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Anomalous winter temperature and precipitation events in southern China

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Abstract: This paper analyzed the anomalous low-temperature events and the anomalous rain-abundant events in January since 1951 and winter since 1880 for southern China. The anomalous events are defined using ±1σ thresholds. Twelve cold Januaries are identified where temperature anomaly below –1σ, and ten wet Januaries are identified where precipitation anomaly above +1σ. Among these events there are three patterns of cold-wet Januaries, namely 1969, 1993 and 2008. The NCEP/NCAR reanalysis data are used to check the atmospheric circulation changes in association with the anomalous temperature and precipitation events. The results show that the strong Siberian High (SBH), East Asian trough (EAT) and East Asian jet stream (EAJS) are favorable conditions for low-temperature in southern China. While the anomalous southerly flow at 850 hPa, the weak EAT at 500 hPa, the strong Middle East jet stream (MEJS) and the weaker EAJS are found to accompany a wetter southern China. The cold-wet winters in southern China, such as January of 2008, are mainly related to a stronger SBH, and the circulation in the middle to upper troposphere is precipitation-favorable. In wet winters, the water vapor below 500 hPa is mainly transported by the anomalous southwesterly flow and the anomalous southern flow over the Indo-China Peninsula and the South China Sea area. The correlation coefficients of MEJS, EAMW (East Asian meridional wind) and EU (Eurasian pattern) to southern China precipitation in January are +0.65, –0.59 and –0.48 respectively, and the correlations for high-pass filtered data are +0.63, –0.55 and –0.44 respectively, the significant level is all at 99%. MEJS, EAMW and EU together can explain 49.4% variance in January precipitation. Explained variance for January and winter temperature by SBH, EU, WP (west Pacific pattern) and AO (Arctic Oscillation) are 47.2% and 51.5%, respectively. There is more precipitation in southern China during El Niño winters, and less precipitation during La Niña winters. And there is no clear evidence that the occurrence of anomalous temperature events in winter over southern China is closely linked to ENSO events.

Keywords: southern China; low-temperature; rainfall and snowfall; freezing; atmospheric circulation; water vapor transport

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1 Introduction

Low-temperature and snow disaster are the two common meteorological disasters in winter over China. Snow disasters occur mainly in the Tibetan Plateau, northern Xinjiang, Inner Mongolia and Northeast China (Qin *et al*., 2005; Dong *et al*., 2001; Qin *et al*., 2006), while rarely happen in southern China. In recent decades, obvious warming trend in winter minimum temperature has occurred throughout the country (Qin *et al*., 2005; Zhai *et al*., 1997; Ren *et al*., 1998; Chen *et al*., 1999). Many previous studies have paid much attention to regional warming in context of global climate change (e.g., Li *et al*., 1989a; He *et al*., 2008; Gong *et al*., 1999a; and others). However, there is less research on winter low-temperature and snow disaster in southern China.

China suffered from severe climate from middle January to early February 2008 when low-temperature, glaze and heavy snowfall significantly struck the transportation, communication and electricity transmission lines in the south of the country. It stimulates great interest in studying the severe winter. Climatic data show that negative temperature anomaly of this winter probably was moderate, near or less than the threshold of cold (anomaly<–1.5℃) and much less than that of severe winters (anomaly<–2.5℃) (Wang, 2008). Furthermore, he considered that the temperature fluctuation in early 2008 may belong to an interannual variability, not a reflection of interdecadal variability. However, another research showed that the maximal persistent low-temperature days, snowy days and the freezing days all broke the records since 1951, being of a probability of once-in-a-century (Wang *et al.*, 2008). The study of Gao *et al*. (2008) stated that, a La Niña event began in August 2007 and developed very quickly, leading to the anomalous general circulations in the Northern Hemisphere, which was considered to be the most important causes of the unprecedented disasters in early 2008 over southern China. All the previous studies play important roles to understand the nation-wide or regional anomalous temperature and precipitation events in winter. However, there is still a lack of systematic researches on atmospheric circulations of the simultaneously anomalous low-temperature and rain-abundant events in January or winter over southern China. The purpose of this paper is to check the anomalous low-temperature and rain-abundant events in winter over southern China from long climate time series, and to analyze the atmospheric circulation features associated with the anomalous events, especially to focus on the circulation conditions when there exist anomalous low-temperature and rain-abundant events simultaneously. Therefore we hope that this study will get a further understanding of the circulation background of the anomalous events, and provide useful information and reference for predicting.

2 Research area and data

The severest area suffered from low-temperature, freezing, heavy rainfall and snowfall in early 2008 are selected as research area in the present study, including Hunan, Hubei, Anhui, Jiangsu, Jiangxi and Guizhou provinces and the city of Shanghai, also called southern China for short. Monthly temperature and precipitation datasets for the period from January 1951 to February 2008 at 28 base stations covering the research area are used (Figure 1). These datasets are taken from the National Meteorological Information Center and they are passed quality control by the homogenization method. To eliminate the effect of stations distant difference, we first standardize each station record (referring to the period of 1971–2000), and then take the mean series of the 28 stations as temperature and precipitation indices for the research area. In addition, the seasonal temperature and precipitation datasets from historical documents or early observations since 1880 at 20 stations (big circles in Figure 1) in the research area are also analyzed (Pu *et al.*, 2007; Wang *et al.*, 2000). The data employed in the present study are also the NCEP/NCAR monthly reanalysis data from January 1948 to February 2008 with a 2.5°×2.5° spatial resolution and on 12 levels (from the surface to 100 hPa), including height field (h), zonal wind (u), meridional wind (v), vertical wind (ω) and specific humidity (q), etc. Monthly sea level pressure (SLP) data with 5°×5° spatial resolution from January 1850 to February 2008 are also used, which are taken from British Met Office Hadley Centre.

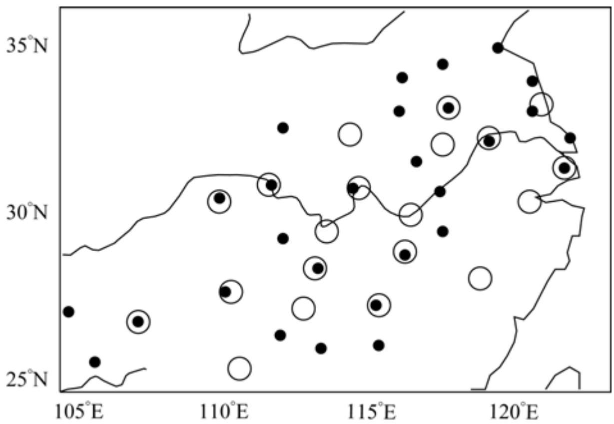

Figure 1 Distribution of meteorological sites (the filled dots are 28 observational sites, and the open circles are 20 historical data sites.)

3 Anomalous low-temperature events and associated circulation features

3.1 Anomalous low-temperature events

Firstly the anomalous temperature events in January since 1951 were checked (Figure 2a). It shows an obvious warming trend during the past ~60 years (+0.22℃/10a, significant at the 99% level). It is consistent with previous researches that implied the influence of climate warming upon warm winter frequency (Zhai *et al.*, 1997; Ren *et al.*, 1998; Gong *et al.*, 1999a). At the same time, there are evident annual fluctuations occurring with the warming trend, and some low-temperature events also appeared in the warm phase accompanied by the annual fluctuations. There are twelve anomalous cold Januaries and five anomalous warm Januaries since 1951 according to ±1σ statistical standard (Table 1). The mean temperature anomaly of the four lowest January is up to –2.28σ, and January 2008 is only next to 1977, 1955, 1984 and 1956, ranking the fifth. Since 1951, the probability of anomalous cold January reached or exceeded January 2008 is approximately once every 11.6 years. In addition, the distribution of the mean temperature anomaly of the 12 anomalous low-temperature Januaries present that the temperature is lower than normal over most part of the country (not shown), the middle and lower Yangtze River basin reaches up to –1.5℃-

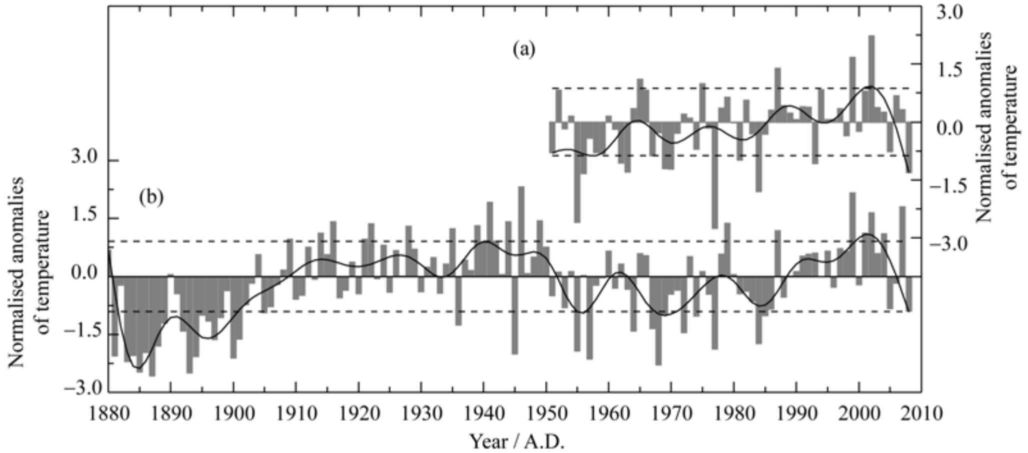

Figure 2 The regional mean temperature of January (a) and winter (b) in southern China (Dashed lines are +1σ and –1σ respectively, smoothed lines are low-frequency variations.)

Table 1 Extremely warm and cold January/winter as defined as temperature anomaly in excess of ±1σ

		Year
T′>+1σ	January	1965, 1975, 1987, 1999, 2002
	Winter	1909, 1914, 1916, 1921, 1922, 1928, 1935, 1939, 1941, 1942, 1944, 1946, 1949, 1979, 1987, 1999, 2001, 2002, 2004, 2007
T′<–1σ	January	1955, 1956, 1962, 1963, 1967, 1969, 1970, 1977, 1981, 1984, 1993, 2008
	Winter	1881, 1883–1889, 1892–1894, 1896–1898, 1900, 1901, 1905, 1936, 1945, 1955, 1957, 1964, 1967, 1968, 1972, 1974, 1977, 1984, 1985

(T' for temperature anomaly, 1881 for 1880/1881winter, and so on.)

–2℃, being one of the three negative anomaly centers of temperature (the other two centers are southern Xinjiang and Inner Mongolia Plateau).

We further analyzed the anomalous wintertime temperature events since 1880. Because there are only seasonal temperature data in the early period, so we checked only the anomalous temperature events in winter. There is a well consistency between winter mean temperature and January mean temperature, they correlate at +0.64 during the period of 1950/51–2007/08, significant at the 99% level. It shows that winter mean temperature can reflect temperature fluctuations of January generally well, and also indicates the temperature variations of January are related closely to the whole winter climate background. Figure 2b shows the winter temperature series since 1879/80. There are 29 anomalous cold winters and 20 anomalous warm winters since 1880 according to ±1σ statistical standard (Table 1). It is worth noting that, although there exist high similarity between winter mean temperature and Januaries temperature, there are certain differences between them, especially some anomalous events are not in one-to-one correspondence between the two series. In the period of 1951–2008, there are ten anomalous cold winters, of which there are only four years with anomalous cold Januaries simultaneously, namely 1955, 1967, 1977 and 1984. January 2008 is an anomalous cold event, while 2007/08 winter mean temperature anomaly is –0.99σ, very close to but does not reach the –1σ statistical threshold. So considering since 1880, the probability of anomalous cold winter reached or exceeded 2007/08 winter is approximately once every 4.4 years, obviously higher than the frequency of cold Januaries. This may be related to the higher variability of the single January temperature than winter.

There are obvious stage characteristics in the anomalous low-temperature events of southern China during the past 130 years. This may be related to the interdecadal fluctuation of average temperature. The low-frequency changes of the overall winter temperature could be divided into four sessions: colder in 1880–1905, warmer in 1906–1950, colder in 1951–1985 and warmer since 1986. The four stages have 17, 2, 10 and 0 anomalous cold winters, and 0, 13, 1 and 6 anomalous warm winters respectively. These indicate that anomalous low-temperature events occur mainly in decadal colder periods, and anomalous warm winters occur mainly in decadal warmer periods. The winter temperature in southern China presents a warming trend during the last one hundred years on the whole, accompanied by a decreasing trend in low-temperature events and an increasing trend in warm winter, this phenomenon may be connected with the context of global warming.

Intense interannual variability plays an important role for low-temperature events under the background of global warming (Wang *et al*., 2008). Although a warming trend has dominated and more warm winters appeared since the late 1980s, we can not ignore the strong interannual fluctuations may lead to the anomalous low-temperature event like that in 2007/08 winter, especially January 2008. The same situation also appeared in the 1930s–1940s, when the winter temperature is as warm as that in the 1990s, but two anomalous low-temperature events occurred in 1936 and 1945 with -1.4σ and $-2.2\ \sigma$ temperature anomaly respectively, all exceeding the low-temperature in 2007/08 winter (Figure 2b).

3.2 Atmospheric circulation features

Temperature change is strongly affected by the atmospheric circulation. Many studies (Gong *et al*., 1999a, 1999c, 2002; Li *et al*., 2007; Ding *et al*., 1990; Wallace *et al*., 1981; Thompson *et al*., 1998) showed that some circulation systems could affect the East Asian monsoon and then affect winter temperature over China directly or indirectly, including Siberian High (SBH), Eurasian pattern (EU), west Pacific pattern (WP), Arctic oscillation (AO) and so on. Here we further checked the statistical relations between these major circulation factors and winter temperature change in southern China (Table 2). The correlation coefficients between SBH, EU, WP, AO and January temperature in southern China are –0.64 (significant at the 99% level), –0.30 (significant at the 95% level), –0.22 and +0.23, respectively. To avoid the overestimate in correlation coefficients resulting from the low frequency component of time series, we also checked their high frequency components. After high-pass filtered, they correlate at –0.69 (significant at the 99% level), –0.30 (significant at the 95% level), –0.27 (significant at the 95% level) and +0.12, respectively. The results of pre- and post filtering are consistent well. The high significant correlations indicate the four circulation factors are related steadily to temperature variability in January over southern China. The four factors can explain 47.2% variances of January temperature in the observation period (1951–2008). It is worth noting that, Siberian High plays the role of a bridge while connecting these circulation factors with temperature in East Asia. The correlation coefficient between Siberian High and winter temperature is –0.48, after high-pass filtered they correlate up to –0.69, significant at 99% level. It shows a stable relationship between them during the last century. Based on the comparison of Siberian High index with winter temperature in southern China (Figure 3), it can be found that some extreme low-temperature events (e.g., 1976/77,

Table 2 Correlation coefficients between January temperature, precipitation of southern China and atmospheric circulation factors

		SBH	MEJS	EAMW	EU	WP	AO
T	r1	–0.64**	+0.04	+0.07	–0.30*	–0.22	+0.23
	r2	–0.69**	–0.17	+0.10	–0.30*	–0.27*	+0.12
P	r1	–0.03	+0.65**	–0.59**	–0.48**	–0.14	+0.29*
	r2	–0.02	+0.63**	–0.55**	–0.44**	–0.06	+0.22

(**: significant at the 99% level, *: significant at the 95% level. T for temperature, P for precipitation, r1 is the raw data correlation coefficient, r2 is the correlation coefficient after high-pass filtered, SBH indicates Siberian High, MEJS for the Middle East jet stream, EAMW for the East Asia meridional wind, EU for the Eurasian pattern, WP for the west Pacific pattern and AO for the Arctic Oscillation.)

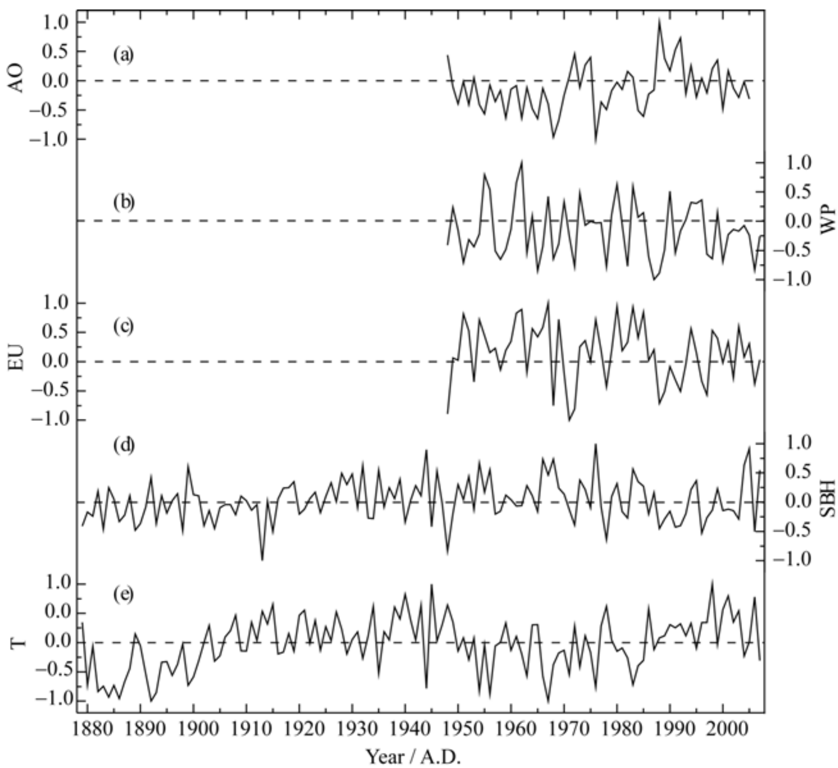

Figure 3 Comparison of Arctic oscillation (a), west Pacific pattern (b), Eurasian pattern (c), Siberian High (d) with winter temperature of southern China (d) (All series are standardized to [–1, 1])

2007/08) correspond well to anomalous strong Siberian High. So, we need pay much more attention to the variability of Siberian High when understanding the anomalous low-temperature in southern China.

The lower atmosphere circulation and climate change are closely related with the circulation system of the middle to upper troposphere. Applying composite analysis, we focused on analyzing the circulation changes in lower to upper troposphere corresponding to the anomalous low-temperature in January over southern China. Composite anomaly fields of seal level pressure (SLP), wind vector at 850 hPa, geopotential heights at 500 hPa and zonal wind at 200 hPa for 12 cold Januaries in southern China are shown in Figure 4. There exists significant positive SLP anomaly in Siberian area, the centre value of which is up to 3–4 hPa (Figure 4a). The maximum positive anomaly in Siberian centre is 11 hPa in January 2008, and it even reached 17 hPa in January 1977 when southern China was the coldest since 1951. It concludes that anomalous strong Siberian High may play an important role in influencing the low-temperature in southern China, because strong Siberian High can lead to strong northerlies prevailing in East Asia. We can see it clearly from wind vector at 850 hPa (Figure 4b), in which the dominated anomalous northerlies occur from northeast to south China. It is obvious that the temperature advection coming from high latitude exerts an important impact on the low-temperature in southern China. Meanwhile, significant positive anomaly in the high latitude over Asian continent and significant negative anomaly in 30–40°N area over East Asia are the outstanding features at the middle troposphere (Figure 4c). This circulation pattern implied a strong East Asia trough (EAT) that means the meridional circulation prevailed over East Asia. The intensified northwest steering flow at the middle to upper troposphere is favorable for cold air moving southward at the lower layer and strengthening the low-temperature in southern China (Huang *et al*., 2007). Composite anomaly fields of zonal wind at 200 hPa shows that the East Asia jet stream (EAJS) is weaker while there is low-temperature in southern China (Figure 4d). Those changes may induce lower temperature in southern China via affecting East Asia meridional secondary circulations and intensifying weather disturbance at the lower troposphere (Mao *et al*., 2007). Figure 5 shows the height–latitude profile of vertical circulation anomaly along the 115°E for the 12 cold Januaries in southern China. It reappears partly the anomalous circulation features from lower to upper troposphere, e.g. the anomalous northerly wind. An anomalous low temperature at 20–60°N extends from the surface to 400 hPa level, with the maximum negative

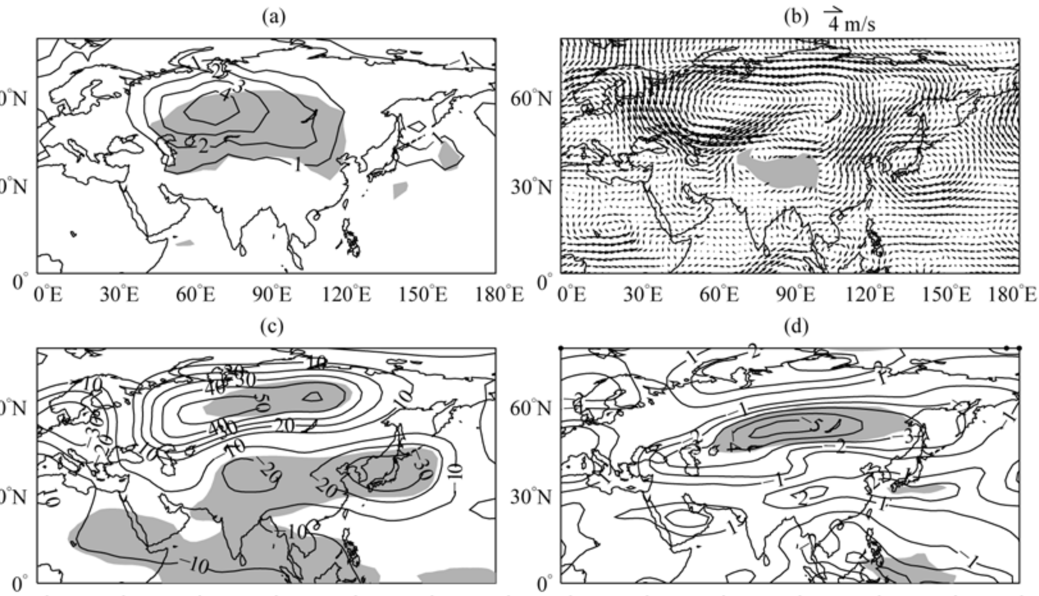

Figure 4 Composite anomaly fields of SLP (a, unit is hPa), wind vector at 850 hPa (b, unit is m/s), geopotential heights at 500 hPa (c, unit is gpm) and zonal wind at 200 hPa (d, unit is m/s) for 12 cold Januaries in southern China (Areas significant at the 95% level are shaded in a, c and d. Shaded area is Qinghai–Tibet Plateau in b)

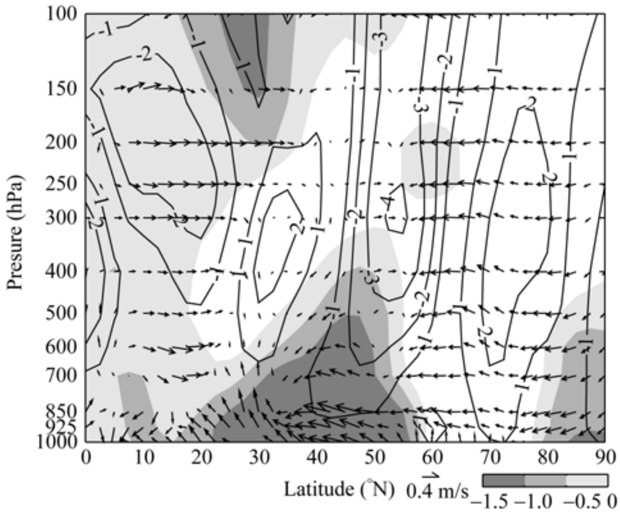

Figure 5 Composite anomaly fields of wind vector along 115°E for 12 cold Januaries in southern China
(The vector are vertical wind and meridional wind, and Vertical wind velocity are multiplied by 10, unit is m/s; the isolines are zonal wind, solid lines are positive anomalies, dashed lines are negative anomalies, unit is m/s; the negative air temperature anomaly areas are shaded, unit is ℃.)

value exceeding –1℃, and the anomalous northerly wind is evident below 700 hPa. Therefore the distribution of negative temperature anomaly may be related with anomalous sinking motion below the north of jet stream, and the anomalous northerlies in lower to middle troposphere.

4 Anomalous precipitation events and associated circulation features

4.1 Anomalous precipitation events

In this section we check the anomalous precipitation events in January over southern China. Like temperature, the mean precipitation of 28 stations was taken as precipitation index. A January precipitation series since 1951 is shown in Figure 6a. There are ten anomalous

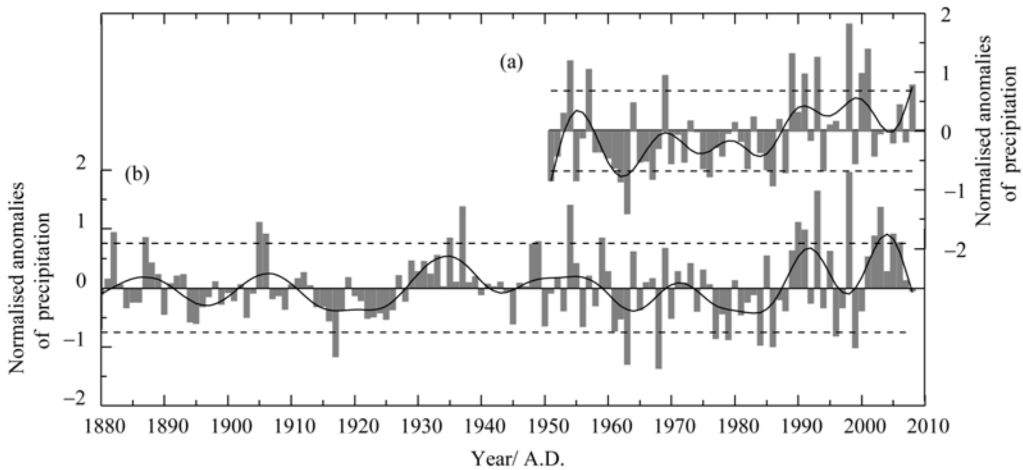

Figure 6 The regional mean precipitation of January (a) and winter (b) in southern China (Dashed lines are +1σ and –1σ respectively, smoothed lines are low-frequency variations.)

rain-abundant Januaries and five anomalous rain-scarce Januaries since 1951 according to ±1σ statistical standard (Table 3). The mean precipitation anomaly of the ten rain-abundant Januaries is up to +1.71σ. The precipitation anomaly of January 2008 is +1.14σ, ranking the last one of the ten anomalous rain-abundant Januaries. So, the probability of anomalous rain-abundant events as January 2008 is approximately once every 5.8 years. But for some single meteorological elements, e.g. the maximal persistent low-temperature days, snowy days and the freezing days, they all broke the records since 1951, showing a centennial probability (Wang *et al*., 2008).

Table 3 Extremely wet and dry January/winter as defined as precipitation departures in excess of ±1σ

		Year
P′>+1σ	January	1954, 1957, 1969, 1989, 1991, 1993, 1998, 2000, 2001, 2008
	Winter	1882, 1887, 1905, 1906, 1935, 1937, 1949, 1954, 1959, 1990, 1991, 1993, 1998, 2003, 2005, 2006
P′<−1σ	January	1951, 1955, 1962, 1963, 1967, 1976, 1986, 1988
	Winter	1917, 1963, 1968, 1977, 1979, 1984, 1986, 1996, 1999

(P' for precipitation anomaly, 1881 for 1880/1881winter, and so on)

Like temperature, there are only seasonally precipitation data in the early period, so we checked only the anomalous precipitation events in winter. There is a well consistency between winter total precipitation and January precipitation with the high correlation coefficient (+0.56) during the period of 1950/51–2007/08, significant at the 99% level. There are sixteen anomalous rain-abundant winters and nine anomalous rain-scarce winters since 1880 according to ±1σ statistical standard (Table 3). The precipitation in January 2008 exceeds +1σ statistical standard, but the total precipitation in 2007/08 winter is close to the mean climate state. It concludes that the total precipitation in 2007/08 winter is not abnormal, but the rainfall distribution is extreme uneven, which concentrated mainly in middle January to early February. Precipitation has a higher variability than temperature, which may lead to regional and monthly extreme rainfall or snowfall events.

Although the decadal fluctuation of winter precipitation in southern China is weaker than temperature, it can also identify the relative lower precipitation in the 1910s–1920s, 1960s to early 1980s, and relative higher precipitation in the 1930s, 1950s and 1990s winters. Moreover, the variance of winter precipitation is 0.52 since 1950, higher than the total variance of 0.35 since 1880. It showed that the interdecadal fluctuation of winter precipitation is intensified in the past 60 years. It is worth noting that, there are seven anomalous rain-abundant Januaries occurring since 1989 corresponding to the rapid global warming. Whether the increase of winter precipitation variability in recent decades is related to global warming, it is an open question and needs more researches.

4.2 Atmospheric circulation features

To understand the change of atmospheric circulation corresponding to anomalous wintertime rain-abundant in southern China, we checked the composite anomaly fields of circulation for the ten rain-abundant Januaries in southern China, and compared with the eight rain-scarce Januaries. In composite anomaly field of SLP (Figure 7a), Siberian High is slightly stronger than normal, with the maximum positive anomaly of 1 hPa and not significant, which is obvious different from the pattern of low-temperature (Figure 4a). The correlation coefficient between Siberian High and precipitation index is close to 0 (Table 2). It implies that the Siberian High is not an important factor to the January precipitation in southern China. Wind vector at 850 hPa (Figure 7b) shows that anomalous southerly wind occurs from the South China Sea to North China, which indicates that the intensified East Asian winter monsoon is favorable for rain increase in southern China. At the same time, there is the "+–+" wave train pattern of geopotential height anomalies crossing Eurasia in the mid-high latitude from west to east found in the composite anomaly fields of geopotential height at 500 hPa (Figure 7c). There are significant negative anomalies in inland of 30–50°N and 60–90°E with a maximum negative anomaly of –30 gpm, and the East Asian region is around 10–20 gpm of positive anomaly, which implies the East Asian trough is weaker. Corresponding to such distribution of height field anomaly there is anomalous southerly wind in the east of China. The circulation features are also reflected in 850 hPa, 500 hPa and upper troposphere, being a vertically equivalent barotropic structure. So the abnormal northward meridional circulation is an important feature of rain-abundant Januaries in southern China. Furthermore, the significant positive anomaly in the east coast of Mediterranean Sea to Iranian Plateau and negative anomaly in East Asia and western Pacific are identified in zonal wind anomaly field at 200 hPa (Figure 7d), which indicate that the zonal wind is anomalous strong in Middle East and weak in East Asia. Yang *et al*. (1990, 2002) pointed out a strong East Asian jet stream (EAJS) is associated with an intensification of the weather and climate systems in Asia and over the Pacific such as deepening of the East Asian trough and the Aleutian low and strengthening of the East Asian winter monsoon, and vice versa. In Figure 7d, the Middle East zonal wind at 200 hPa is stronger with 4–8 m/s above normal value. Here we define

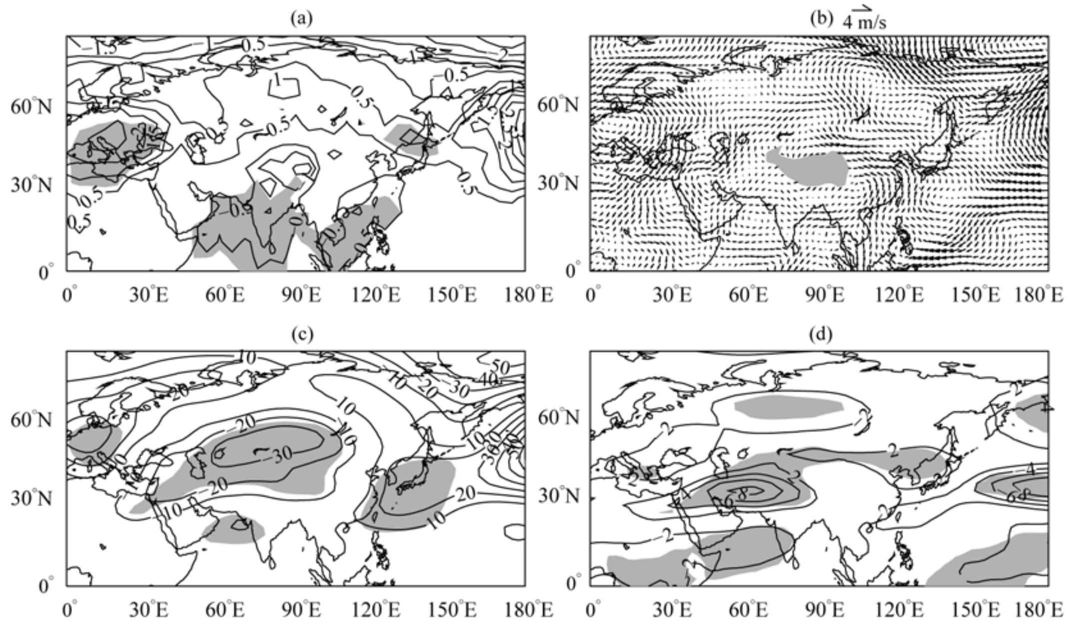

Figure 7 Composite anomaly fields of SLP (a, unit is hPa), wind vector at 850 hPa (b, unit is m/s), geopotential heights at 500 hPa (c, unit is gpm) and zonal wind at 200 hPa (d, unit is m/s) for 10 rain-abundant Januaries in southern China. (Areas significant at the 95% level are shaded in a, c and d. Shaded area is the Qinghai–Tibet Plateau in b)

the Middle East jet stream (MEJS) index as the mean zonal wind in 30–40°N and 50–70°E at 200 hPa. The correlation coefficient between the MEJS and the precipitation index in January in southern China is up to +0.65, significant at the 99% level, much higher than the other indicators of atmospheric circulation (Table 2). However, the mechanism of the MEJS upon weather and precipitation in East Asia is still not very clear and needs further studies.

Stable large-scale convergence of cold and warm masses and ascending motion are the important conditions for durative rainfalls in winter. Vertical motion in lower to middle troposphere shows notable ascending motion when it's rain-abundant in January over southern China (Figure 8a). In the height–latitude profile of vertical circulation anomaly along 115°E for the ten rain-abundant Januaries over southern China (Figure 8b), there are ascending motions in the lower to middle troposphere in the south of the westerly flow. The updraft ranges from near surface at the 25ºN to about 500 hPa level at 35ºN, with the strongest ascending motion occurring at 600 hPa to 700 hPa. At the same time, air moisture in the south of 40ºN is increasing unusually, with positive anomalies dominated at the lower to middle troposphere. Therefore, anomalous southerly wind, adequate water vapor and large-scale ascending motions are the favorable conditions for large-scale persistent precipitation in winter over southern China.

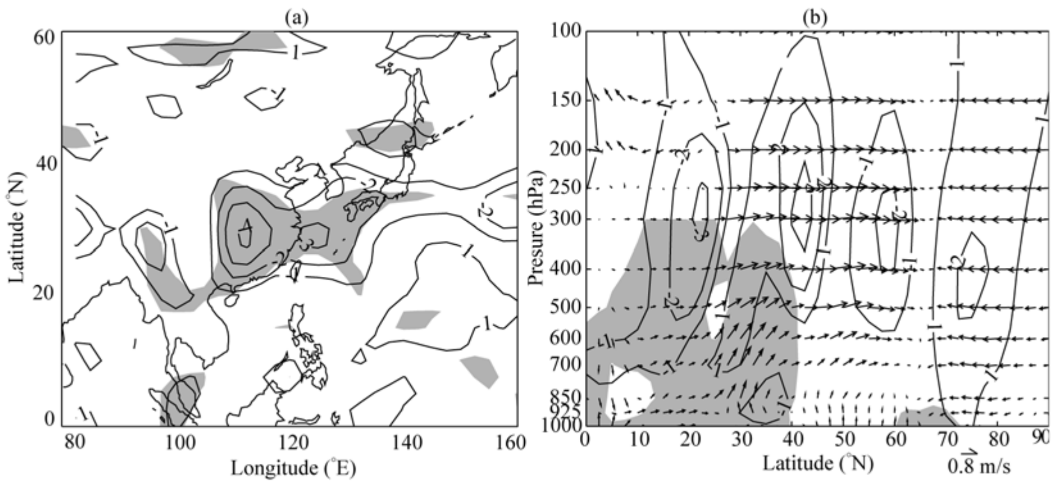

Figure 8 Composite anomaly fields of mean vertical velocity at 600 hPa and 700 hPa (a) and wind vector along 115°E (b) for 10 rain-abundant Januaries in southern China. (Areas significant at the 95% level are shaded in a, and unit is 10^{-2} Pa·s^{-1}. The vector are vertical wind and meridional wind in Figure 8b, the vertical velocity is multiplied by 10; the isolines are zonal wind, solid lines are positive anomalies, dashed lines are negative anomalies, unit is m/s; the positive specific humidity anomalies more than 0.02 g/kg are shaded in b.)

We did further quantitative analyses on relations between the atmospheric circulation factors and precipitation in southern China. Previous analyses show anomalous southerly wind in East Asia exerts important actions on precipitation in southern China. Here an East Asian meridional wind index (EAMW) is defined as the height difference between the Asian inland and East Asia at 500 hPa, namely EAMW = h*500 (45–55°N, 75–85°E) – h*500 (30–40°N, 130–140°E), of which h*500 represents geopotential height anomalies at 500 hPa. A high positive EAMW indicates anomalous northerly wind, and a high negative EAMW means anomalous southerly wind. In addition, the indices of MEJS, EU, WP and AO are also examined simultaneously (Figure 9). The correlation coefficients between MEJS, EAMW, EU, WP, AO and January precipitation of southern China are +0.65, –0.59, –0.48, –0.14 and +0.29, respectively. After high-pass filtered, the high-frequency correlations are +0.63, –0.55, –0.44, –0.06 and +0.22, respectively. Of which, MEJS, EAMW and EU are all at 99% significant level in both raw and high-frequency correlations. This indicates that the relations of the three circulation factors to precipitation are stable. MEJS, EAMW and EU all together can explain 49.4% and 48.4% variances of January and winter precipitation in southern China. The ten years of rain-abundant January are shaded in Figure 9. In general, the anomalous rain-abundant events are corresponding to a strong Middle East jet stream, a weak Eurasian pattern and a strong meridional wind in East Asia.

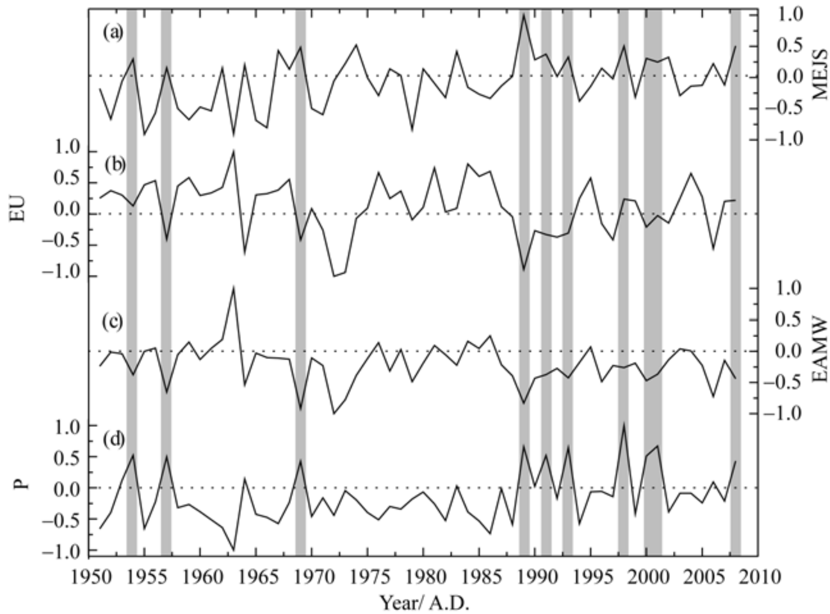

Figure 9 Comparison of Middle East jet stream (a), Eurasian pattern (b), East Asian meridional wind index (c) with January precipitation of southern China (d) (All series are standardized to [–1,1], rain-abundant Januaries are shaded)

4.3 Water vapor transport features

Water vapor is a necessary condition for precipitation. The wide range persistent precipitation needs inevitably the stable persistent water vapor. So, anomalous precipitation is closely correlated with the variation of water vapor transport. He *et al*. (2006) pointed out that the water vapor over southern China in winter comes mainly from the southwesterly flow ahead of south branch westerly troughs and the turning flow over the South China Sea and Indo-China Peninsula area, and the channels of moisture transfer varies significantly with height. Figure 10 shows vertically integrated water vapor transfer from 1000 hPa to 500 hPa for rain-abundant (a) and rain-scarce (b) Januaries in southern China. According to Figure 10, the low latitude is dominated by stable easterly water vapor transport in January for both rain-abundant and rain-scarce in southern China. However, westerly water vapor transport along the south branch troughs dominates the region from the Yunnan–Guizhou Plateau to the middle and lower Yangtze River Basin. The differences of water vapor transfer are more obvious in the vertically integrated anomaly fields (Figure 11). Figure 11 shows that the southwesterly flow ahead of south branch westerly troughs and the turning flow over the South China Sea and Indo-China Peninsula are stronger in rain-abundant Januaries, and they are weaker in rain-scarce Januaries. The significant feature in water vapor transfer anomaly field of January 2008 (not shown) is that there is anomalous southerly water vapor transfer, which indicates the southwesterly flow and turning flow are all stronger than normal. This may be one of the direct reasons for the rain-abundant in January 2008. In addition, there is an anomalous water vapor transfer flow in Figure 11a, passing by northeast Australia, across the equator and merging into the turning flow over the South China Sea. Whether it means that the changes of Southern Hemisphere atmospheric circulation have an impact on winter rainfalls in southern China, it is not clear and needs further study.

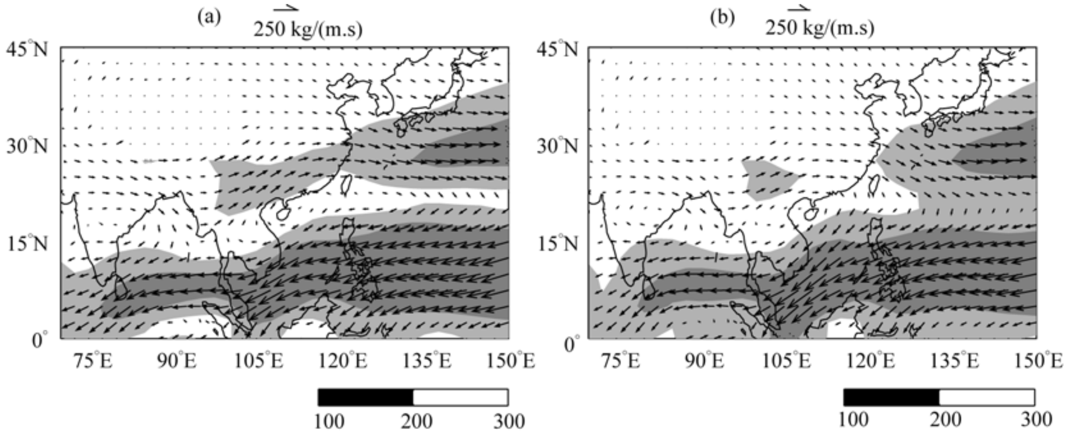

Figure 10 Vertically integrated water vapor transfer from 1000 hPa to 500 hPa for rain-abundant (a) and rain-scarce (b) Januaries in southern China

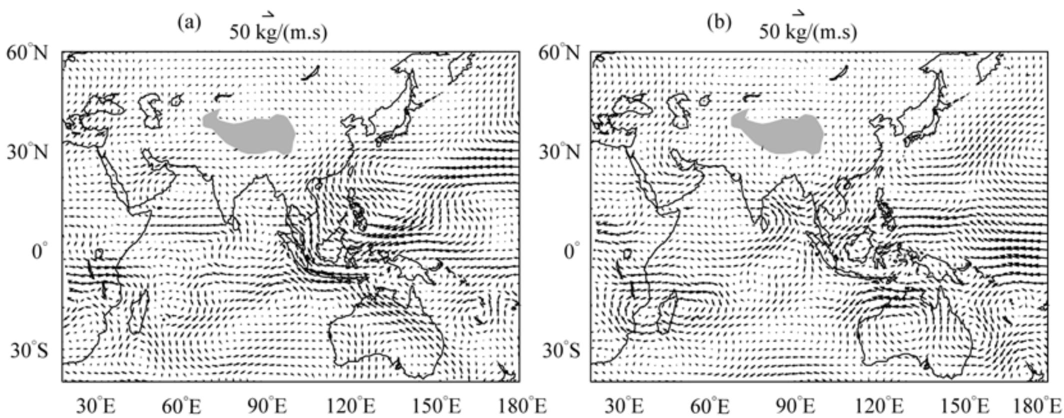

Figure 11 Vertically integrated anomaly water vapor transfer from 1000 hPa to 500 hPa for rain-abundant (a) and rain-scarce (b) Januaries in southern China (The shaded area is the Qinghai-Tibet Plateau)

5 Discussion

5.1 Cold-wet events and associated circulation background

We statistically define the anomalous low-temperature events and the anomalous rain-abundant events in wintertime in southern China. It's a cold-wet pattern in January 2008, with low-temperature event ($T'<-1\sigma$) and rain-abundant event ($P'>+1\sigma$) occurring simultaneously. Since January 1951, there have been four patterns of cold-dry January (namely, 1955, 1962, 1963 and 1967) and three patterns of cold-wet January (namely, 1969, 1993 and 2008). The other two patterns are warm-dry and warm-wet events, while they did not occur since 1951. It is concluded that the anomalous cold-wet Januaries as 2008 in the past 58 years occurred every 20 years. The cold-wet events can cause serious freezing and rainfall and snowfall disasters in wintertime in southern China, of which the same situations took place in 1969 and 1993 (National Statistics Bureau of P. R. China *et al*., 1995).

Analyses on atmospheric circulation show that, the stronger Siberian High, East Asian trough, East Asian winter monsoon and East Asian jet stream are favorable for low-temperature conditions in wintertime in southern China. However, the weaker East Asian trough, East Asian winter monsoon, East Asian jet stream and anomalous southerly wind are favorable for rain-abundant conditions. Thus, the favorable circulation conditions to low-temperature and rain-abundant events are partly paradoxical. Low-temperature events tend to be accompanied with rain-scarce conditions in wintertime in southern China, and vice versa. To further understand the circulation background of the cold-wet winter in southern China, circulation composite analyses for the three cold-wet Januaries (1969, 1993 and 2008) are performed in Figure 12. A significant strong Siberian High can be found in the composite anomaly field of SLP (Figure 12a), with a maximum positive anomaly of 6.6 hPa, which is higher than the mean anomaly of the 12 low-temperature Januaries (4.6 hPa). Meanwhile, there is anomalous southerly wind over the region from the middle and lower Yangtze River Basin to South China according to the composite anomaly field of wind

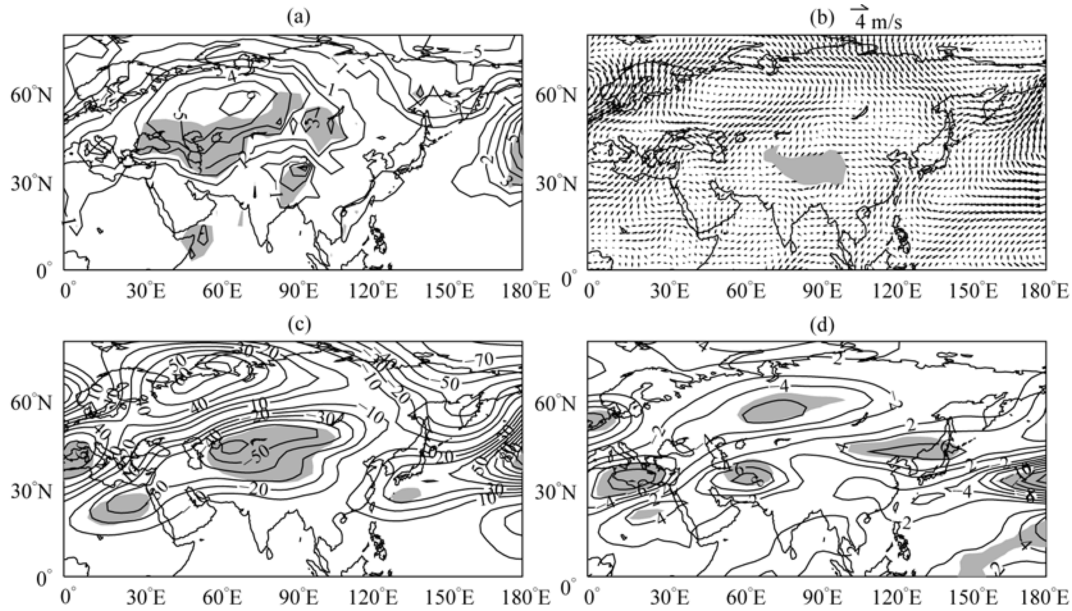

Figure 12 Composite anomaly fields of SLP (a, unit is hPa), wind vector at 850 hPa (b, unit is m/s), geopotential heights at 500 hPa (c, unit is gpm) and zonal wind at 200 hPa (d, unit is m/s) for 3 cold and rain-abundant Januaries in southern China (Areas significant at the 95% level are shaded in a, c and d. Shaded area is the Qinghai–Tibet Plateau in b)

vector at 850 hPa (Figure 12b). The characteristics of composite field of geopotential heights at 500 hPa (Figure 12c) are similar to Figure 7c, with negative anomaly in the Asian interior and positive anomaly in East Asia respectively. And the composite anomaly field of zonal wind at 200 hPa (Figure 12d) is also consistent with Figure 7d, presenting a strong Middle East jet stream and a weak East Asian jet stream. Comprehensively, the cold-wet winter in southern China is closely related to anomalous stronger Siberian High and anomalous precipitation-favorable circulation changes in middle to upper troposphere.

As for the three cold-wet patterns in wintertime, January 2008 was approximately the same as the last two events according to cold and wet intensity (temperature was slight lower and precipitation was much more than the last two). However, the disaster and social influence in January 2008 are more serious. This is because the severity level of disaster is not completely depended on hazard factors, but also related to hazard bearing body. With the rapid economic growth in the last decades, industrial production, transportation and communication industry have obtained great development. And the dependence to power is also increasing more and more. So, once the power system is interrupted by unexpected and severe natural disaster, which can result in a series of serious social problem. It is also a non-negligible reason for the large-scale catastrophe suffered in southern China in January 2008.

5.2 Relations to ENSO

Many studies (Gong *et al*., 1998, 1999b; Huang *et al*., 2003; Zhu *et al*., 1988; Pu *et al*., 2006; Guo *et al*., 1990; Zong *et al*., 2008; Jin *et al*., 1999; Wang *et al*., 1999; Li *et al*., 1989b) show that East Asian winter monsoon is connected to ENSO. Tao *et al*. (1998) pointed out that during winter in El Niño (La Niña) years the following pattern in East Asia is not favorable (favorable) for the outbreaks of cold air southward leading to weak (strong) winter monsoons; and that during winter in El Niño (La Niña) years there is above normal (below normal) precipitation in South China and the Tibetan Plateau. Gong *et al*. (1999b) concluded that the rainfall of winter and autumn over southern China increases usually, and that over northern China decreases in El Niño years. A recent study (Gao *et al*., 2008) stated that La Niña event led to the anomalous general circulations in the Northern Hemisphere, which was thought to be the most important causes of unprecedented disasters in January 2008 over southern China. Obviously, these results are not consistent well. Here we further checked the relations between the winter climate in southern China and ENSO during the past 130 years (Table 4). The results show that there were 33 El Niño winters and 41 La Niña winters since 1880, of which there were 9, 4, 1 and 5 El Niño winters and 9, 6, 3 and 1 La Niña winters in the anomalous cold, warm, dry and wet winters respectively. According to Table 4, it is

Table 4 Statistics for anomalous winter temperature and precipitation in southern China with ENSO events

		Cold	Warm	Dry	Wet
El Niño (33)	±1σ	9 (27.3%)	4 (12.1%)	1 (3%)	5 (15.2%)
	±0.5σ	11 (33.3%)	15 (45.5%)	4 (12.1%)	9 (27.3%)
La Niña (41)	±1σ	9 (22%)	6 (14.6%)	3 (7.3%)	1 (2.4%)
	±0.5σ	15 (33.6%)	10 (24.4%)	14 (34.1%)	5 (12.2%)

concluded that there are relatively obvious corresponding relationships between the anomalous precipitation events in winter over southern China and ENSO system, while the relationships between anomalous temperature and ENSO are not significant. That is, the probability of anomalous rain-abundant winter (rain-scarce winter) in southern China is higher than normal during the El Niño (La Niña) years.

We also checked the association between anomalous precipitation and temperature events and global sea surface temperature (SST) (Figure omitted). The results show that negative SST anomaly occurs in Middle and East Pacific and positive anomaly in Northwest Pacific and Indian Ocean during the rain-abundant Januaries in southern China, with the maximum positive anomaly in the near sea from the South China Sea to Sea of Japan. While during the rain-scarce Januaries, the pattern of SST anomaly is approximately opposite. The features of SST anomaly corresponding to low-temperature years in southern China are similar to rain-scarce years. Negative SST anomaly dominates Indian Ocean and the Northwest and Middle to East Pacific, and the lower SST in near sea is the most outstanding characteristic, the negative SST anomaly is in excess of –0.5 ℃ from the north of the South China Sea to Sea of Japan. It is worth noting that the near sea around China is also controlled by East Asia winter monsoon in wintertime (Qin *et al*., 2006). Although there exists high correlation between winter temperature of southern China and near sea SST, it has not been indicated the SST of the near sea area can explain winter temperature changes in southern China. But on the other hand, the warm sea water can be favorable for increasing air moisture and water vapor transfer, so the offshore water temperature may explain partly winter precipitation in southern China. Compared to the SST anomaly in January 2008, the Middle to East Pacific is the negative anomaly, while positive anomaly in the Northwest Pacific and Indian Ocean, with the positive SST anomaly in excess of 1.5℃ from the north of the South China Sea to Sea of Japan. This may be a favorable condition for rain-abundant winter in January 2008 over southern China.

6 Conclusions

From the above studies, we can conclude that there are 12 low-temperature Januaries ($T'<-1\sigma$) and 10 rain-abundant Januaries ($P'>1\sigma$) since 1951, and three patterns of cold-wet Januaries (1969, 1993 and 2008). This indicates that the probability of cold-wet events like January 2008 is approximately every 20 years. Based on NCEP/NCAR reanalysis data and others, composite analyses of atmospheric circulations for the anomalous temperature and precipitation in January over southern China are performed. The main results are summarized as follows.

(1) The favorable atmospheric conditions for low-temperature winter events over southern China are the abnormal stronger Siberian High, the anomalous northerly wind at 850 hPa, the stronger East Asia trough and meridional circulation over East Asia, and the stronger East Asia jet stream at 200 hPa. SHB, EP, WP and AO, the four factors can explain 47.2% and 51.5% variances of January and winter temperature respectively.

(2) The favorable atmospheric conditions for rain-abundant winter events over southern China are the weaker East Asia trough, the abnormal stronger Middle East jet stream and weaker East Asia jet stream at 200 hPa, and the anomalous southerly wind at both lower and

middle to upper troposphere. The correlation coefficients between MEJS, EAMW, EU and January precipitation are +0.65, –0.59 and –0.48 respectively, and the three factors together can explain 49.4% and 48.4% variances of January and winter precipitation in southern China.

(3) When there occurred cold-wet events as January 2008 in southern China, the low-temperature is mainly related to the stronger Siberian High, and the circulation anomalousness from middle to upper troposphere is precipitation-favorable.

(4) There is a higher probability of rain-abundant (rain-scarce) winter in southern China during El Niño (La Niña) events. And there is no significant statistic relation between ENSO and winter temperature in southern China.

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