, and the depth of mean mixed layer is approximately only 25 meters. Thus, the SST changes are sensitive to the changes in the surface heat flux in this region. It is assumed that the sensible heat flux has an order of magnitude smaller intraseasonal variations than the latent heat flux over the warm pool (e.g., Webster, 1994). Hendon and Glick (1997) examined the relationships between the intraseasonal variations of SSTs and surface fluxes of latent heat and solar radiation in the tropical Indian and Pacific Oceans. They postulated that the SST anomalies are driven by a

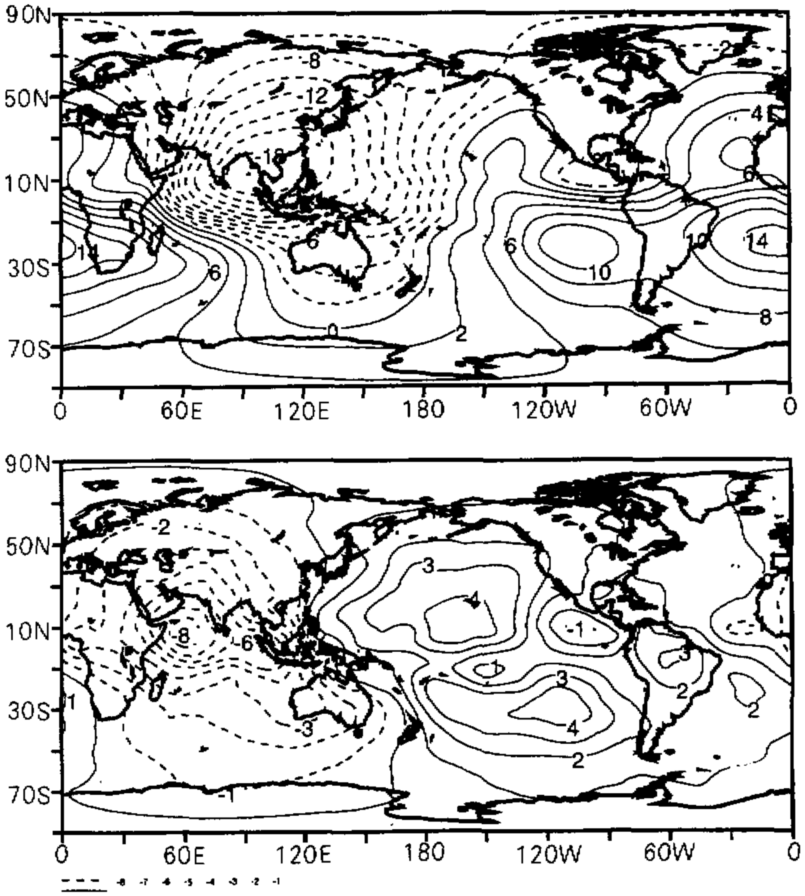

Fig. 8. Mean (upper one with contour interval 2) and anomalous (lower one with contour interval 1) velocity potential at 200 hPa during the summer of 1998. For the sake of clarity, the values have been divided by a factor of 10^6.

combination of the anomalous latent heat flux and insolation at the surface in the western Pacific, and are driven predominantly by the surface insolation anomalies associated with the anomalous large–scale convection in the Indian Ocean.

In order to find the reason for the positive SST anomalies in the warm pool region in the summer of 1998, the anomalies of the latent heat flux and the net solar radiation at the surface are examined. However, the anomalies of the latent heat flux and the net solar radiation flux in the summer of 1998 (not shown here) are both negative in the tropical Indian Ocean and the western Pacific. Since the negative fluxes at the surface mean less heat fluxes into the sea, the analyzed result for the summer of 1998 appears to show that neither anomalous latent heat flux nor anomalous insolation is the reason for warmer SST in the warm pool of the western Pacific and Indian Ocean. We attribute this to the mismatch between the data of the summer of 1998, which are produced by ECMWF operational analyses, and the ERA–15 data. A preliminary study suggested that there would exist great differences in the fluxes at the surface between these two datasets (Kållberg, personal communication). These differences may be large enough to affect the results of analyses on the surface flux anomalies in the summer of 1998 in this study. Stendel and Arpe (1997) indicated that the consistency of ERA–15 has much been improved as compared to ECMWF's operational analyses. This means that there should be considerable inconsistency between them. There may be a systematical difference in the surface fluxes, whose accuracy may be significantly improved by the recent changes in the ECMWF operational analyses.

Since there are many similarities in the SSTA and the atmospheric circulation anomalies between the summers of 1988 and 1998, we assume that the surface flux anomalies are also similar between these two periods. To avoid the inconsistency between different datasets, we examined the surface fluxes in the summer of 1988, which was included in the period of re–analysis. Fig. 9 shows the anomalies of the latent heat flux and the net solar radiation at the surface in the summer of 1988. The reason for the above–normal SSTs is basically the latent heat flux at the surface in the tropical Indian Ocean and the net solar radiation flux at the surface in the tropical western Pacific.

However, these results may not be used to explain quantitatively the reason for the positive SST anomalies in the warm pool region, since the acceptance and use of mismatched observations in re–analysis lead to large spin–up or spin–down in the surface fluxes. Mismatches between the assimilation system and biased surface wind observations, from SHIPs (too strong winds) and from isolated island SYNOPs (too weak winds), generate large increases (spin–up) in the latent heat flux during the forecasting. In the tropics and the subtropics the latent heat flux increases with time, in large areas with 10–20 W/m^2, and locally up to 40 W/m^2 (see Fig. 1 in the report of Kållberg (1997)). The net solar flux at the surface also shows the spin–up or spin–down, but with a smaller magnitude of 5–15 W/m^2 in the tropical Indian and Pacific Oceans (see Fig. 2 in the report of Kållberg (1997)). Though these values of spin–up or spin–down are somewhat comparable with the anomalies in the summer of 1988, the errors in ERA data are much smaller than these values of spin–up or spin–down, if we assume that the spin–up and spin–down appear somewhat stable in each forecasting. Thus, the analysis on the anomalies of the latent heat flux and the net solar radiation flux at the surface is convincing at least for the summer of 1988, though not for the summer of 1998.

Stendel and Arpe (1997) showed that around 1988 there are questionable trends of increasing precipitation and decreasing the latent heat flux over the tropical oceans and decreasing precipitation over the tropical land masses in ERA. These trends may be related to a long–term variation, or may just be a spurious one. If the decreasing trend in the latent heat flux is a spurious one, it will produce a spurious negative anomaly for the summer of 1988. Since a negative value means a flux from air to the surface, therefore, these trends do not damage the reliability of the present analysis on the anomaly of the latent heat flux in the summer of 1988.

7. Summary and discussion

East Asia suffered a severe flood in the summer of 1998. In this study, we examined the anomalies in the tropics associated with this flood, and investigated the possible linkages among these tropical anomalies. The anomalies of 1998 are obtained by removing the

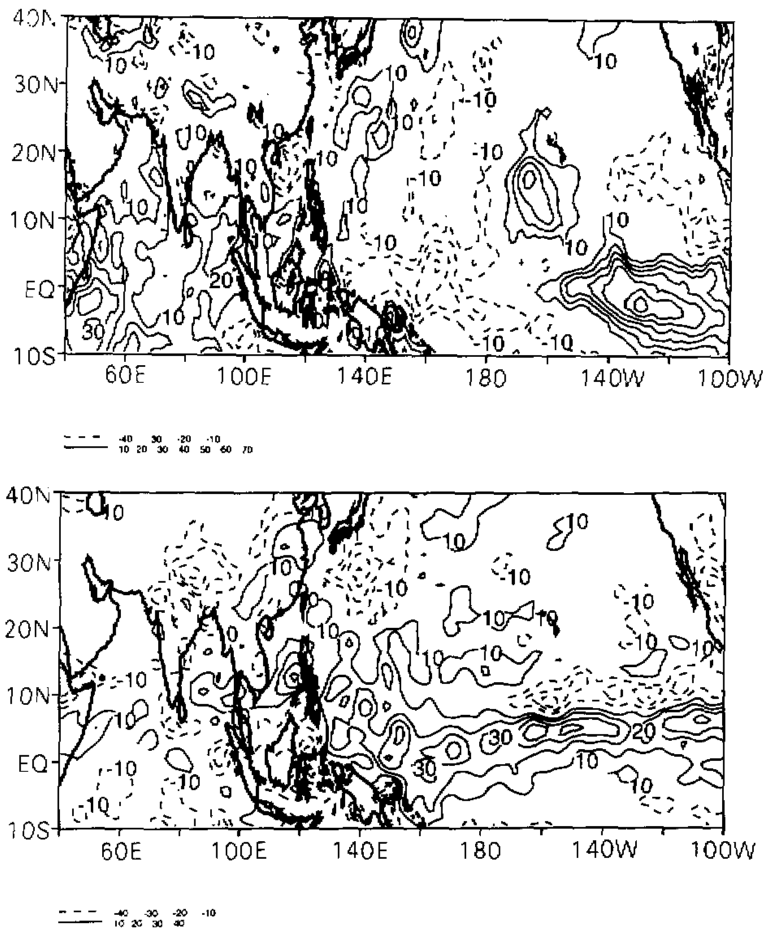

Fig. 9. The anomalies of latent heat flux (upper one) and net solar radiation flux (lower one) at the surface in the summer of 1988. Downward flux is positive. Units: W m^{-2}.

climatology, which is the averages of the ECMWF Re–Analysis (ERA) data over 15 years from 1979 to 1993, from the corresponding fields of 1998, which are obtained from the ECMWF operational analyses.

It has been found that there are considerable similarities in the atmospheric circulation anomalies in middle–high latitudes as well as in the tropics between the summers of 1998 and 1988. This study shows that the atmospheric convection is slightly suppressed over the tropical western Pacific. This slightly suppressed convection may not provide a viable forcing mechanism for the severe flood in East Asia. We postulated that the zonal wind anomalies in the tropics are closely associated with the position and strength of the North Pacific subtropical high, which influences greatly the position and strength of the East Asian summer monsoon rainfall.

In general, the suppressed convection corresponds to a negative anomaly of SST in the warm pool region. In the summers of 1998 and 1988, however, there are slightly above-normal SSTs in the tropical western Pacific, with the suppressed convection over there. Correlation between SST and atmospheric convection above is good sometimes in some places, but poor at other times and in other places. The warmer SSTs–enhanced convection relationship is broken in the tropical western Pacific in the summer of 1998 due to the large-scale circulation in the tropics, which is supposed to be driven by the warmer SST in the tropical Indian Ocean. However, there are only two cases (summers of 1988 and 1998) showing that the warmer SSTs in the tropical Indian Ocean may suppress the convection over the tropical western Pacific, even though there are warmer SSTs in the tropical western Pacific. Some further studies are necessary to find out a clearer relationship between SST and OLR in the tropics.

Using the ERA–15 data, we have examined the heat fluxes at the surface in the warm pool of the tropical western Pacific and tropical Indian Ocean. We suggest that the reason for the negative anomalies of both latent heat flux and net solar radiation flux in the warm pool region in the summer of 1998 is the great systematical errors in the heat fluxes at the surface between the ERA–15 and the operational analyses. To avoid the inconsistency, we have examined the anomalies of the heat fluxes at the surface in the warm pool region in the summer of 1988. The anomalous latent heat flux and net solar radiation flux are the main reason for the positive anomalies of SSTs in the tropical Indian Ocean and in the tropical western Pacific, respectively. In the tropical western Pacific, the convection is suppressed over the warmer SSTs. The suppressed convection over the tropical western Pacific allows more solar radiation fluxes downward onto the surface, which increase the SSTs.

The physical processes are hypothesized as follows based on the aforementioned results. At first, over the tropical Indian Ocean, the positive SST anomalies enhance in situ convection. A heating source caused by this enhanced convection leads to a cyclone–like atmospheric circulation anomaly (Gill, 1980), which decreases the Indian summer monsoon circulation and further decreases the latent heat flux from ocean to air. By this way, the positive SST anomalies are maintained over the tropical Indian Ocean. The second hypothesis is with regard to the interaction between the tropical western Pacific and Indian Ocean. The results in this study imply that the large-scale atmospheric circulation anomalies caused by the positive SST anomalies in the tropical Indian Ocean suppress the convection over the tropical western Pacific, and hence allow more solar radiation to reach the surface of sea. The SSTs increased by this solar radiation will trigger strong convection over the tropical western Pacific. When the convection center moves from the Indian Ocean to the tropical western Pacific, there will be the westerly anomaly over the tropical Indian Ocean. The enhanced Indian summer monsoon circulation will increase the latent heat flux from ocean to air, and hence decrease the SSTs in the tropical Indian Ocean.

Fig. 10 shows the variations of anomalies of SST and OLR over the warm pool region (From 50°E to 180°, averaged over 0°–10°N). Generally, the SSTs are above normal in the warm pool region in 1998, while stronger atmospheric convection appears over the Indian Ocean. From summer on, the positive SST anomalies and negative OLR anomalies have a tendency of eastward moving. These changes provide one more evidence to the aforementioned two hypotheses.

Though there are many similarities between the summers of 1998 and 1988, some differences exist. One major difference is in the precipitation. In the Yangtze River basin, there is a significantly positive anomaly of the precipitation in the summer of 1998, whereas the precipitation is normal during the summer of 1988. This difference is generated from the different

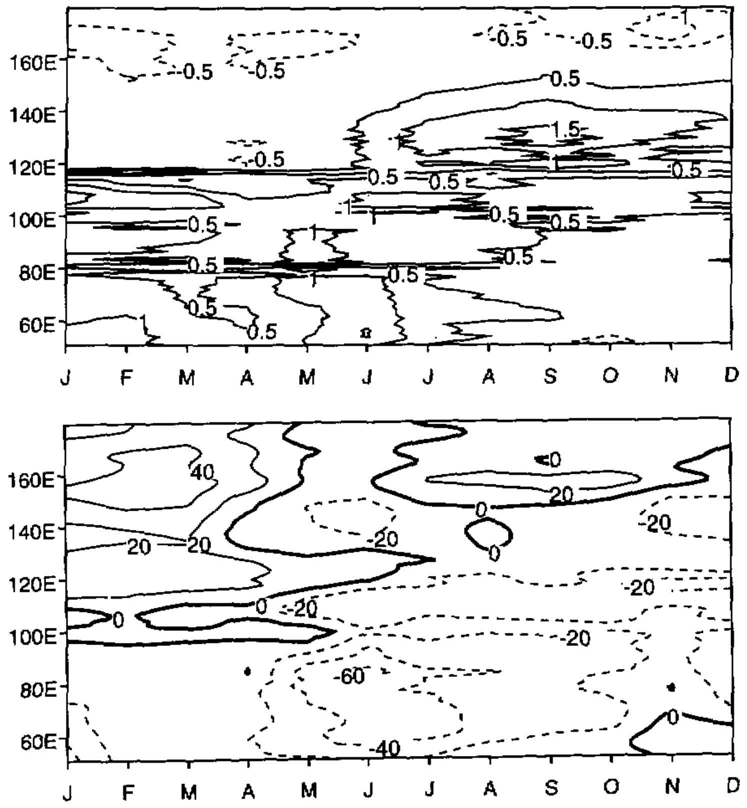

Fig. 10. Variations of anomalies of SST and OLR over the warm pool region (From 50°E to 180°, averaged over 0°–10°N) in 1998. Contour interval is 0.5°C for SST anomalies and 20 W m^{-2} for OLR anomalies. Positive contours are shown solid, negative contours dashed, and zero contour of SST anomalies is not shown for the sake of clarity.

westward extensions of the subtropical high (comparing Fig. 7 in this paper with Fig. 7 in the paper of Nitta (1990)). Further studies are needed to examine these differences in detail, which may be related to the atmospheric circulation in the middle–high latitudes, the land surface condition, and so on.

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