SCIENCE CHINA
Earth Sciences

• **RESEARCH PAPER** •

January 2012 Vol.55 No.1: 98–112
doi: 10.1007/s11430-011-4348-1

The influence of the Madden-Julian Oscillation activity anomalies on Yunnan's extreme drought of 2009–2010

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Received January 27, 2011; accepted July 8, 2011; published online November 26, 2011

Yunnan Province of China suffered a record-breaking drought that persisted from autumn 2009 into spring 2010. The present study examined the physical causes of this extreme drought event in terms of persistent anomalies of intraseasonal oscillation in the tropical atmosphere (the Madden-Julian Oscillation hereafter the MJO). The results show that the occurrence of severe drought in Yunnan was caused directly by deficient rainfall lasting from the summer of 2009 to the spring of 2010. Further exploration reveals a persistent positive variation of MJO index 1 from June to October. Accordingly, the convective activity over the Bay of Bengal (BOB) weakened continuously, and then an anomalous descending airflow was induced over the tropical Indian Ocean, resulted in the anomalous weakening of vertical Asian monsoon circulation in South Asia. Consequently, the transport of water vapor from the tropical Indian Ocean to Yunnan decreased abnormally, leading to persistent below-normal rainfall over Yunnan from summer to autumn in 2009. As a result, a severe drought began to appear in autumn. In the winter of 2009–2010, MJO index 1 remained persistently positive, indicating the continuous weakening of convective activity over the BOB. The atmospheric circulation associated with the persistent positive anomalies in the MJO also demonstrated anomalous patterns. Specifically, there was an anomalous high-pressure ridge stretching from South Asia through the Tibetan Plateau and into the western part of southwestern China. This indicates that the atmospheric circulation over Yunnan was dominated by vertical descending airflow in the high-pressure ridge. Simultaneously, the India-Burma trough was weakened, which resulted in unfavorable conditions for the transport of water vapor from the BOB to Yunnan, causing the observed persistent deficient precipitation in winter and the subsequently intensified drought. Therefore, the persistent anomalies in MJO activity in the tropical atmosphere played an important role in the occurrence of the extreme drought event in Yunnan in 2009–2010.

Yunnan, extreme drought, MJO, persistent anomalies

Citation: Lü J M, Ju J H, Ren J Z, et al. The influence of the Madden-Julian Oscillation activity anomalies on Yunnan's extreme drought of 2009–2010. Sci China Earth Sci, 2012, 55: 98–112, doi: 10.1007/s11430-011-4348-1

China is frequently stricken by natural disasters. Of all the damage caused by these disasters, including loss of life, property damage and unsustainable development of the social economy, the damage caused by meteorological disasters forms the largest proportion. According to the government statistics, the damages from meteorological disasters could cost up to 3%–6% of the China's gross national product; in particular, the economic losses caused by severe climate disasters such as drought and flood exceed 200 billion RMB per year [1]. The percentages of crop areas affected by drought and flood are 55% and 27%, respectively and 11% are affected by typhoon and hail; another 7% are affected by other severe weather phenomena [2]. It is obvi-

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ous that among all meteorological disasters, a prolonged and large-scale drought causes the most severe damage and economic loss. With respect to the physical mechanisms involved in the occurrence of drought, most previous studies have focused on North China and the Yangtze-Huaihe River valley areas. A large number of studies have reported that a sea surface temperature (SST) anomaly is one physical reason for drought in North China and the Yangtze Huaihe River valley areas. In summer, drought-hit regions in East China exhibit obvious diversity during different phases of the ENSO (El Niño-Southern Oscillation) cycle. Below-normal rainfall generally favors drought over the Yellow River valley and North China during the developing phase of El Niño, whereas low rainfall favors drought over the Huaihe River valley during the developing phase of La Niña [3, 4]. Huang et al. [5, 6] proposed that the conditions in thermal state and convective activity over the western tropical Pacific warm pool may induce anomalous East Asia-Pacific (EAP) teleconnection wave trains, causing drought over the Yangtze-Huaihe River valleys. At the interdecadal time scale, the "decadal El Niño phenomena" have occurred in the central-eastern tropical Pacific, and caused persistent droughts in North China since the late 1970s [7]. Furthermore, the evolution and long persistence of anomalous atmospheric circulation patterns also result in drought. Wei et al. [8] demonstrated that the positive geopotential height anomaly was overlapped by a Eurasian-like (EU) teleconnection wave train in the 35°–45°N latitudinal zone over Eurasia, indicating that North China was frequently dominated by a high-pressure ridge. During these conditions, severe droughts struck North China in 1999 and 2000.

Yunnan is located in a low-latitude plateau. The rainy season in Yunnan usually starts in May and ends in October due to the influence of the monsoon climate. Therefore, there is abundant rainfall over Yunnan from May to October. Droughts occur almost every year in Yunnan, but they occur at different times and to various degrees. The two most common forms of drought in Yunnan are spring drought and summer drought. Previous studies have documented that the occurrence of drought in spring and early summer is associated not only with continuous strengthening and westward expansion of the western Pacific subtropical high (WPSH) but also with the late onset of summer monsoon over the Indo-China peninsula. Furthermore, when the meridional water vapor transport from the Bay of Bengal (BOB) and convective activity around Sumatra appear to be weaker than normal in the previous season, this foretells the appearance of drought during spring and early summer [9, 10]. In summer, drought is caused primarily by persistent strengthening and stable westward expansion of the WPSH and the weakening and westward shift of the monsoon low, indicating that the atmospheric circulation over Yunnan is dominated by descending airflow between the eastern and western vertical circulations, with suppressed convective activities and a decreased incidence of rain-bearing clouds [11].

From autumn 2009 to spring 2010, a record-breaking and persistent drought hit Yunnan. A meteorological drought with return periods greater than 80 years covered the whole area, and a meteorological drought with return periods greater than 100 years covered the middle part of Yunnan, East Yunnan and the eastern part of West Yunnan. This extreme event had a widespread influence. The disaster-affected population of Yunnan reached 25.12 million by May 31, 2010; critically, 7.57 million people suffered from a lack of drinking water. An area of over 21741 km^2 of crops planted in autumn and winter was also affected. The direct economic losses to agriculture exceeded 20 billion RMB. A persistent drought is generally induced by the continuous evolution and prolonged maintenance of anomalous atmospheric circulation patterns. In this event, anomalies were evidenced by the observation that the Madden-Julian Oscillation (MJO) index 1 (80°E) remained persistently positive from the summer of 2009 through the winter of 2009–2010, indicative of continuously suppressed convective activity over the BOB. Did the persistent intraseasonal anomalies in the MJO play a significant role in the occurrence of the extreme drought in Yunnan during 2009–2010? This appears to be an important issue worth further exploration.

The MJO is an intraseasonal oscillation phenomenon occurring in the global tropical atmosphere. It is manifested as eastward-propagating tropical convective anomalies from the Indian Ocean to the Atlantic. Thus, the different phases of the MJO represent ascending and descending air motions in different parts of the tropics [12, 13]. MJO-induced atmospheric circulation anomalies may reinforce the amplification of moderate to extreme cold surges. Therefore, the MJO modulates wintertime precipitation and temperature in East Asia [14, 15]. In summer, the MJO derived from the tropical Indian Ocean induces an intensification of the westerlies in the South China Sea, triggering the monsoon surge in the southern part of China. The monsoon surge, which carries abundant water vapor, propagates northward and encounters cold air moving down from the pole, resulted in heavy storm rainfall and valley-wide flooding in South China [16, 17]. Numerous studies have investigated the significant roles of the MJO in global weather and climate anomalies. However, further studies are required to explore the physical process through which the MJO plays a role in drought. The investigation of extreme disaster events is becoming a new issue of international focus. The dynamical mechanisms involved in the occurrence of extreme drought events have not yet been clarified. During 2009 and 2010, Yunnan experienced a large-scale and long-duration extreme drought event. There is important scientific significance in exploring and revealing the reasons for this event. The results of this study may also be beneficial in improving current monitoring and prediction technology for extreme climate events such as droughts in China. This study is to examine the physical reasons for the occurrence of the 2009–2010 drought in terms of the persistent intraseasonal anomalies in the MJO and to provide scientific evidence for the monitoring and prediction of extreme drought.

1 Data

Here we employed daily precipitation records from 124 weather stations in Yunnan. Analysis of the observed rainfall data indicated that 87 stations had complete records for the period from 1961 to 2010, and 98 stations had complete records for 1979 to 2010. Thus, we used precipitation data with different numbers of observation stations in different periods according to the calculation method. The MJO index was also used in our study. The definition of this index is provided by the US National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center (CPC) and is available online at http://www.cpc.noaa.gov/products/precip/CWlink/daily_mjo_index/mjo_index.shtml). To denote different phases of MJO activity, the CPC defined ten MJO indices (MJO index 1 to MJO index 10) according to the locations of the center of intensified convection (20°E, 70°E, 80°E, 100°E, 120°E, 140°E, 160°E, 120°W, 40°W, and 10°W). Therefore, these ten indices represent enhanced and suppressed convective activities in different parts of the tropics ranging from the Indian Ocean to the Atlantic. According to the previous studies, the intensity of convective activity over the southern part of the BOB and the eastern equatorial Indian Ocean is related to the amount of rainfall in the eastern part of southwestern China [18]. Consequently, we selected MJO index 1 (80°E) as defined by CPC to investigate the influence of the convective activity over the BOB on the Yunnan 2009–2010 drought. The pentad-mean MJO index in the period 1978 to 2010 was used in this paper. Other data used included the daily mean and monthly mean reanalysis data from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) [19] for the period 1951–2010.

2 Process analysis for Yunnan's extreme drought in 2009–2010

Yunnan experienced a record-breaking and persistent drought that began in autumn, continued through winter and into spring during 2009–2010. The persistence of deficient precipitation directly caused the drought. Figure 1 shows the percentage departures from normal rainfall in Yunnan

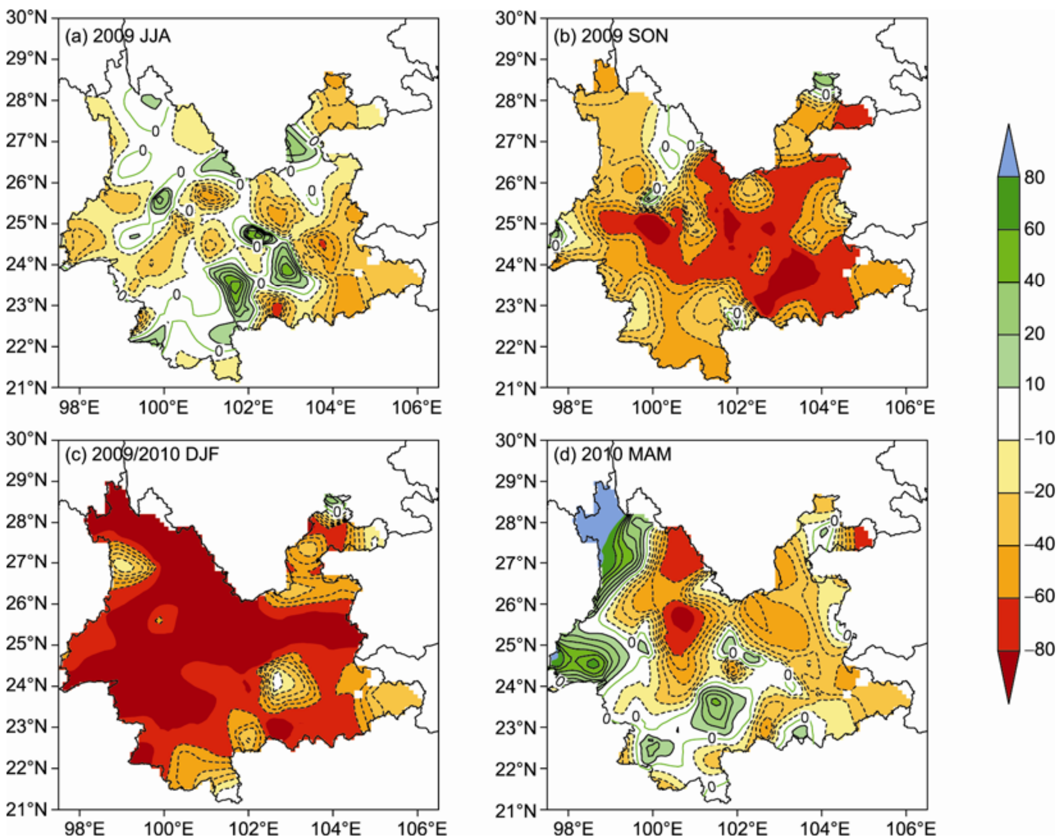

Figure 1 Distribution of rainfall percentage departures from normal over Yunnan in summer 2009 (a), autumn 2009 (b), winter 2009–2010 (c), and spring 2010 (d).

from autumn 2009 to spring 2010. Here, it is shown that the rainfall was reduced over most of Yunnan in autumn 2009 and that the rainfall was 60% less than normal over 50 percent of the area, suggesting that a drought had emerged. In the winter of 2009–2010, when the dry season came, the rainfall continued to be deficient. The rainfall over most of Yunnan was 60% less than normal. As a result, the drought intensified. In spring of 2010, the rainfall over most of Yunnan was still below normal, with the exception of that over western Yunnan, resulted in a severe persistent drought. We defined the rainfall index of Yunnan by averaging the rainfall percentage departures over 87 weather stations from 1961 to 2010. The seasonal rainfall index is characterized by interannual variability. In autumn of 2009, the precipitation of Yunnan apparently reached its minimum since 1961 (Figure 2(b)). However, the autumn drought was not the most severe stage in the total drought process; the severest drought occurred in the winter of 2009–2010, although the winter rainfall index was not at a minimum value compared with other winters (Figure 2(c)). The average rainfall in Yunnan was slightly above normal in spring 2010 (Figure 2(d)). However, the drought still persisted, suggesting that the intensity of the drought was closely related to the duration of deficient rainfall, but not positively correlated with the amount of rainfall.

Note also that the average rainfall in Yunnan was already reduced in the summer of 2009 (Figure 2(a)), preceding the occurrence of autumn drought. It can be seen from the distribution of rainfall percentage departures that the rainfall over most of Yunnan was below normal in the summer of 2009 except for the central, northern and southwestern parts of Yunnan (Figure 1(a)). The negative departure of the rainfall over most of Yunnan was 20% less than normal. Thus, the persistence of deficient precipitation for several seasons led to the occurrence of a drought process. In the preceding summer, the rainfall over Yunnan started to decrease, resulted in low soil moisture, and provided a favorable condition for the occurrence of autumn drought. Furthermore, in 2009–2010, the temperature in Yunnan tended to be higher from autumn through winter and into spring due to the persistent deficient precipitation (figures not shown), causing a relatively large amount of soil-moisture evaporation. Finally, a record-breaking extreme drought struck most parts of Yunnan from autumn 2009 to spring 2010. Additionally, the main reservoirs in Yunnan principally retain water in the late rainy season (August–October) due to the plateau monsoon climate at low latitudes. In 2009, the rainy season started late and ended early. Rainfall deficiency began in summer and became serious in autumn (Figure 1(b)), causing a severe reduction of water storage in Yunnan's reservoirs, intensifying the damage induced by this extreme drought to some extent.

The drought process in Yunnan is characterized by a persistent deficit in rainfall amounts. We defined a persistent anomalous precipitation index R_{persis} to investigate the relationship between drought and persistent deficient precipita-

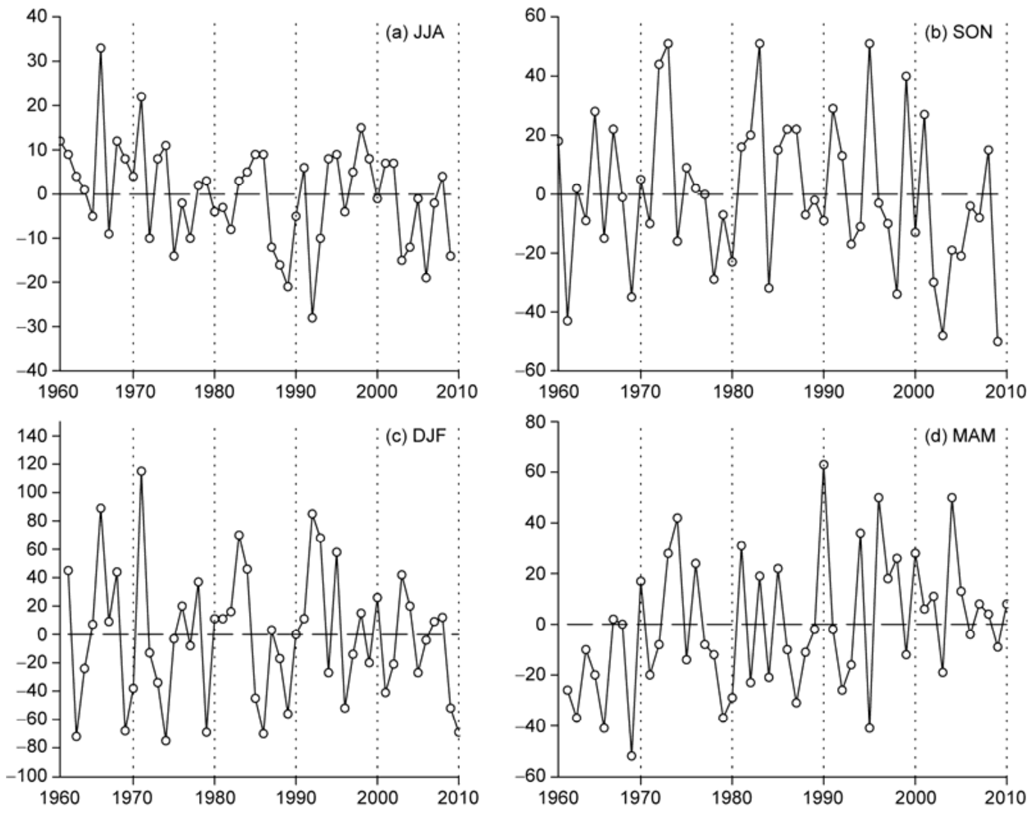

Figure 2 Rainfall index for Yunnan from 1961 to 2010 in summer (a), autumn (b), winter (c), and spring (d).

tion. First, the climatology of Yunnan precipitation was analyzed. Figure 3 displays the climatology of month-to-month rainfall over Yunnan (solid line) and the monthly rainfalls as corresponding percentages of the annual rainfall (bar). It is found that the greatest percentage of the annual rainfall occurs in the summer, from June through August. Additionally, the rainfall is relatively sufficient in late spring (May) and early autumn (September through October). Eighty-five percent of the annual rainfall occurs over six months, from May through October. The rainy season in Yunnan generally starts in May and ends in October due to the influence of the Asian summer monsoon (ASM). According to the climatic features of monthly rainfall, the month-to-month rainfall percentage departure (R_{depar}) from May through December in each year was multiplied by the percentage of monthly rainfall (R_{percent}, denoted by a bar in Figure 3), and then the sum of the products from May to December was defined as the persistent anomalous precipitation index. The mathematical definition of the index used in the study is described below.

$$R_{\mathrm{persis}}(i) = \sum_{j=5}^{j=12} R_{\mathrm{depar}}(i, j) \times R_{\mathrm{percent}}(j), \quad (1)$$

where i is the year (i = 1961, 1962, …, 2009) and j is the month (j = 5, 6, …, 12).

Figure 4 displays the interannual variability of the persistent anomalous precipitation index in Yunnan from 1961 to 2009. Based on the interannual variability of this index, seven years with obvious persistent rainfall deficiencies were identified (1969, 1988, 1989, 1992, 2003, 2005, and 2009); Yunnan suffered droughts in all these years. Thus, the persistent anomalous precipitation index defined herein may indicate the occurrence of drought events in Yunnan very well. It is obvious that the value of R_{persis} in 2009 was the smallest on record, suggesting that the persistent rainfall deficiency in 2009 was the most severe in the past 49 years. In fact, the drought of 2009–2010 was the most serious to occur in Yunan since 1951, the earliest year for which weather records are available.

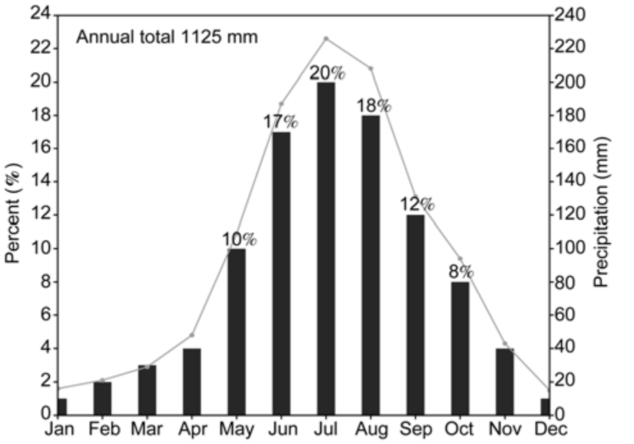

Figure 3 Climatology of month-to-month rainfall over Yunnan (1961–2009) (line) and the monthly rainfall as a percentage of the annual rainfall (bar).

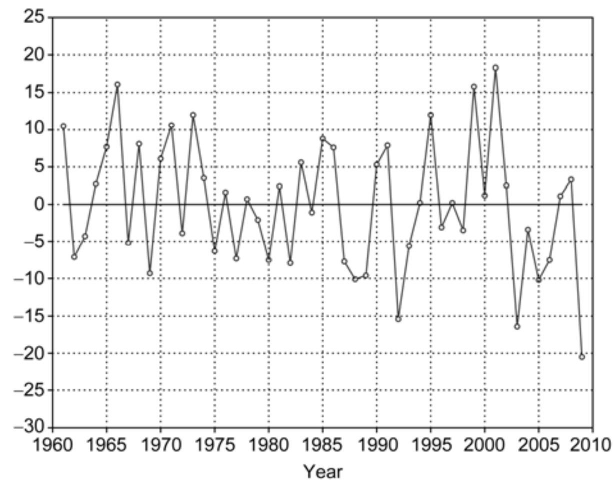

Figure 4 Time series of persistent anomalous precipitation index over Yunnan from 1961 to 2009.

3 Relation between Yunnan precipitation and persistent positive anomalies in the MJO from summer to autumn

The below-normal rainfall in summer was an important preceding condition for the formation of drought in 2009–2010. Therefore, we first examined the causes of rainfall deficiency from summer to autumn of 2009. Anomalous patterns in atmospheric circulation directly induced the rainfall deficiency over Yunnan. It is well known that there is a zonal mean monsoon circulation over South Asia (0°–20°N) in summer under climatological mean conditions. The ascending branch of this vertical circulation is located over the eastern tropical Indian Ocean and Maritime Continental region, and the descending branch is located over eastern Africa. Correspondingly, the convections over the BOB and Maritime Continental region are active in summer, favoring the transportation of large amounts of water vapor to Yunnan and leading to precipitation. Relative to the climatological mean of the 1979–2009 period, anomalous ascending airflow was shifted to Africa through the western Indian Ocean and the western Pacific in the summer and autumn of 2009, whereas anomalous descending airflow dominated the eastern tropical Indian Ocean, Maritime Continental region and the South China Sea (Figure 5). This type of anomalous vertical circulation indicates that the ASM circulation was weaker than normal in 2009. We calculated the ASM index from 1961 to 2009 following Webster and Yang [20]. The results show that the intensity of the ASM in 2009 was at its weakest since 1961 (figure not shown). Thus, the ASM circulation in 2009 was weakened, which was not beneficial for the transportation of water vapor to Yunnan.

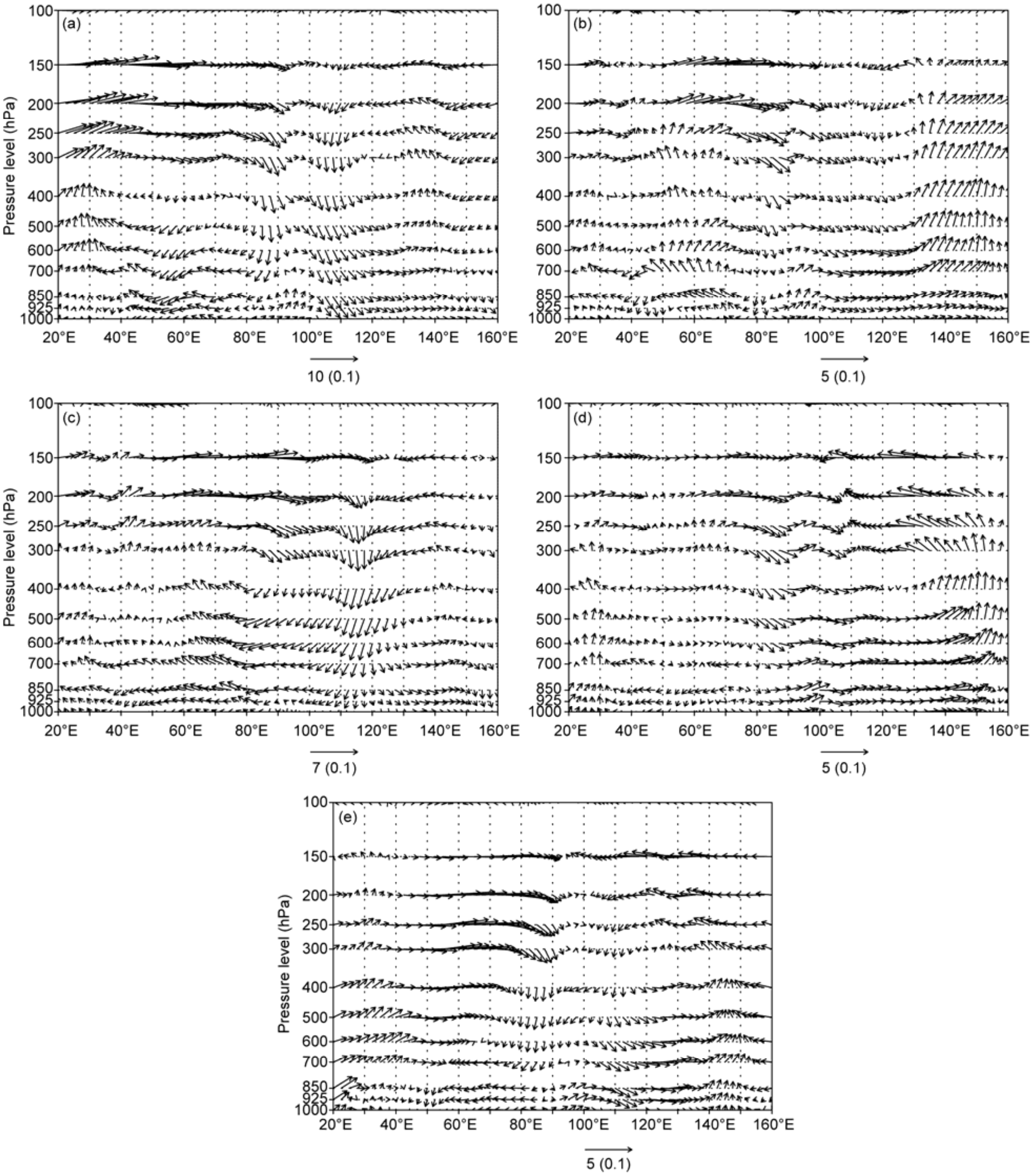

Figure 5 Longitude-press cross section of the anomalous zonal mean vertical circulation along 0°–20°N in 2009 for June (a), July (b), August (c), September (d), and October (e). The horizontal (vertical) scale of vectors is shown at the bottom of the panel. The values outside parentheses represent zonal wind anomalies (unit: m s^{-1}). The values inside parentheses represent vertical velocity anomalies (unit: Pa s^{-1}). The anomalies were computed relative to the climatological mean for 1979–2009.

Figure 6 shows the patterns of vertically integrated (surface to 300 hPa) water vapor divergence anomalies and water vapor flux anomalies in the summer and autumn of 2009. As shown, in the summer of 2009 (Figure 6(a), (b)), water vapor over the western tropical Indian Ocean was abnormally transported westward, which is inconsistent with the cross-equatorial Somali jet. Furthermore, water vapor over the BOB was abnormally transported southward. These anomalous patterns of water vapor flux do not favor the transport of water vapor from the tropical Indian Ocean to

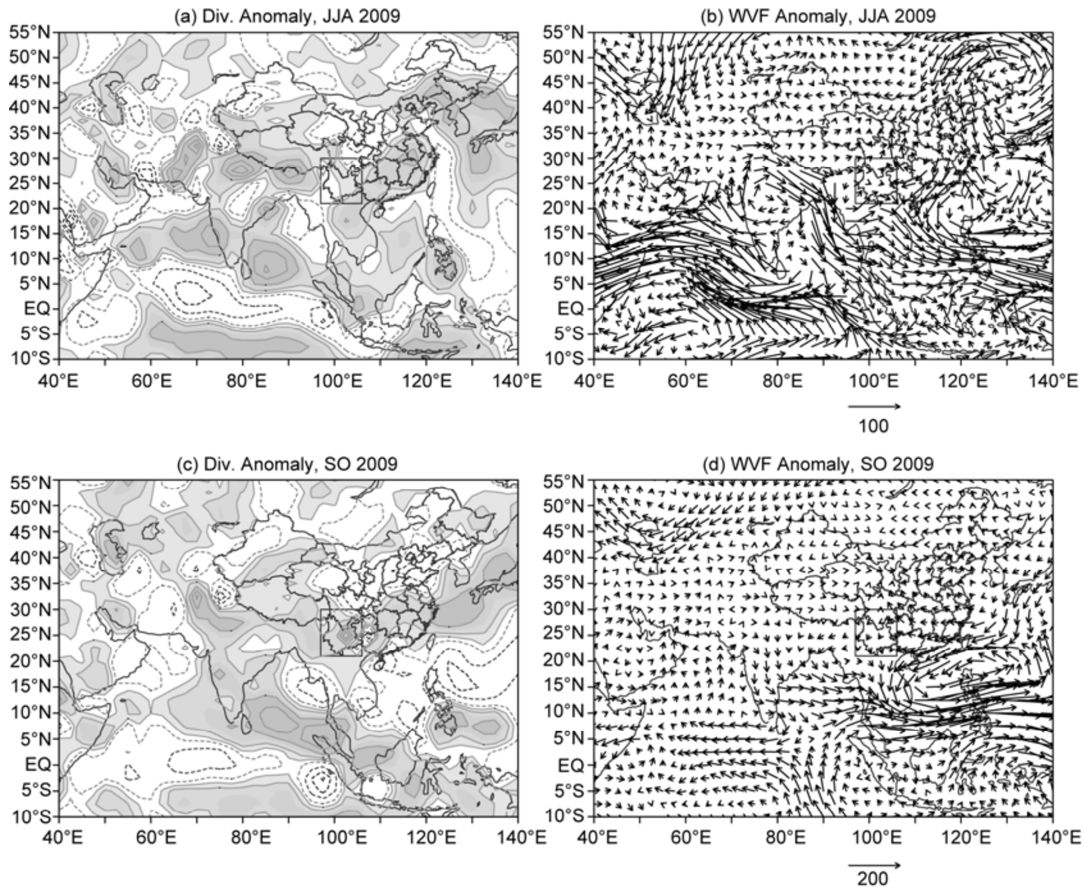

Figure 6 Mean vertically integrated (surface to 300 hPa) water vapor divergence anomalies (shadings denote divergence, dashed lines denote convergence; unit: 10^{-6} kg m^{-2} s^{-1}) and water vapor flux anomalies (vectors; unit: kg m^{-1} s^{-1}) for summer ((a), (b)) and autumn ((c), (d)) 2009. The anomalies were computed relative to the climatological mean for 1979–2009. The box illustrates the location of Yunnan Province.

Yunnan in the summer. Moreover, an anomalous water vapor divergence was evident over the Arabian Sea, the Indian Peninsula, the BOB, and central-eastern Indochina through South China, especially over central-eastern Yunnan. It should also be noted that there was a patch of anomalous water vapor convergence over southwestern Yunnan. Correspondingly, summer rainfall was below normal over most of Yunnan, while it was above normal in southwestern Yunnan. In the autumn of 2009 (Figure 6(c), (d)), anomalous water vapor divergence was distributed over the southern Arabian Sea, throughout the Indian Peninsula, over the southern BOB, and into the Maritime continent, while anomalous water vapor convergence was distributed in the eastern BOB and central Indochina through the South China Sea. Yunnan was located in a zone of subtropical divergence of water vapor, with a divergence center in eastern Yunnan. Additionally, water vapor was transported southward over the northern BOB through Indochina, which is again disadvantageous for water vapor transport to Yunnan. As a result, autumn rainfall over Yunnan was abnormally reduced.

We further discuss the physical process through which the MJO activity anomalies caused deficient precipitation during summer and autumn in Yunnan. The summer pentad-to-pentad variation of MJO index 1 from 1978 to 2009 was analyzed. The results show that the pentad-to-pentad variability of MJO index 1 can be divided into three categories: persistent positive mode, persistent negative mode, and oscillatory mode. Figure 7 shows the variation curve of the summer MJO index 1 in persistent positive and negative years. In persistent positive years (Figure 7(a)), MJO index 1 primarily maintains a positive value in summer as a whole, indicative of weak convective activity around the BOB. In contrast, in persistent negative years (Figure 7(b)), MJO index 1 remains negative in summer, which is associated with strong convective activity over the BOB. Further exploration revealed that an El Niño event appeared in the eastern equatorial Pacific in years when MJO index 1 remained persistently positive (1982, 1987, 1997, and 2009), whereas a La Niña event occurred when MJO index 1 remained persistently negative (1988, 1995, 1996, 1998, 2007, and 2008). Li [21] proposed that the low-frequency kinetic energy should decrease after an El Niño event, resulted in the weakening of the MJO. Furthermore, the distribution of tropical convection is changed due to El Niño, leading to a shift in strong convection from Indonesia toward the date

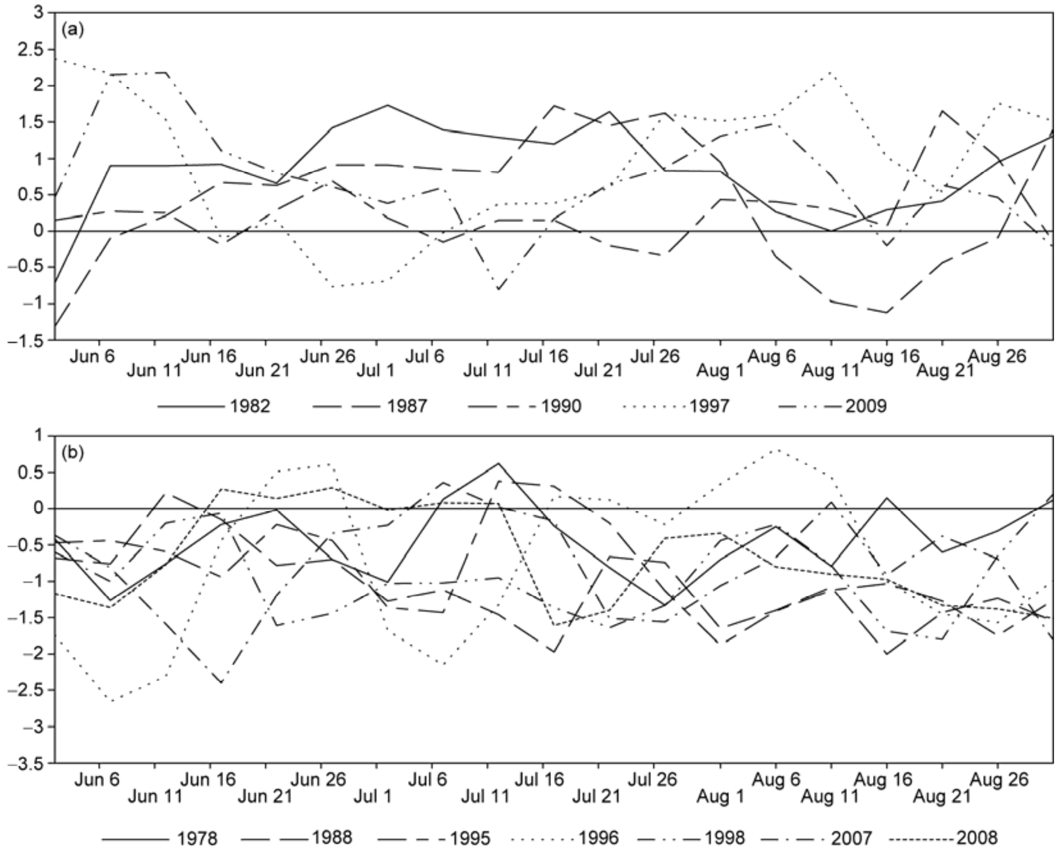

Figure 7 Variation curve of summer MJO index 1 in persistent anomalous years for persistent positive years (a) and persistent negative years (b).

line. Thus, after the occurrence of ENSO events, a persistent positive (negative) MJO index 1 and its corresponding weak (strong) convective activity over the BOB manifest the responses of the intraseasonal oscillation in the tropical atmosphere to anomalous SST forcing in the eastern equatorial Pacific.

To determine the impact of the persistent anomalous MJO index 1 on summer rainfall over Yunnan, the composites of summer rainfall percentage departures for persistent positive and negative years of MJO index 1 were constructed, as shown in Figure 8. When MJO index 1 remains persistently positive, the convection over the BOB is suppressed, favoring the occurrence of summer drought in the entire Yunnan Province. In contrast, when MJO index 1 is persistently negative and the convective activity over the BOB is strong, summer rainfall over most of Yunnan is above normal, with exceptions over some areas of eastern and western Yunnan. These results suggest that, on the interannual time scale, persistent anomalies in MJO index 1 play a role in Yunnan summer precipitation.

We further examined whether the MJO has impacts on the intraseasonal time scale. Figure 9 shows the pentad-to-pentad variability of the MJO over the central-eastern tropical Indian Ocean from June, 2009 to February, 2010. The variation of MJO index1 was characterized by a persistent positive value from June to October of 2009. Given the variational characteristics of the MJO and the seasonal variation in rainfall, the simultaneous correlations between Yunnan precipitation and MJO index 1 from June to August and from September to October were calculated (Figure 10). For the summer of 2009, MJO index 1 is significantly and negatively correlated with the rainfall over most of Yunnan but positively correlated with the rainfall over some areas of central and northeastern Yunnan. For autumn, there exists a significant negative correlation between MJO index 1 and the rainfall over most of Yunnan, with exceptions over some areas of eastern and northeastern Yunnan. Therefore, on the intraseasonal time scale, persistent positive anomalies of MJO index 1 lead to below-average rainfall over most of Yunnan during summer into autumn. This factor was one of the main reasons for the occurrence of extreme drought in Yunnan in 2009–2010.

To investigate the relationship between the weakening of the ASM circulation in 2009 and the MJO, a simultaneous correlation analysis was performed between MJO index 1 and zonal mean vertical circulation along 0°–20°N from June to August and from September to October, 2009. The results show that, as MJO index 1 remained persistently positive from summer into autumn, particularly anomalous descending airflow was induced over the tropical Indian Ocean from 70°E to 110°E (Figure 11). Thus, during the period from June to October, 2009, the persistent positive

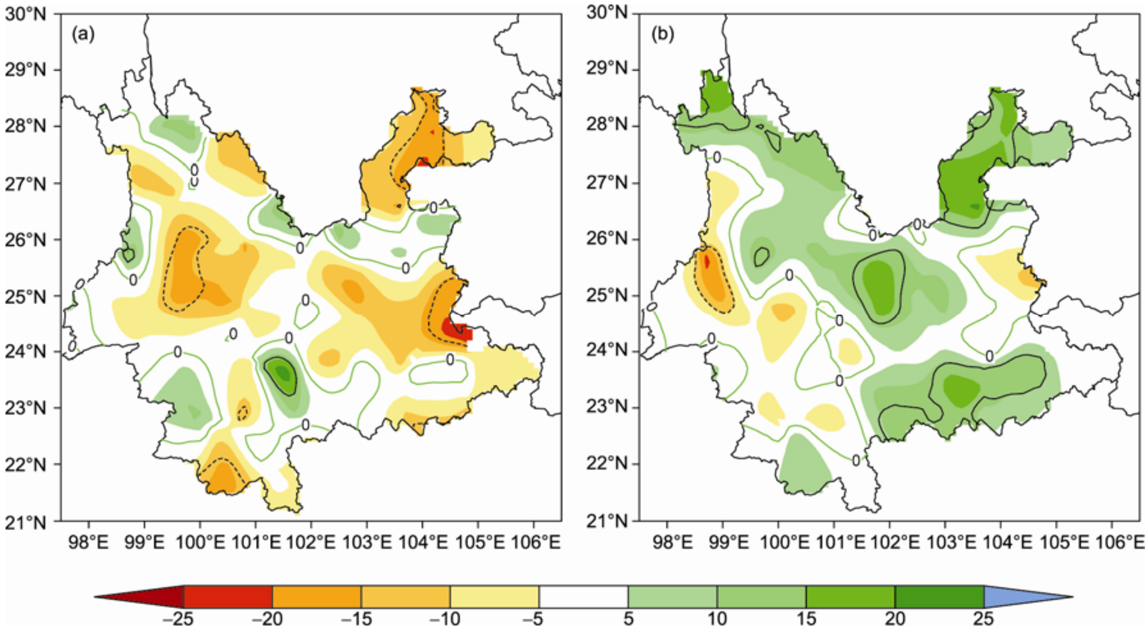

Figure 8 Composites of summer rainfall percentage departures for years with persistent (a) positive and (b) negative values of MJO index 1. Areas of statistical significance exceeding the 90% confidence level (by Student's *t*-test) are highlighted with thick lines.

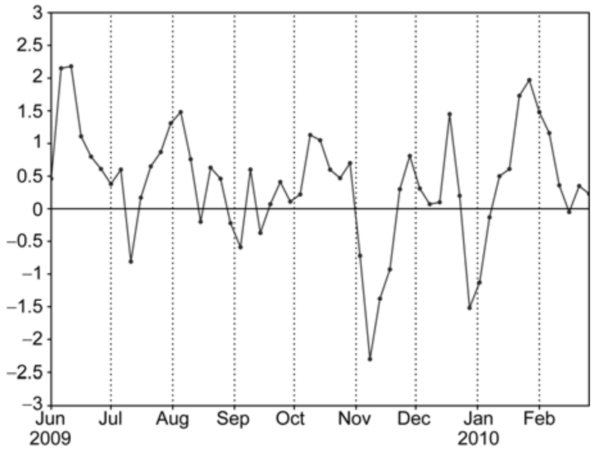

Figure 9 Variation curve of pentad-to-pentad MJO index 1 from June 2009 to February 2010.

phase of the MJO caused persistent weak convection over the BOB, resulted in anomalous weakening of the ASM circulation; additionally, the transport of water vapor to Yunnan was abnormally reduced. These conditions finally led to persistent deficient precipitation over Yunnan from summer into autumn.

4 The influences of persistent positive MJO on winter rainfall over Yunnan

The precipitation in Yunnan remained persistently deficient in the winter of 2009–2010. The atmospheric circulation associated with winter rainfall is mostly manifested following anomalous patterns. Figure 12(a) illustrates the geopotential height anomalies observed at the 700 hPa pressure level, showing weak negative anomalies in geopotential height over the northern Arabian Sea but positive anomalies in other regions south of 20°N. An anomalous high-pressure belt stretched from the Middle East through South Asia to western Yunnan within the latitudes 20°–35°N. Correspondingly, the 700-hPa anomalous wind field over Yunnan was dominated by dry northwesterly winds west of this anomalous high-pressure ridge (Figure 12(b)). Simultaneously, anomalous southwesterly winds prevailed over East China, which were unfavorable to the invasion of cold air from the north. Additionally, anomalous easterly winds prevailed from the northern BOB to Saudi Arabia, indicative of anomalous weakening of the India-Burma trough in the winter of 2009–2010. It has long been noted that the trough moving from India and Burma in winter plays an important role in the weather of South China [22]. The India-Burma trough is a fluctuation embedded in the southern branch of the subtropical westerlies over the southern Tibetan Plateau. Previous studies have documented that when this trough deepens and stretches southward to the BOB, the subtropical high over the South China Sea extends westward to Indochina, and then a warm, moist, southwesterly airflow derived from the BOB is transported to the low-latitude Yunnan plateau. If cold air from the north intrudes into Yunnan at that time, then the main precipitation process in winter and spring should occur [23]. Obviously, the India-Burma trough was weaker than normal in the winter of 2009–2010, resulted in conditions unfavorable for adequate rainfall over Yunnan.

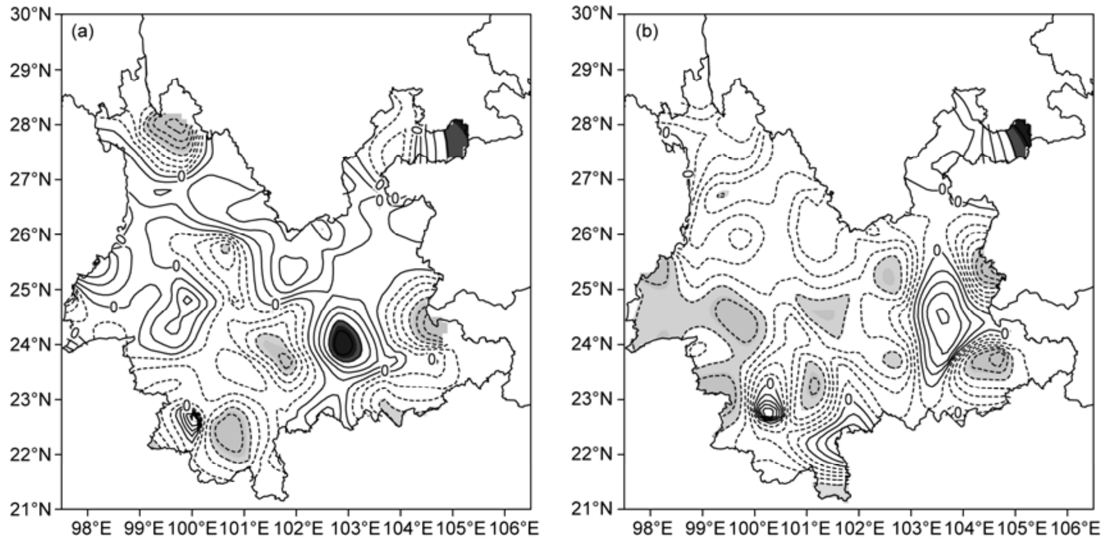

Figure 10 Patterns of correlation between MJO index 1 and Yunnan precipitation from June to August (a) and September to October (b). The contour interval is 0.1. Shaded areas indicate statistical significance exceeding the 90% and 95% confidence levels (t-test).

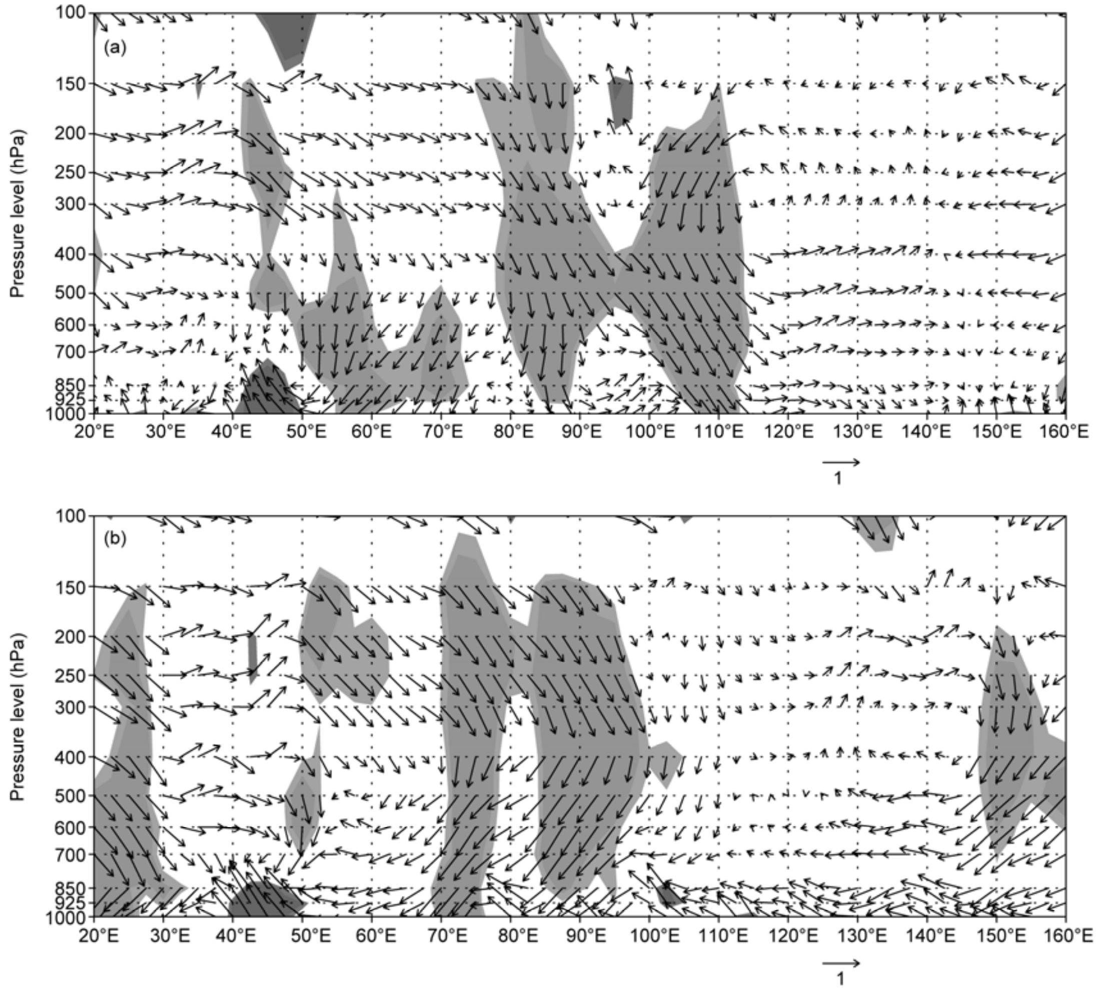

Figure 11 Patterns of correlation between MJO index 1 and zonal mean vertical circulation along 0°–20°N from June to August (a) and September to October (b). Shaded areas indicate statistical significance of vertical velocity exceeding the 90% and 95% confidence levels (t-test).

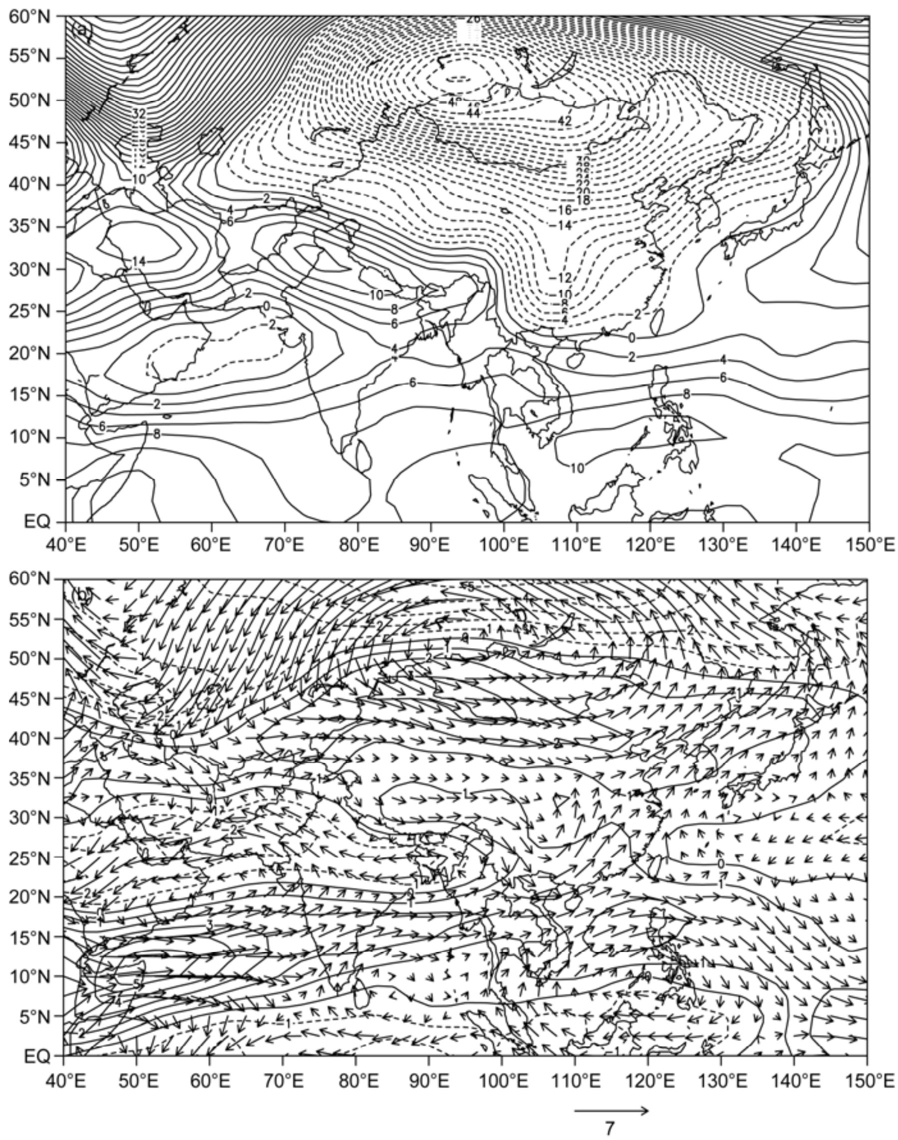

Figure 12 700-hPa geopotential height anomalies (a) and wind field anomalies (b) for the winter of 2009–2010. The anomalies were computed relative to the climatological mean for 1979–2009.

Figure 13 is a longitude-pressure cross section of the anomalous zonal mean vertical circulation along 20°–35°N, showing an anomalous high-pressure belt at the 700 hPa pressure level. It can be seen here that anomalous descending airflow dominates the atmospheric circulation over the Tibetan Plateau, the area to the south of the Tibetan Plateau and southwestern China, which is consistent with the anomalous high-pressure belt, causing below-normal winter rainfall over Yunnan, Guizhou, and Sichuan, whereas anomalous ascending airflow appears 70°E and east of 110°E. Simply put, anomalous weakening of India-Burma trough and descending airflow dominated by an anomalous high-pressure ridge are exactly the primary atmospheric circulation patterns that might be responsible for the below-normal precipitation over Yunnan in the winter of 2009–2010.

To investigate the impact of the interannual variation of the winter MJO on the India-Burma trough, we defined an India-Burma trough index as the normalized negative value of the 700-hPa geopotential height averaged over 85°–95°E to 17.5°–27.5°N. Figure 14 displays the interannual variabilities of the MJO and India-Burma trough during the winter seasons from 1979 to 2010. It is obvious that the variabilities in the MJO index and India-Burma trough index are out of phase. When the MJO index is positive, the convective activity over the central-eastern tropical Indian Ocean is suppressed. During these periods, the India-Burma trough index is negative, suggesting that the trough is weakened. In contrast, when the MJO index is negative, the convective activity is enhanced over the central-eastern tropical Indian Ocean, indicative of the strengthening of the India-Burma trough. The correlation coefficient between these two time

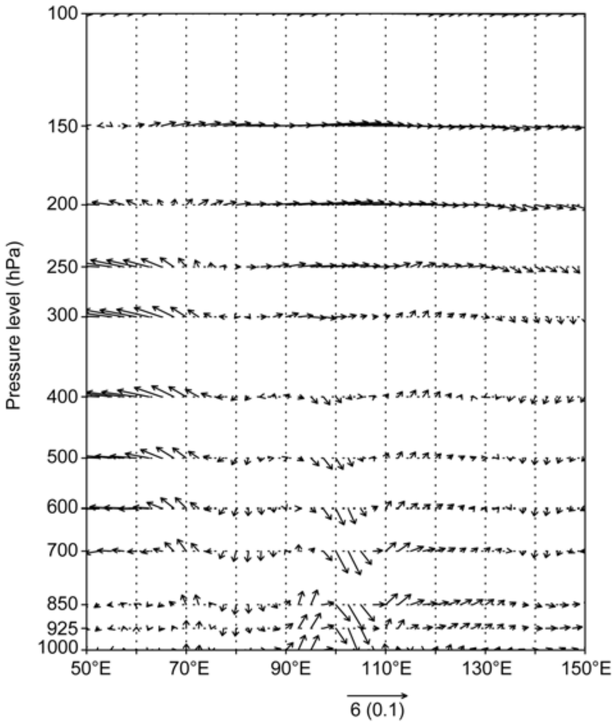

Figure 13 Longitude-pressure cross section of the anomalous zonal mean vertical circulation along 20°–35°N for the winter of 2009–2010. The horizontal (vertical) scale of vectors is shown at the bottom of the panel. The values outside parentheses represent zonal wind anomalies (unit: m s^{-1}). The values inside parentheses represent vertical velocity anomalies (unit: Pa s^{-1}). The anomalies were computed relative to the climatological mean for 1979–2009.

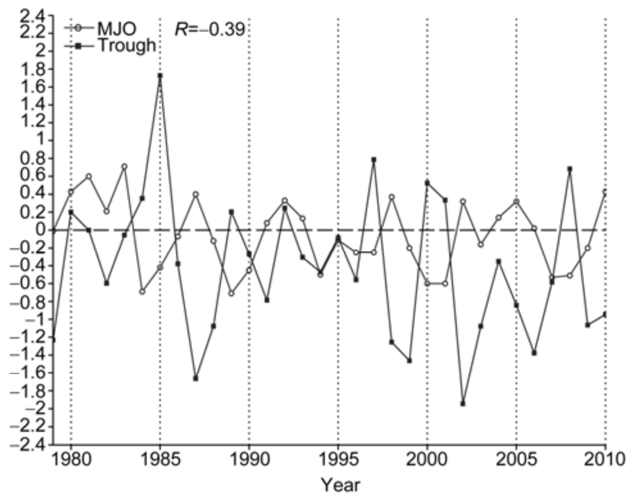

Figure 14 Interannual variability curves for the MJO and India-Burma trough indices during the winter seasons from 1979 to 2010.

series is −0.39, exceeding the 95% confidence level. This result suggests that MJO activity anomalies over the central-eastern tropical Indian Ocean are significantly correlated with intensity variations in the Indian-Burma trough.

The correlations of the 700-hPa geopotential height, the wind field and zonal mean vertical circulation along 20°–35°N with the winter MJO index were then calculated for 1979–2009. As shown in Figure 15, which contains the correlation of the 700-hPa geopotential height with the MJO index, there exists significant positive correlation over the tropics, in particular, a remarkable positive correlation center extending from South Asia through the Tibetan Plateau. Figure 16 displays the correlation between the MJO index and the 700-hPa wind field. Here, there is a pronounced anticyclone stretching from South Asia to the Tibetan Plateau with a high-pressure center over northwestern India. The atmospheric circulation over southwestern China and the northern Indo-China peninsula was dominated by northerly flow before the high-pressure ridge. Remarkable westerly anomalies prevailed over the latitudes 10°–15°N. The correlation of zonal mean vertical circulation along 20°–35°N with the MJO demonstrates that a positive MJO index can induce particularly anomalous ascending airflow around the longitude range of 60°–70°E but anomalous descending airflow over the longitude ranges of 92°–105°E and 107°–118°E (Figure 17).

Observational data show that the MJO remained in a persistent positive state in the winter of 2009–2010 (Figure 9). This state caused the appearance of an anomalous high-pressure ridge over South Asia, the Tibetan Plateau, and the western part of southwestern China, according to the aforementioned significant relationships between the MJO and atmospheric circulation. The atmospheric circulation over Yunnan was completely dominated by vertical descending airflow in the high-pressure ridge. Simultaneously, the India-Burma trough was weaker than normal, which was unfavorable for water vapor transport from the BOB to Yunnan, leading to persistent deficient winter precipitation over Yunnan. Therefore, in the winter of 2009/2010, the persistent positive MJO may have been mostly responsible for the continuous deficiency of rainfall over Yunnan.

5 Discussion and conclusions

Yunnan Province underwent an extreme drought event from autumn 2009 to spring 2010. This event was directly caused by the persistent deficiency of rainfall over Yunnan from the summer of 2009 to the spring of 2010. In particular, the persistent deficiency of rainfall in 2009 was the most serious occurrence in the past 49 years. Additionally, the temperature remained above normal through autumn 2009 and into spring 2010, increasing the soil-moisture evaporation. As a result, the drought was intensified, leading to an extreme drought event.

The results of this study suggest that from summer 2009 to winter 2010, the atmospheric circulation anomalies caused by persistent intraseasonal anomalies in MJO activity over the central-eastern tropical Indian Ocean (Figure 9) played an important role in Yunnan drought lasting from autumn 2009 to spring 2010. From June to October, 2009,

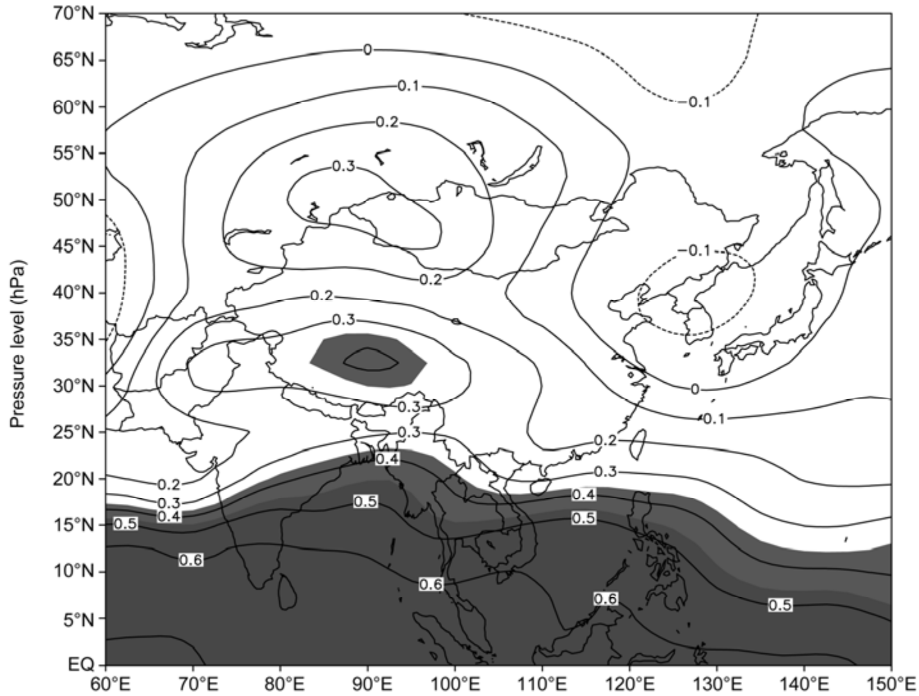

Figure 15 Correlation between the winter MJO index and the 700-hPa geopotential height from 1979 to 2009. Shaded areas indicate statistical significance exceeding the 95% and 99% confidence levels (*t*-test).

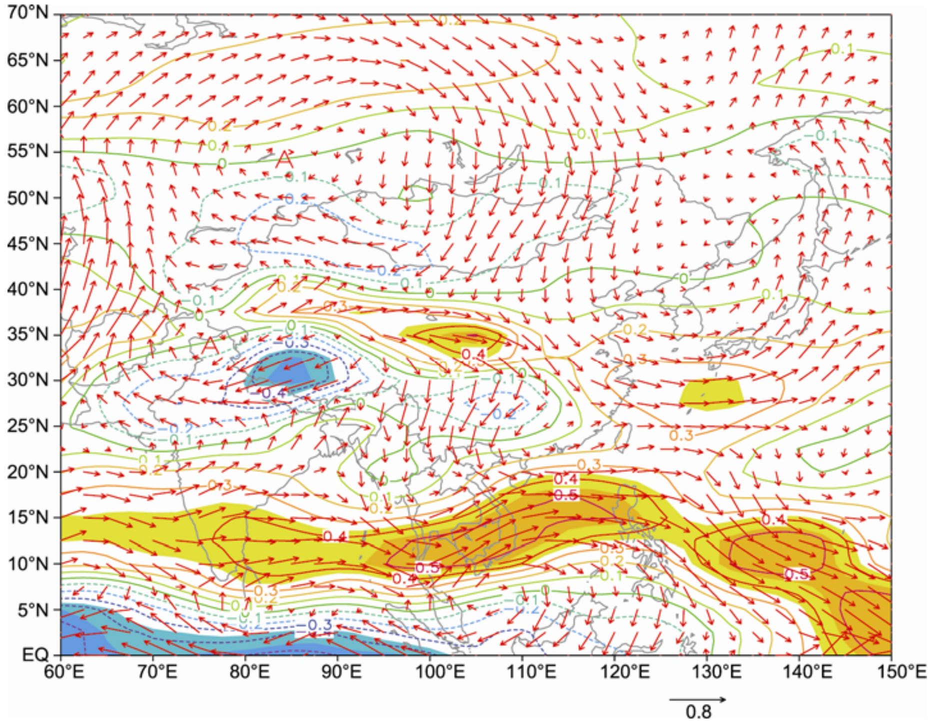

Figure 16 Correlation between the winter MJO index and the 700-hPa wind field from 1979 to 2009. Contours denote zonal wind. Shaded areas indicate statistical significance of zonal wind exceeding the 95% and 99% confidence levels (*t*-test).

MJO index 1 remained in a persistent positive state, resulted in below-normal summer rainfall over most of Yunnan, except for the central and northeastern parts of Yunnan. Furthermore, the rainfall-deficient areas were greatly extended in autumn, indicative of the occurrence of drought. The MJO may influence the summer and autumn rainfall over Yunnan through such a physical process. When an El Niño event appeared in the eastern equatorial Pacific from

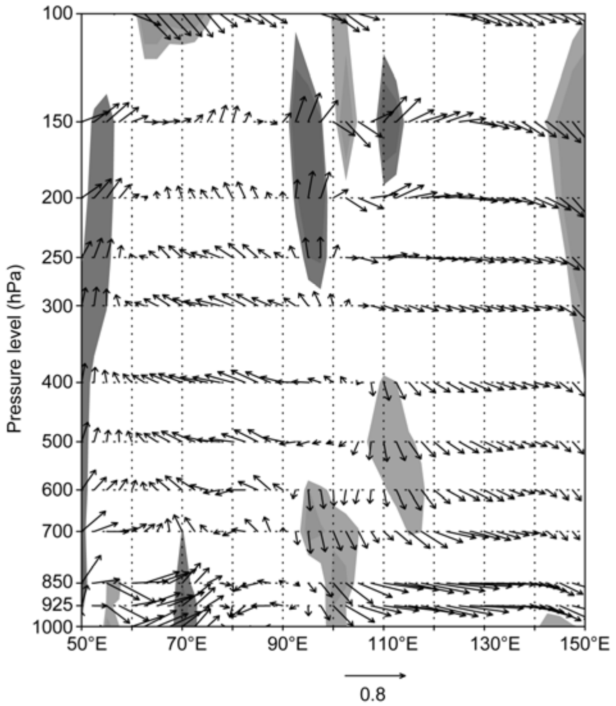

Figure 17 Correlation between the winter MJO index and zonal mean vertical circulation along 20°–35°N from 1979 to 2009. Shaded areas indicate statistical significance exceeding the 90% and 95% confidence levels (*t*-test).

June to October, 2009, MJO index 1 remained persistently positive, resulted from the response of the tropical atmospheric intraseasonal oscillation to anomalous SST forcing in the tropical eastern Pacific. Consequently, the convective activity over the BOB was suppressed, and anomalous descending airflow was then induced over the eastern tropical Indian Ocean, Maritime Continent, and the South China Sea, causing the anomalous weakening of vertical circulation associated with the ASM from June to October. This anomalous atmospheric circulation pattern caused the weakening of water vapor transport from the tropical Indian Ocean to Yunnan and ultimately the persistent deficient rainfall over Yunnan. A drought began to appear in autumn.

In winter, the main precipitation processes over Yunnan are related to the deepening of the India-Burma trough and activities of cold air from the north. Our results suggest that in the winter of 2009–2010, there existed an anomalous high-pressure belt stretching from the Middle East through South Asia to western Yunnan at the 700 hPa pressure level. The atmospheric circulation over Yunnan was dominated by northwesterly winds before an anomalous high-pressure ridge. Moreover, the India-Burma trough around the BOB was weaker than normal, which was unfavorable for water vapor transport from the tropical Indian Ocean to Yunnan. At the same time, the southwesterly winds prevailing over East China were not beneficial for the southward intrusion of cold air. Anomalous descending airflow associated with anomalous high pressure dominated the atmospheric circulation over the Tibetan Plateau, the area to the south of the Tibetan Plateau and southwestern China within the latitudes 20°–35°N. These anomalous atmospheric circulation patterns led to serious rainfall deficiency over Yunnan in the winter. In winter of 2009–2010, the MJO Index 1 remained in a persistent positive state, which was then able to induce anomalous atmospheric circulation patterns similar to the aforementioned patterns. In other words, the convective activity over the BOB was continuously suppressed. An anomalous high-pressure belt through the Middle East to the Tibetan Plateau was induced by the anomalous MJO activity. The atmospheric circulation over Yunnan was dominated by descending airflow associated with the anomalous high-pressure ridge. Moreover, the persistent positive MJO index caused the weakening of the India-Burma trough over the BOB, which was unfavorable for water vapor transport from the BOB to Yunnan, and finally led to a persistent deficiency of winter rainfall over Yunnan. The drought conditions were further intensified due to the anomalous MJO activity.

We concluded that from the summer of 2009 to the winter of 2009–2010, the persistent positive MJO index 1 was an important reason for the simultaneous persistent deficiency of rainfall over Yunnan. In particular, the effects of anomalous MJO activity persisted for several seasons, which played an important role in the occurrence of this record-breaking drought event. Therefore, we should reinforce the monitoring of persistent anomalous MJO activity in the future, thus improving prediction technology for extreme drought events.

We are grateful to the three anonymous reviewers for their constructive comments. This work was supported by Union Fund of the National Natural Science Foundation of China and Yunnan Province (Grant No. U0833602), Special Project of the China Meteorological Administration (Grant No. GYHY200906017), National Natural Science Foundation of China (Grant Nos. 40705026, 40805036 and 40905043), Basic Research Fund of the Chinese Academy of Meteorological Sciences (Grant No. 2010Z001), and Science and Technology Program of Yunnan Province for the Development of Society (Grant No. 2009CA023).

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