Analysis on Anomalous Precipitation in Southern China During Winter Monsoons*

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(Received July 22, 2007)

ABSTRACT

The winters of 1997/1998 and 1998/1999, corresponding to El Niño and La Niña episodes, respectively, were two typical rain-abundant and -scarce seasons for the southern China. In order to understand the cause of the anomalous precipitation during the two winters, a comparative analysis technique has been employed to investigate the differences in general circulation and moisture transportation between the two seasons. The results show that the abundant rainfall during the winter of 1997/1998 was associated with the ENSO warm episode event, eastward shifted weak westerly trough/ridge, weakened East Asian winter monsoon (EAWM), strengthened subtropical high, and presented two anti-cyclonic circulations over Hokkaido and the Philippine Sea, respectively, as well as one cyclonic circulation over the Yangtze River Basin in the anomalous wind fields of the lower troposphere. During the rain-scarce winter, however, the patterns of equatorial sea surface temperature anomalies and the circulation systems both in upper and lower levels were nearly the opposite of those during the rain-abundant winter. It has also been discovered that the water vapor over southern China during the winters came mainly from the southwesterly flow ahead of troughs in the southern branch of westerlies and the turning flow over the South China Sea−Indo-China Peninsula area; and the moisture transportation channels varied significantly with regard to height. The intensified flow in the southern branch of westerlies and the anti-cyclonic circulation anomaly over the Philippine Sea during the winter of 1997/1998 were favorable for moisture transportation to mainland China, however the two moisture transportation streams were dramatically weakened during the winter of 1998/1999 due to weak westerly flow and the dominance of a cold high system in the lower level over the southeast coast of China. Such a significant inter-annual change of moisture transportation is a key factor resulting in the obvious difference in precipitation between the two winters.

Key words: winter monsoon, precipitation, circulation differences, moisture transport

1. Introduction

East Asia is one of the famous monsoon regions in the world, and the East Asian winter monsoon (EAWM) is not only the most prominent circulation pattern during winter, but also it plays an important role in the winter climate of China. With the development of society and economy, more public attention focused on the winter climate and its effects on agriculture, energy, water resource, etc., forecasting winter precipitation and temperature has already been an important service to the China Meteorological Administration (CMA). Winter rainfall presents interdecadal change (Xu et al., 1999) and interannual variation under the effects of winter monsoon. In some years, the abnormally abundant precipitation may cause winter floods, while the abnormal scarcity may cause drought in some other years.

The Winter Monsoon Experiments in the late 1970s and researches after that revealed some observations about winter monsoon and cold surges. It especially pointed out the relationship between middle and low latitude circulations while cold surges occur (Chang and Lau, 1980; Lu and Ding, 1987). Chang

*Supported by the project from the Ministry of Science and Technology of the People's Republic of China under Grant No. 2001BA611B-01.
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and Lau (1982) studied eight typical active periods and five inactive ones among four winters by composite analysis, and proposed that the development of baroclinic disturbances generated cold surges, enhanced the convection activities near the equator, caused planetary scale divergence airflow at the upper troposphere by heat convection, and then strengthened the Hadley and Walker circulations. In the recent decade, many studies have been carried out on the EAWM and scientists have found that ENSO events have crucial influences on the EAWM. Guo and Wang (1990) suggested that the path of the cold air at the sea level pressure field over the East Asian continent is different between El Niño and La Niña events, the cold air going easterly (westerly) during winter with El Niño (La Niña) events, and causing rain-abundance (-scarcity) in South China. From the diagnosis of the departure of SST and characteristics of atmospheric circulation in two events during 1986/1987 and 1991/1992 (Zhang et al., 1996), it can be seen that in the mature phase of El Niño (summer of 1987 and winter of 1991/1992), the convection over the equatorial West Pacific was restrained, with the south wind departing at low levels from East Asia, causing the strong summer monsoon in 1987 and the weak winter monsoon in 1991/1992. Tao and Zhang (1998) suggested that during winter in El Niño (La Niña) years the circulation pattern in East Asia is not favorable (favorable) for outbreaks of cold air southward, leading to a weak (strong) winter monsoon in Asia and above normal (below normal) precipitation in South China. With the observed global month mean data from 1950 to 1989, Mu and Li (1999) investigated the interannual variability of EAWM, and the results showed that the anomalous activities of EAWM have an obvious relationship with the occurrence of ENSO, as the EAWM becomes weaker after most El Niño events occur and stronger after most events occur. Wang and Fu (2000) presented that there is a Pacific-East Asia teleconnection during the extreme phases of ENSO cycles, and pointed out that the anomalous Philippine Sea anticyclones results from a Rossby wave respond to suppressed convective heating. The development of the anticyclone is nearly concurrent with the enhancement of the local sea surface cooling. The development and persistence of the teleconnection is primarily attributed to a positive thermodynamic feedback between the anticyclone and the sea surface cooling in the presence of mean northeasterly trades, and is favorable for the abnormal southerlies over the South China Sea. Using composite El Niño and La Niña data, Chen (2002) addressed that the cycles of the East Asian winter and summer monsoons are significantly influenced by ENSO events. In the preceding El Niño event, there are anomalous northerly winds over the East Asian region, while anomalous southerly winds appear in the winter during the mature phase of an El Niño event.

All of the previous studies have improved our knowledge about the EAWM, and have also indicated that ENSO events are an important effect factor on the intensity of EAWM. However, compared with studies on summer monsoons, there were few works focusing on winter monsoons, especially with regard to the characteristics of the circulation and moisture transition associated with winter precipitation in South China. Therefore, to better understand the circulation, when anomalous winter precipitation occurrs, the strong El Niño event in 1997/1998 and strong La Niña event in 1998/1999 are cited in this paper as typical cases and the different winter circulations and moisture transitions between rain-abundant and rain-scarce years in China and their relationship to ENSO events are analyzed.

2. Data and method

The datasets used to study circulation anomalies are NCAR/NCEP monthly mean and daily mean reanalysis data, with a resolution of 2.5°×2.5°, including sea level pressure, geopotential height, wind, specific humidity, etc. The daily observational rainfalls from 687 stations on China mainland during the period from January 1951 to December 2000 are provided by the CMA.

In this paper, the winter of 1997 (1998) is short for the period from December 1997 (1998) to February 1998 (1999), with winter precipitation being the accumulative rainfall of the three months. The long-term mean winter circulation is the average of 36 years from 1968 to 2003, and the departure is the difference between the annual mean winter circulation and the long-term mean winter circulation.

In this paper the formula below is used to calculate the whole vertical integrated zonal and meridional moisture transition:

$$Q_\lambda = \frac{1}{g}\int_{300}^{p_s} qu\mathrm{d}p$$

$$Q_\phi = \frac{1}{g}\int_{300}^{p_s} qv\mathrm{d}p,$$

where the λ as longitude, ϕ as latitude, p_s as surface pressure, u and v as zonal wind and meridional wind, respectively, and q as specific humidity.

The water vapor transportation on the isobaric surface is defined as $\boldsymbol{Q}_k = \frac{1}{g}\boldsymbol{V}_k q_k$, where the footnote k is for vertical level.

3. Precipitations and ENSO events in both the 1997 and 1998 winters

The winter of 1997 was a typical rain-abundant season for most regions of China, especially for east coast and south of Yangtze River. From the observation station precipitation data over the China mainland in winter of 1997 (Fig.1a), it can be seen that the precipitation in the mid-lower Yangtze River Basins and most southern China are above 200 mm, with over 500 mm in the center located southwest of Zhejiang and north of Jiangxi and Fujian Provinces. The rainfall mainly occurred near the East Asian front, and shaped a band from east to west. The situation was just the opposite during the 1998 winter (Fig.1b), when most regions of China had less rainfall, especially in the southern China, with precipitation center less than 200 mm which was one third of that fell during the 1997 winter.

Figure 1 also shows that the precipitation center during winter is not in the coastal areas of South China but in the region between 25° and 30°N. As the cold and dry northerly wind that controls northern China during winter, the accumulated precipitation was small over there, although there were strong snowfalls sometimes.

Climate variation is affected by the ocean heating anomaly. The evolution of the monthly mean Nino 3.4 (5°S-5°N, 120°-170°W) SST anomalies (Fig.2) showed that the temperature of the equatorial East Pacific started to rise in March 1997 and reached its climax in the end of 1997 with a Nino index of 2.8. After that, the index fell rapidly, and reached -0.78 in June and the minimum value of -1.69 in December 1998. Since mature phases of ENSO events are commonly defined as periods when the Nino index exceeds 1.0 (Zhang et al., 1996), the winter of 1997 and 1998 are categorized as mature phases El Niño of and La Niña, respectively.

4. Differences in atmospheric circulation between rain-abundant and -scarce winters

In order to reveal the different atmospheric circulations between rain-abundant and -scarce winters, the factors that influenced the China season-scale anomaly precipitation during winter such as ENSO events, westerly planet-scale trough and subtropical high were analyzed.

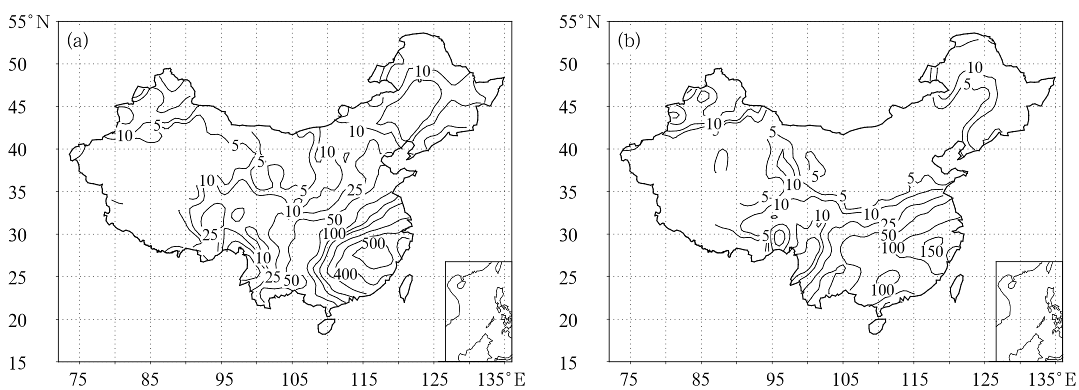

Fig.1. Precipitation over the China mainland in the winter of 1997 (a) and 1998 (b) (units: mm).

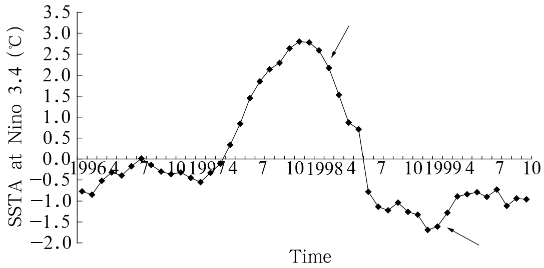

Fig.2. Evolution of monthly mean Nino 3.4 SST anomalies from January 1996 to October 1999. The arrows highlight the values of January 1998 and January 1999, respectively.

4.1 Sea level pressure field

The Siberian high (Mongolia high) and Aleutian low are the main planetary systems over Asia and the North Pacific during winter, and the intensity of a Siberian high presents a good positive correlation with the Asian winter monsoon. In both the winters of 1997 and 1998, the location of the Siberian high was near normal, but the peak pressure during 1997 (1998) was lower (higher) than the long-term average. The position of the Aleutian low changed greatly during the two winters. In 1997 the low center located at 150°W, by 30° easterly to the climate average, but in 1998 the Aleutian low split into two sections, with the main section centered at 165°E, by 15° westerly to the climate average. The difference in sea level pressure is revealed clearly from the departure fields of 1997 and 1998. As Fig.3 shown, the center of the positive value in the low latitudes over the Pacific Ocean, east of the Philippines proves that the West Pacific subtropical high during 1997 was stronger than that in 1998. In mid- and high-latitudes, negative value areas situated from central Siberia to South China while positive values were over the Northwest Pacific, so the East Asian planetary system was weak during 1997 resulting in a weak winter monsoon year. For the same reason, it was a strong one during 1998.

4.2 500-hPa geopotential height field

There are three troughs and three ridges on the long-term mean 500-hPa geopotential height in mid- and high latitudes during winter, including the East Asian trough and European trough near 140° and 30°E, respectively. On the geopotential height field during the winter of 1997 (the solid lines in Fig.4a), a wide low located over the North Pacific accompanied with weak East Asian trough, the European trough shifted eastward to about 55°E, and the ridge between the two troughs became weak. However, the subtropical high was obviously stronger than normal, as the 5880-gpm contour covered the whole Indian Ocean and the West Pacific.

The departure field (the dashed lines in Fig.4a) shows a center of −120 gpm over the Northeast Pacific, a negative area near the Ural Mountains and

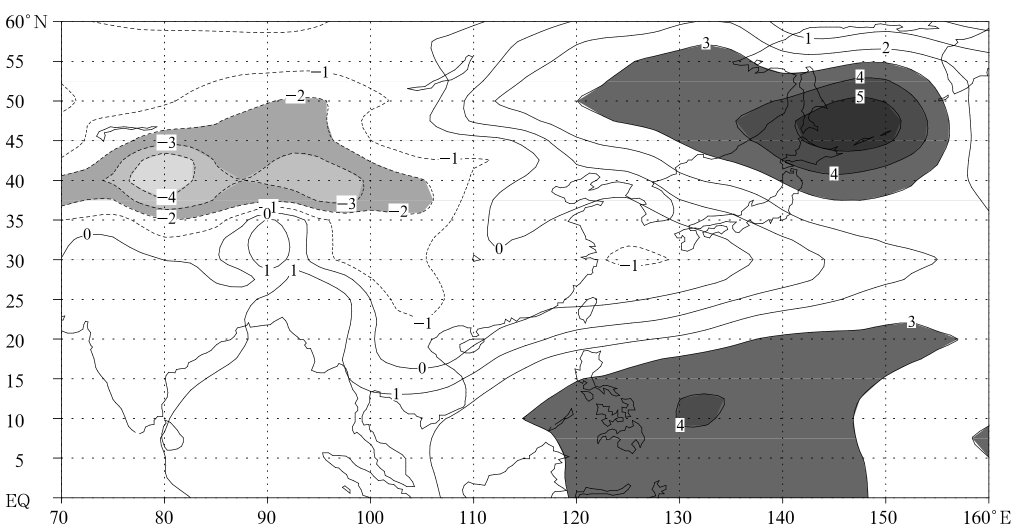

Fig.3. Differences in winter sea level pressure between 1997 and 1998. The heavy shaded areas denote the regions where sea level pressures are above 3 hPa, and the light shaded areas are below −2 hPa.

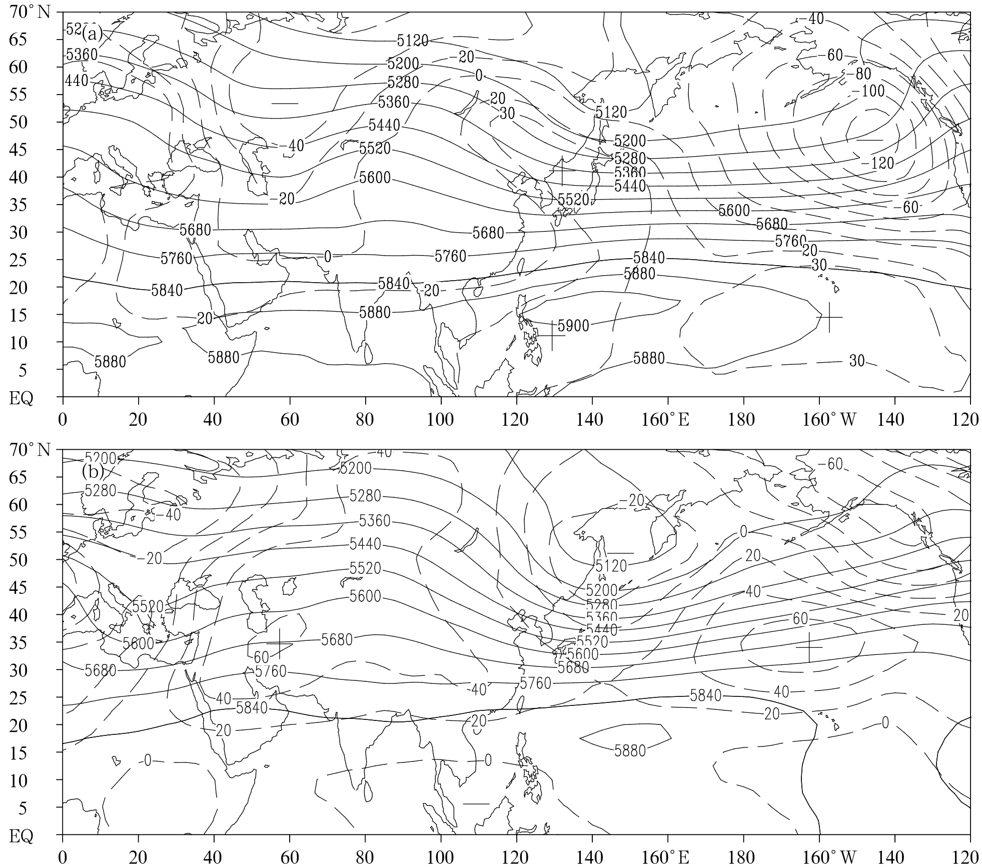

Fig.4. Winter mean 500-hPa geopotential heights (solid lines) and anomalies (dashed lines) during 1997 (a) and 1998 (b), respectively (units: gpm).

a positive area in East Asia with the center from Lake Baikal to the Japan Sea. The distribution means that the high level sheering flow over East Asia was too weak to impel the cold air at low level southward, leading to weaken northerly winter monsoon. However, the subtropical area was covered by a positive departure with a center of 33 gpm over the Philippine Sea, which strengthened the southwest airflow on the northwest side of the subtropical high.

The situation during the winter of 1998 was just the opposite of that during 1997. There were negative anomalies near the East Asian trough and the European trough, while there was a positive center of 60 gpm located at the mid-Siberian ridge. Since the height departure and long-term mean planetary wave were superposed in phase, the meridian wind in the middle and high latitudes was increased, which was favorable for outbreaks of cold air southward, resulting in the strong EAWM. In lower latitudes, the subtropical high was much weaker than the previous years, for instance the 5880-gpm contour shrunk to 140°-160°E, and the negative departure center located in the South China Sea, as a result the northerly wind in southern China was strengthened.

Regarding typical El Niño and La Niña events during 1997 and 1998, respectively, the analysis results above is in accordance with the conclusions of composite analysis of the ten El Niño and seven La Niña events during 1950-1989 (Mu and Li, 1999).

Figure 5 shows the meridional distribution of geopotential height anomalies, zonal wind, vorticity, and temperature anomolies averaged over 70°-120°E at 500 hPa for the winters of 1997 (solid circle) and 1998 (open circle). It can be seen that different characteristics appeared during rain-abundant and rain-scarce years (Fig.5a). During 1997, a strong

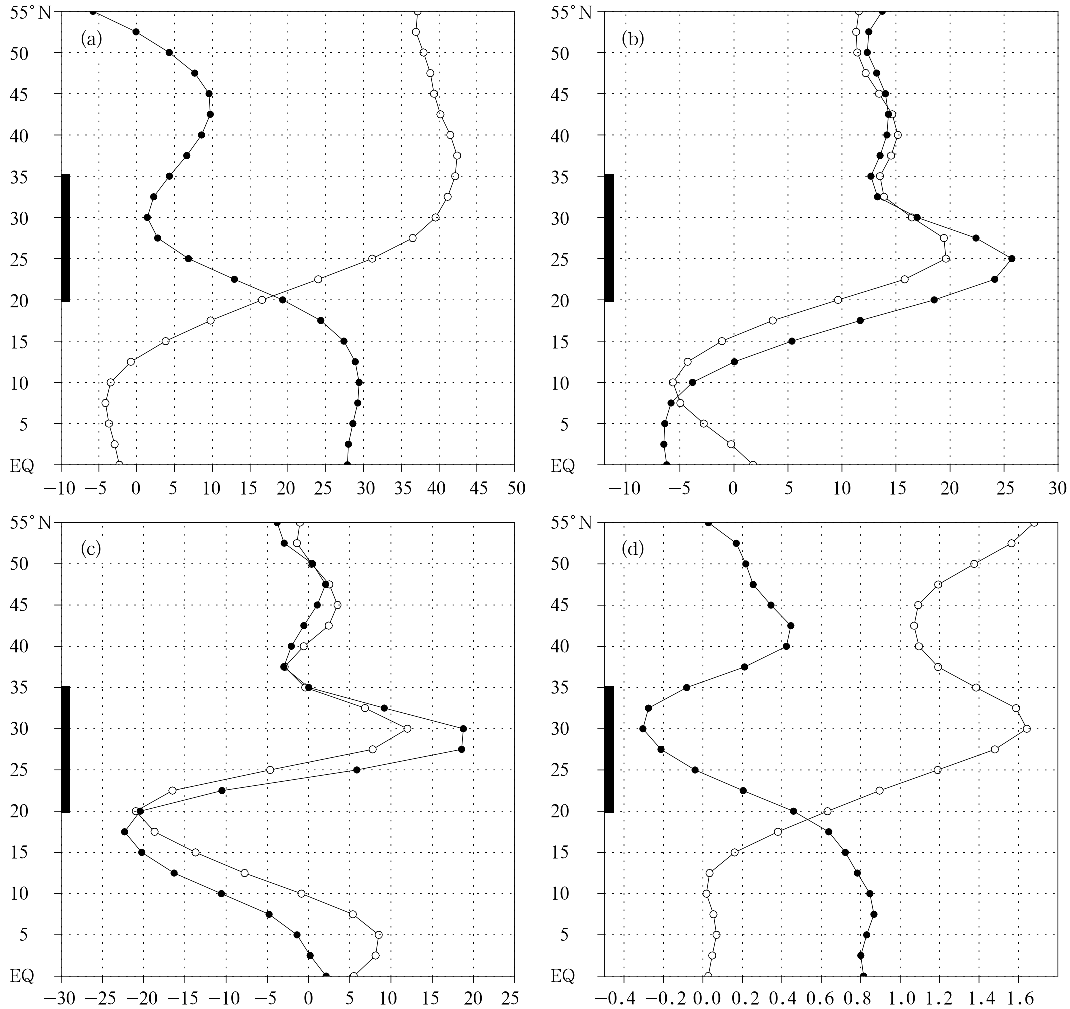

Fig.5. Meridional distribution of geopotential height anomalies (a; gpm), zonal wind (b; m s^{-1}), vorticity (c; $10^{-6}s^{-1}$), and temperature anomolies (d; °C) averaged over 70°-120°E at 500 hPa. Curves with solid and open circle for the winters of 1997 and 1998, respectively; thick black segment on ordinate denotes the latitude range of precipitation.

subtropical high formed a large positive departure in the lower latitudes, which made a difference of 28 gpm between 10° and 30°N, and increased the meridional gradient of geopotential height in the regions. However, during 1998 the strong mid-Siberian long wave ridge formed a large positive departure in the middle latitudes, induced a difference of −43 gpm between 10° and 30°N, and then decreased the meridional gradient. According to the geostrophic wind rule, the strength of a west wind is directly proportionate to the meriditional gradient of a geopotential height. As a result, the flow in the southern branch of westerlies was strengthened during 1997, and the maximum west wind reached 26 m s^{-1} at 25°N, 6 m s^{-1} larger than that during 1998 (Fig.5b). A strengthened west wind increased the cyclonic vorticity to the north of the maximum west wind latitude, leading to active south branch westerly troughs and more precipitation in frontal zones (Fig.5c). Furthermore, from the distribution of temperature anomalies (Fig.5d), it can be seen that during the 1997 winter the positive departure located near the Japan Sea due to the weakened East Asian trough, and the positive at low latitudes because of the stronger subtropical high, and the negative departure appeared in southern China as cold air activities forced frequently by upstream westerly troughs. But during 1998 the distribution was quite the other way. Figure 5d also shows that the temperature departure gradient between 10° and 30°N during 1997 (1998) was the same sign with (opposite to) the long-term mean, therefore strengthened (weakened) the meridional temperature gradient in that area, and the opposite situation occurred in the band between 30° and 42.5°N.

4.3 850-hPa wind field

The difference of circulations in rain-abundant and -scarce years is also clear on the wind departure field at 850 hPa. Influenced by ENSO and a weak winter monsoon, strong zonal wind departure appeared near the equator during the winter of 1997. At the same time, southerly wind departure appeared in the eastern China and South China Sea. In Fig.6a, the anticyclone A_1 with the center located in the Philippine Sea controlled the subtropical region. Its stable maintenance strengthened the southwest flow on the northwest side and was conducive to the warm moisture flow transport northward in the lower latitudes. The other anticyclone A_2 near Hokkaido reflected the positive departure at 500-hPa geopotential height. Between the two anticyclones there was a cyclonic circulation, with the center over the the Yangtze River Basin. The cyclone and warm cyclonic shear on the east side could be a benefit to the convergence of warm and wet air,

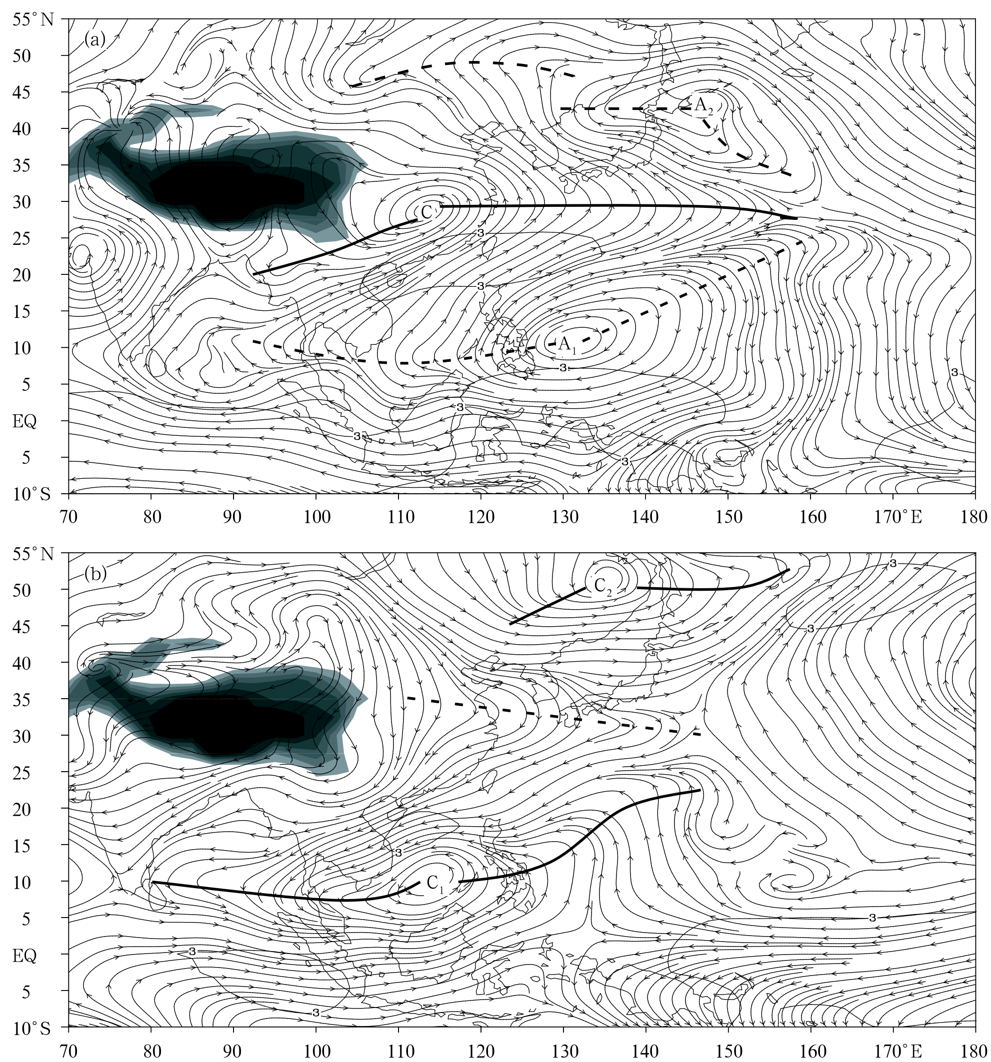

Fig.6. Winter 850-hPa anomalous streamline fields for 1997 (a) and 1998 (b). Thin solid line: anomalous isotaches, m s^{-1}; thick solid/dashed line: trough/ridge line, respectively.

making it the principal system leading to the abundant precipitation in southern China. Figure 6b shows the departure flow field in 1998. Cyclonic circulation with its center in the southern South China Sea was over the subtropical region, accompanied with another close-up cyclonic circulation in the west of Sakhalin and a ridge near 32.5°N in East Asia. A stronger northeasterly monsoon and anticyclonic vorticity led to less precipitation in southern China.

Compared Figs.6a with b, it can be found that the circulation systems are opposite between the winters of 1997 and 1998. In the first year there were ridges, trough, and ridges in the lower, middle, and high latitudes, respectively, but in the second year, the inverse pattern dominated.

4.4 200-hPa wind field

The most significant characteristic at the 200-hPa anomalous wind field during 1997 is the cyclonic circulation in East Asia. The cyclone also appeared in other warm episodes of ENSO events. Wang and Fu (2000) proposed that it was a member of the Pacific-East Asia teleconnection, and Lau and Nath (2000) using a GCM model revealed the anomalous cyclone existed at the upper troposphere in the warm episodes of ENSO events, but they did not pay more attention to the cyclone. From the analysis in this section, the results reveal that the cyclone has a different vertical structure from the Philippine Sea anomalous anticyclone. The former is equivalent-barotropical, stronger

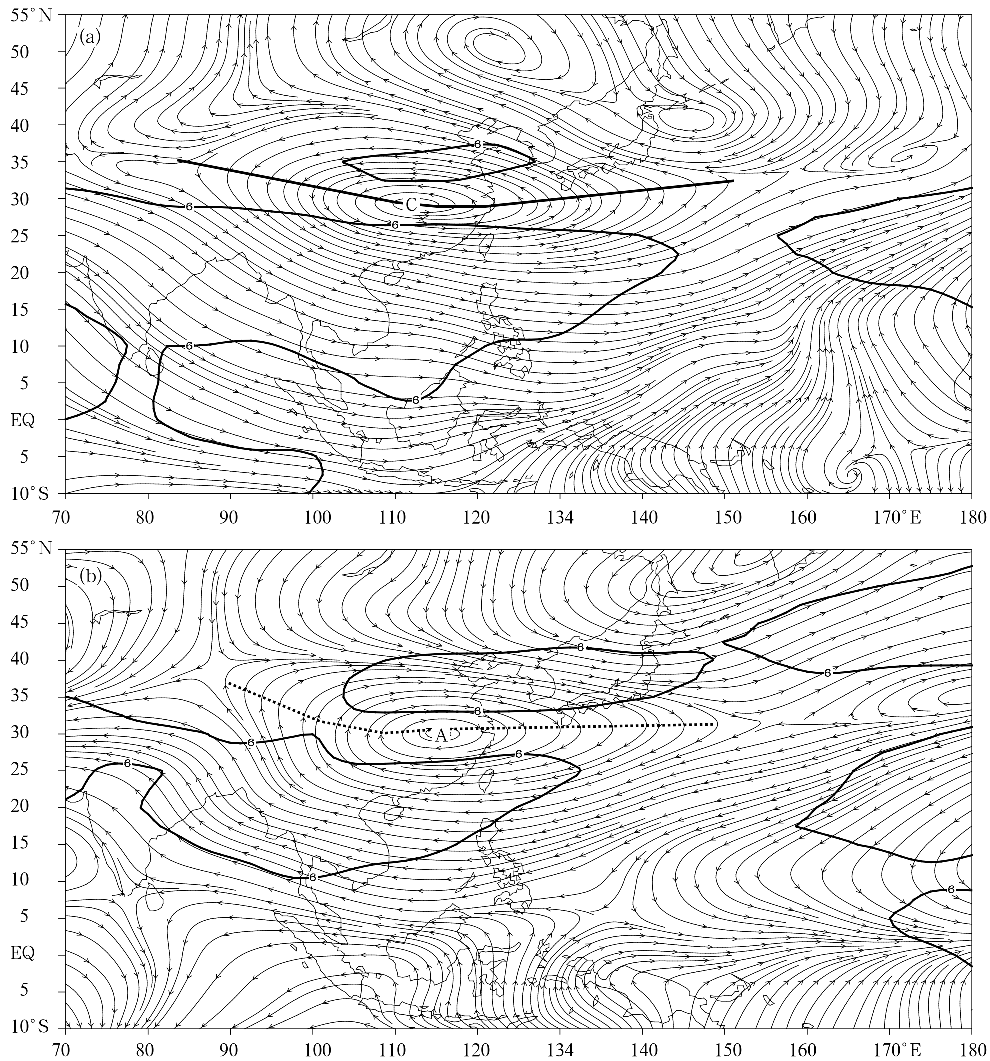

Fig.7. As in Fig.6, but for 200 hPa.

at higher levels, but the latter is only obvious at the lower troposphere, weaker at higher levels. Their formational mechanics were also different. The Philippine Sea anomalous anticyclone developed with the local sea temperature cool-down and the thermal force, but the cyclonic circulation in East Asia may be a result of the dynamic force of two anticyclones on both the north and south sides at lower levels. According to the distribution of anomalous temperatures and the thermal-wind relationship, the westerly (easterly) wind departure on the south (north) side of the anomalous cyclone increased with height, so the circulation tends to be more dominant at the upper level.

From the 200-hPa anomalous wind field (Fig.7b), it can be seen that the cyclonic circulation, which was shown in the South China Sea at the lower level, disappeared at 200-hPa field, and an anticyclone dominated in East Asia instead. Besides, the upper divergence related with the deep convection near the marine continent strengthened during 1998, leading to easterly anomalous wind in the Indian Ocean and marine continent, and westerly wind departure in the equatorial West Pacific.

5. Differences in moisture transportation between rain-abundant and -scarce winters

The water vapor transportation characteristics during the two typical winters were studied to understand further the precipitation anomaly during winter. Figure 8 shows the winter average vertically integrated water vapor flux. Besides the westward moisture transportation band in the lower latitudes, there is one band along with the flow in the southern branch of westerlies in the middle latitudes of East Asia and the Northwest Pacific and another northward band by the meridional wind near the South China Sea and Indo-China Peninsula. Therefore the winter moisture in southern China came from both the southwesterly flow in front of the trough in the southern branch of westerlies, and the turning flow in the Indo-China Peninsula and South China Sea. The prevailing winter wind is easterly over the Indian Ocean, so the warm moisture there has little contribution to the precipitation in China. Compared Figs.8a with b, it can be seen that the subtropical anticyclone was southerly during the 1997 winter, transferring water vapor to southern China with the south branch trough in the Bay of Bengal. But in 1998 the anticyclone was westerly and northerly, accompanied by a weak south branch trough, transferred less moisture.

To reveal the different characteristics of winter water vapor transportation at vertical levels, the vertical profiles of area average zonal and meridional moisture transportation in southern China (20°-30°N, 105°-120°E) were calculated, respectively. On the zonal moisture transportation (Fig.9a), it shows easterly wind transportation at 1000 and 925 hPa, weak easterly (westerly) wind in the rain-scarce (rain-abundant) year at 850 hPa, and the maximum westerly moisture transportation at 700 hPa. Due to the weak monsoon during the 1997 winter, the easterly wind weakened at the lower level, and the flow in the southern branch of westerlies enhanced at the middle and high level. As a result, the zonal water vapor transportation during 1997 was larger than that during 1998. On the meridional water vapor transportation (Fig.9b), though the northeast monsoon at 1000 hPa brought water vapor from the East China Sea to South China, the moisture transportation flux in the lower latitudes is often larger than that in higher latitudes, resulting in water vapor divergence over South China and the northern South China Sea at that level. The influence of El Niño events on meridional moisture transportation was more significant at 925 and 850 hPa, where the large southerly moisture transportation happened by the west side of the strong subtropical anticyclone.

From Fig.9 it can be seen that the maximum zonal moisture transportation was near 700 hPa, and the maximum meridional moisture transportation at 850 hPa, so that the moisture transporters at the two levels were analyzed to reveal the moisture source of large regional precipitation in the winter in China. In Figs.10a-d, there are obvious differences between the water vapor transportation at 850 and 700 hPa, as well as large differences between the rain-abundant and

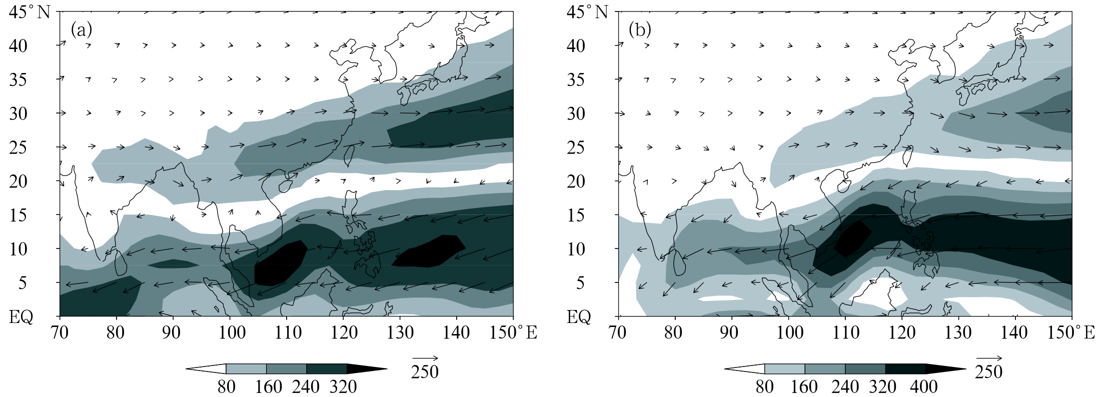

Fig.8. Vertically integrated water vapor transport in the winters of 1997 (a) and 1998 (b). Shading denotes above 80 kg $m^{-1}s^{-1}$, and intervals are 80 kg $m^{-1}s^{-1}$.

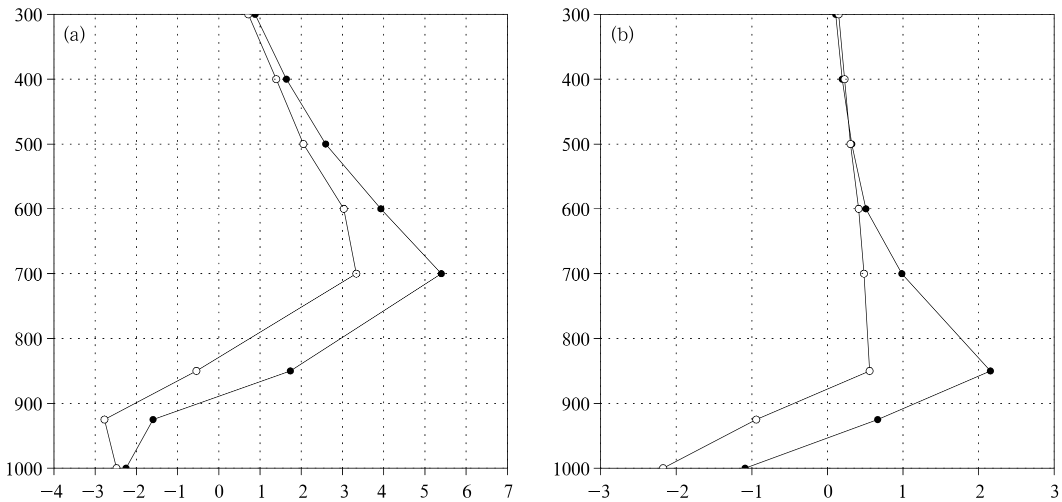

Fig.9. Vertical profiles of zonal (a) and meridional (b) water vapor transport averaged over southern China (20°-30°N, 105°-120°E). Curves with solid/open circle for the winters of 1997/1998, respectively; units: g $s^{-1}m^{-1}Pa^{-1}$.

rain-scarce years. At 850 hPa during 1997, an anticyclone was in the north of Philippine Sea, accompanied by the southerly flow on the west side of the circulation which brought warm and wet air in the tropical ocean to the north of South China Sea and southern China. However, during 1998 the northeasterly wind was dominant in the northern part of the South China Sea under the influence of a strong winter monsoon, and only weak moisture transportation along the west of the continental cold anticyclone to the Indo-China Peninsula and southwestern China. At 700 hPa, the water vapor transportation from the low latitudes turning current tends to be weak, and the moisture transportation on the south side of the Yangtze River Basins mainly comes from the flow in the southern branch of westerlies. Because of the stronger westerlies and active troughs, the water vapor transportation during 1997 is obviously larger than that during 1998.

6. Conclusions

(1) ENSO events and East Asia circulations are the main reasons for the precipitation diversity over South China during the winters of 1997 and 1998. At the mature phase during 1997, weaker and eastward shifted westerly troughs and ridges, a strong subtropical high, and the weak EAWM, enhanced southerly wind at the lower level over South China and the north

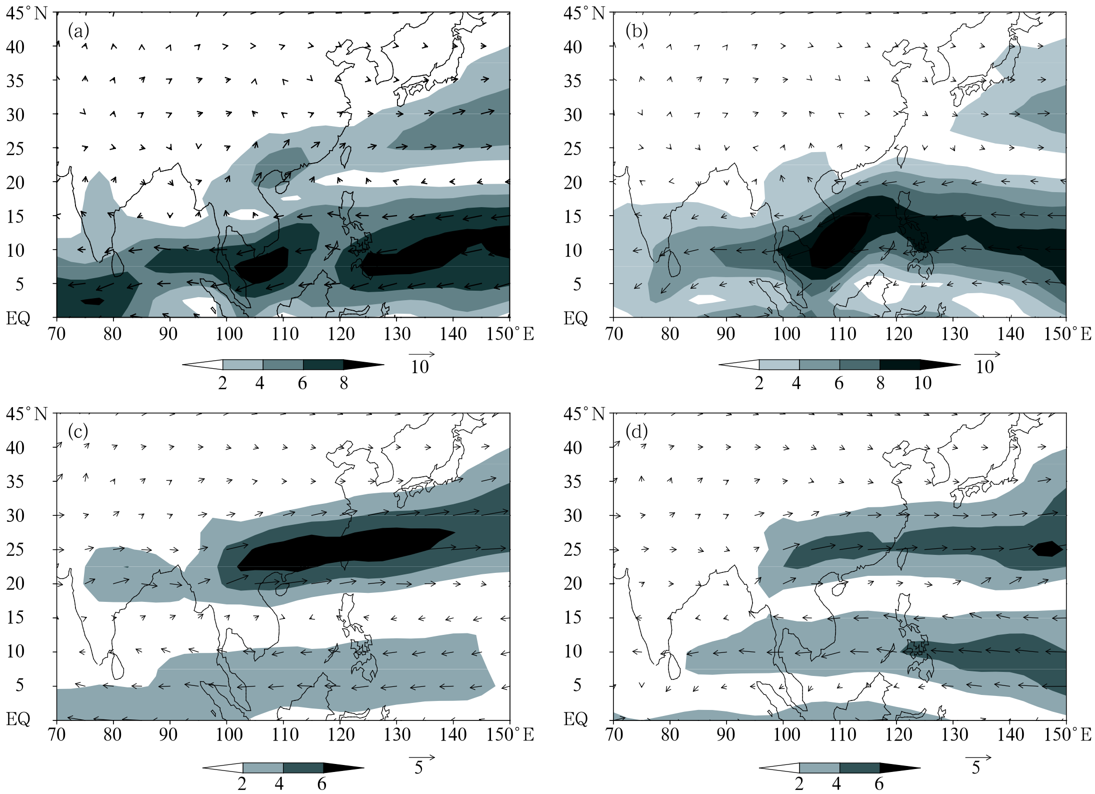

Fig.10. Water vapor transport at 850 hPa (a, b) and 700 hPa (c, d) during the winters of 1997 (a, c) and 1998 (b, d). Shading denotes above 2 g $s^{-1}m^{-1}Pa^{-1}$.

of South China Sea, and active disturbances in the southern branch of westerlies, all contributed to the abundant water vapor transportation in South China. While at the mature phase during 1998, strong westerly troughs and ridges, a weak subtropical high, strong EAWM, and dominant northerly winds were not favorable for rainfall over South China.

(2) During the rain-abundant winter, there are two anomalous anticyclones in the Philippine Sea and Hokkaido, respectively, and a cyclone anomalous circulation in the middle Yangtze River Basin. In the upper troposphere, the Philippine Sea anticyclone tends to disappear, but the cyclonic circulation in the Yangtze River is strengthened. It proves that the mechanism and vertical structure of the cyclonic anomalous circulation is not the same as the Philippine Sea anomalous anticyclone. The cyclone and anticyclone anomalies situation in rain-scarce years is nearly opposite.

(3) Water vapor over southern China during winter mainly comes from the southwesterly current ahead of troughs in the southern branch of westerlies and the turning current in the South China Sea−Indo-China Peninsula. During 1997 the strong flow in the southern branch of westerlies and the south wind on the west side of the Philippine Sea anticyclone strengthened the transportation, while during 1998 the moisture transportation weakened due to the weak flow in the southern branch of westerlies and the cold anticyclone located in southeastern China.

(4) The path of water vapor transportation changed obviously with height. The transportation at middle and lower levels of the troposphere assumed the maximum water vapor. There was some moisture transportation at 925 hPa and below, by the northeasterly wind. At 850 hPa, the southerly current on the west side of the subtropical anticyclone carried tropical warm and wet air northward via the middle and north part of the South China Sea and Indo-China Peninsula. At 700 hPa and above the flow in the southern branch of westerlies transported the

moisture eastward.

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