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EFFECTS OF INDIAN OCEAN SSTA WITH ENSO ON WINTER RAINFALL IN CHINA

ZHANG Xiao-ling (张晓玲)[1, 2], XIAO Zi-niu (肖子牛)[3, 4], LI Yue-feng (李跃凤)[4]

(1.Nanjing University of Information Science & Technology, Department of Atmospheric Science, Nanjing 210044 China; 2. Meteorological Information Center of Beijing, Beijing 100089 China; 3. Training Center, China Meteorological Administration, Beijing 100081 China; 4. Institute of Atmosphere Physics, Chinese Academy of Sciences, Beijing 100029 China)

Abstract: Based on Hadley Center monthly global SST, 1960-2009 NCEP/NCAR reanalysis data and observation rainfall data over 160 stations across China, the combined effect of Indian Ocean Dipole (IOD) and Pacific SSTA (ENSO) on winter rainfall in China and their different roles are investigated in the work. The study focuses on the differences among the winter precipitation pattern during the years with Indian Ocean Dipole (IOD) only, ENSO only, and IOD and ENSO concurrence. It is shown that although the occurrences of the sea surface temperature anomalies of IOD and ENSO are of a high degree of synergy, their impacts on the winter precipitation are not the same. In the year with positive phase of IOD, the winter rainfall will be more than normal in Southwest China (except western Yunnan), North China and Northeast China while it will be less in Yangtze River and Huaihe River Basins. The result is contrary during the year with negative phase of IOD. However, the impact of IOD positive phase on winter precipitation is more significant than that of the negative phase. When the IOD appears along with ENSO, the ENSO signal will enhance the influence of IOD on winter precipitation of Southwest China (except western Yunnan), Inner Mongolia and Northeast China. In addition, this paper makes a preliminary analysis of the circulation causes of the relationship between IOD and the winter rainfall in China.

Key words: Indian Ocean Dipole; Pacific SST; winter rainfall in China; correlation analysis

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1 INTRODUCTION

In 1999, Saji et al.[1], Webster et al.[2] put forward the concept of the Indian Ocean Dipole (IOD) through analysis of the equatorial Indian Ocean SSTA, which is the phenomenon of positive sea surface temperature anomaly (SSTA) near the equator in the western Indian Ocean in contrast to negative SSTA in southeast Indian Ocean. It is a self-sustaining characteristic mode of the climate system in the Indian Ocean that plays an active and independent role in the climate change in seasonal to interannual scales. In recent years, the equatorial Indian Ocean sea surface temperature anomalies have become the international research focus for scholars.

Numerous studies have shown that the equatorial Pacific SSTA has an important effect on the global climate[3-7]. In fact, the Indian Ocean is close to East Asia so that its surface temperature anomalies would also influence the atmospheric systems and the change of climate, just like the ENSO. The occurrences of the Indian Ocean SSTA impose an important impact on the Afro-Asian monsoon and climate. Behera's studies[8] have shown that excluding the effect of ENSO, the IOD alone has a significant impact on the short-term precipitation in East Africa. In a study on the 1997/1998 winter precipitation anomalies in East Africa, Latif and Dommenget[9] also emphasized the effect of IOD without ENSO. Ashok et al.[10, 11] pointed out that the IOD plays an important role in the regulation of the Indian monsoon precipitation and in the relationship between ENSO and the Indian monsoon precipitation. Guan and Yamagata[12] studied the influences of IOD on hot and dry climate in East Asia in 1994. Li and Mu[13] pointed out that the IOD has an significant and direct impact on the Asian summer monsoon by influencing the tropospheric low-level flow field. Corresponding the

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Biography: ZHANG Xiao-ling, Engineer, primarily undertaking research on air-sea interaction and climate change.

Corresponding author: XIAO Zi-niu, e-mail: xiaozn@cma.gov.cn positive phase of IOD, it brings about a strong South China Sea summer monsoon.

Many Chinese scholars made a lot of research on the influence of the tropical Indian Ocean SST anomaly on the climate of China[14-16]. In terms of the effects of rainfall, many scholars have pointed out that the Indian Ocean SST anomaly has very good relationship with the summer precipitation in China, especially in South China. Through a general survey, Xiao et al.[17] determined that the IOD positive phase prompted little rain in the northern region of China and more rain in the southern. Compared to the negative phase of IOD, the IOD positive phase is closer to the influence of the climate in China. A positive phase may have a direct impact on the summer precipitation through the southwest monsoon, and the negative phase may be doing so through the Pacific-Japan (PJ) wave train. Liu et al.[18] pointed out that when the IOD occurs independently, there would be more summer rainfall in southern China centered on Hunan province in the positive phase of the year. Yan and Zhang[19] thought that the IOD affects the precipitation in mainland China by influencing the southwest monsoon. In addition, Wu et al.[20] indicated through numerical experiments that during the El Niño events, much more rainfall in August in Yangtze-Huaihe Rivers basin is not a direct response to the equatorial eastern Pacific warm SST, but mainly a response to the middle and western equatorial Indian Ocean warm SST in the same period. Xiao and Yan[21] also pointed out through an atmospheric circulation model that the SST of the western Indian Ocean and Arabian Sea increases with the decrease of the summer precipitation in the southwest of China but with increase of the rainfall in the Yangtze River basin, the east and south of China.

However, more domestic work is directed more at the influences of Indian Ocean SST anomaly on the summer precipitation in China than at the winter precipitation (snow) Although the winter precipitation is generally less, due to the low winter temperature, a slight strengthening of the precipitation process will result in severe local drought and flood disasters. Therefore, the winter precipitation anomalies may also cause great harm[22]. Especially in recent years, in the background of climate change, the harsh winter climate change in South China brought enormous negative impact on people's life. From mid-January to early February 2008, rare low-temperature, snow and freeze weather took place in the middle and lower reaches of Yangtze River of China to Guizhou area, with the strength never seen in the past fifty or even a hundred years. This disaster seriously influenced the traffic, telecommunications and power transmission. Also in the winter of 2009 to the spring of 2010, Southwest China suffered a severe once-in-a-century drought, affecting more than 61.3 million people in Guangxi, Chongqing, Sichuan, Guizhou, and Yunnan provinces. The duration and extent of the drought are extremely rare in history. The occurrence of these extreme events aroused meteorologists to pay more attention to winter rainfall process.

In the study of Indian Ocean Dipole (IOD), Li and Mu[23] pointed out that the IOD is strongest in the September-November and weakest in January-April. On the consideration of delaying effect of air-sea interaction, autumn Indian Ocean SST anomaly also might affect winter precipitation in China. Therefore, the purpose of this work is to study the characteristics of Indian Ocean SST anomalies and their impact on the Chinese winter rainfall under the background of ENSO, and understand the characteristics of atmospheric circulation anomaly development over the peak period of IOD oscillation. It has an important theoretical significance and practical value to explore the impact factor of abnormal winter climate in China and forecast Chinese winter precipitation.

Section 2 introduces the data and methods used in this study and section 3 introduces the time evolution characteristics of the Indian Ocean SSTA dipole index. In section 4, we will have a discussion on the influence of IOD on Chinese winter rainfall. The main part of section 5 explores the causes for water vapor circulation and analyzes the IOD influence on Chinese winter rainfall. And the last part is the conclusions.

2 DATA AND METHODS

In this study, the main data used include 1°×1° global monthly SST data by Hadley Center from 1950-2009, 1960-2009 NCEP/NCAR reanalysis data of monthly average geopotential height and wind field with the horizontal resolution at 2.5° × 2.5°, 1960-2009 monthly average precipitation data over 160 stations from the China Meteorological Administration.

In this research, the Indian Ocean dipole index defined by Saji et al.[1] is adapted to characterize the strength change in SSTA between differences of the eastern and western equatorial tropical Indian Ocean, which are averaged for (10°S to 10°N, 50 to 70°E) and (10°S to 0°, 90 to 110°E). The intensity changes in ENSO are represented with the SST in Niño3 (150 to 90°W, 5°S to 5°N), and its typical positive and negative anomaly values respectively characterize the occurrence of El Niño and La Niña events.

Diagnosis analysis of the observed data is conducted with statistical analysis methods, which include correlation analysis, partial correlation analysis, *t*-test and composite analysis.

3 TIME EVOLUTION CHARACTERISTICS OF THE INDIAN OCEAN SSTA DIPOLE INDEX

Figure 1 presents the characteristics of the distribution of the interannual (inter-decadal) variation of the annual average Indian Ocean dipole index (IODI) from 1950 to 2009. The chart shows that from 1950 to 2009, the SST in the western Indian Ocean rises more obviously than in the eastern SST region and the IODI presents a slowly rising trend on the whole, and after the 1960s there are more typical years of IODI positive phase. In addition, since the 1950s, the IODI fluctuation amplitude has been bigger and the wave frequency stronger. In terms of the interannual variability cycle, the dipole is characterized with an evident periodic interannual variability of 2 to 3 years before the mid-1960s and afterwards with large-amplitude periodic oscillation of 4 to 5 years. In order to better understand the inter-decadal variation characteristics, we also did 9-point smoothing of IODI to remove the curve trend. It can be seen that the dipole shows significant interannual variation characteristics for the time from the mid-1960s to 1990s, and presents decadal oscillation characteristics for the ten years from the 1950s to the mid 1960s and after the 1990s, but the amplitude is relatively obvious before the mid-1960s. In general, the IODI shows not only obvious interannual oscillation but also noticeable decadal variation in the past 60 years.

In order to quantify the period and strength variation characteristics of Indian Ocean SSTA, Fig. 2 presents the 1950-2009 IODI annual variation of the wavelet power spectrum analysis. It shows that IODI presents a widespread periodic interannual variability of 2 to 3 years, 3 to 4 years and 5 to 6 years. At the same time, a quasi-cycle of about ten years gradually evolves into one of 5 to 6 years after the 1960s, and later into one of 3 to 4 years after the 1980s. These mutation characteristics of IODI from the late 1970s to the early 1980s have also been confirmed[24] in previous studies. As a result, in the last 60 years, the main activity cycle of the Indian Ocean dipole tends to be decreasing.

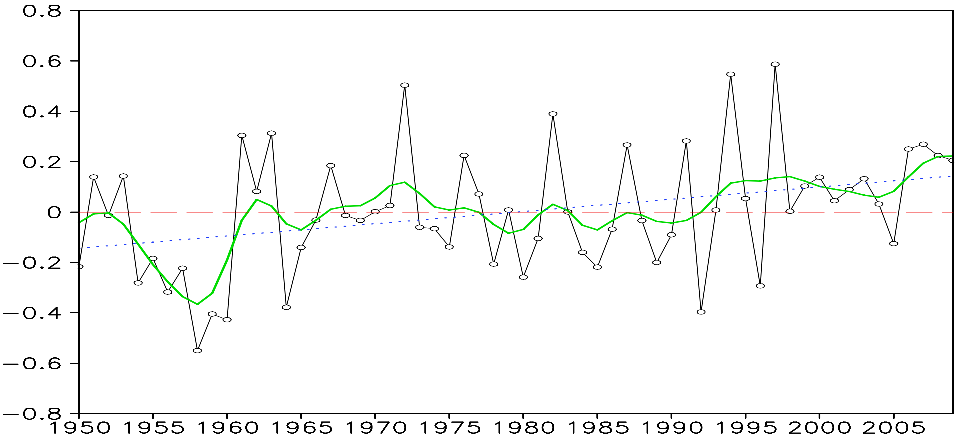


Figure 1. Interannual (inter-decadal) variation characteristics of IODI from 1950 to 2009. Solid line with hollow round is for the index value of dipole characteristic, smooth curve for the 9-point quadratic smoothing line, long dash line for the IODI climate average value, and dotted line for the IODI linear growth trend.

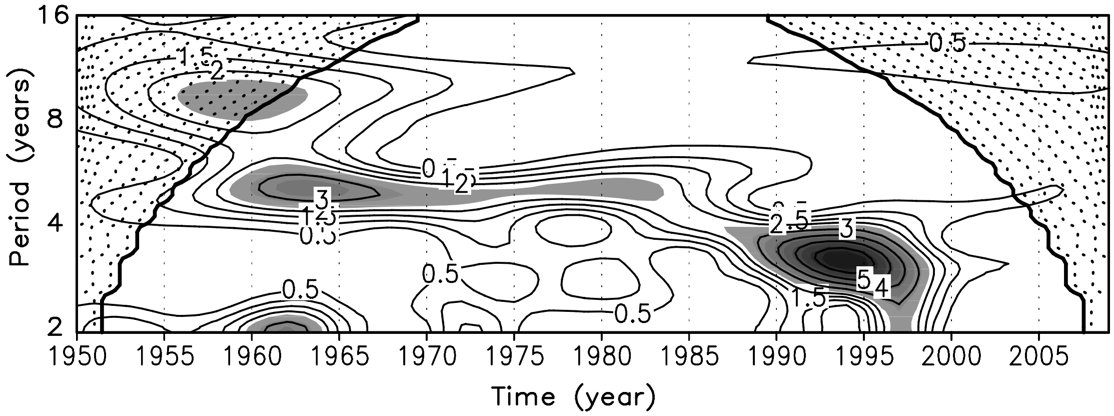


Figure 2. Wavelet power spectrum analysis of the IODI annual change from 1950 to 2009. The vertical axis is for power spectrum period (year), the horizontal axis is for time (year), the shadow parts pass the 0.1 confidence level, and the dotted area indicates significant boundary effect of "head area".

In addition, Fig. 1 also shows that the sliding curve deviated considerably from the average before 1960, presenting a large negative-phase amplitude, while the amplitude is relatively smooth after 1960.

Because the study is mainly to find out the interannual variability characteristics of IODI and its influence on climate, only the data after 1960 will be included in the following discussion.

4 INFLUENCE OF IOD ON WINTER RAINFALL IN CHINA

4.1 *Relationship between autumn IOD and winter rainfall*

It is known that the IODI strength reaches its peak in fall, so in this study, we select the SSTA field from September to November in the typical years of IODI positive and negative phase to represent the basic characteristics of the entire IOD modal SST field. Fig. 3 is the distribution graph of the IODI in autumn and winter rainfall of China in the same year. It shows a very fine correlation between the autumn IODI and winter rainfall in China. The two significantly positive correlation areas that pass the test of significance are located in the regions between the southern part of the Yangtze River Delta and the eastern part of South China, as well as the Inner Mongolia and the northern part of North China. The largest correlation coefficient of the southeast region reaches 0.47. Therefore, when the Indian Ocean dipole index is of positive phase, that is, when the Indian Ocean SST is cold in the east and warm in the west, there will be two significant rain bands with increased winter precipitation in the year in the coastal regions of the southeast, central Inner Mongolia and the northern part of North China. In contrast, when the Indian Ocean dipole index is of negative phase and the SST is warm in the east and cold in the west, the winter precipitation in the southeast and central Inner Mongolia will significantly reduce in the following year. In addition, the region in the Yangtze-Huaihe River Basin is of negative correlation.

From the correlation analysis above, we can see that IODI is well correlated with winter rainfall in China. Some of the early analysis showed that the occurrence of IOD events is usually related to the occurrence of ENSO events. Li et al.[25] pointed out that, although the IOD seems to be independent of ENSO in very few years, the two have a good correlation in general. Chao et al.[26] also believed that there is a certain delay correlation between ENSO and IOD. Some other studies[27] found that after the 1970s, the IOD events always happened along with ENSO events. Meanwhile, some work also concluded that, despite that IOD and ENSO events co-occurred, their impacts on Asian climate are not the same[18, 23, 28]. As a result, the study on the relationship between IOD and winter rainfall in China must include the examination of the complex effects brought about by the interaction between ENSO and IOD. Therefore, by analyzing the partial correlation, this paper will further discuss the influence of IOD on the winter rainfall of China and its differences and connection with the effects of ENSO.

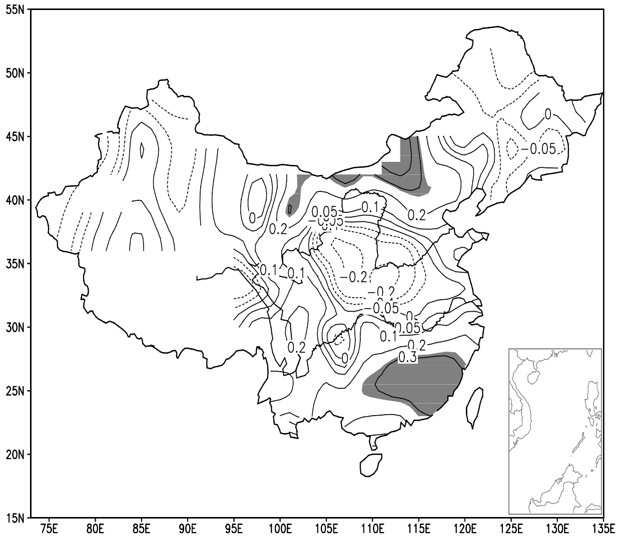


Figure 3. Distribution of the correlation between fall IODI and China's winter rainfall in the same year. The shadow is for the region passing the 0.05 significance test.

Due to the good correlation between IODI with the winter precipitation in Central and East China, where adequate stations are set up that can provide relatively complete precipitation data, we will focus on the change of precipitation in Central and East China in the following discussion.

4.2 *Partial correlation analysis of the relationship between IOD and China's winter rainfall*

We use the Indian Ocean SSTA field in fall to represent the basic characteristics of the entire IOD modal SST field in the above discussion. To keep the consistency of the analysis, we also selected the Niño3 index in the fall of the same period. Thus, in order to exclude the effect of ENSO on China's winter rainfall in the Indian Ocean dipole years, we calculated the coefficient of the partial correlation between autumn IODI and autumn Nino3 index and China's winter rainfall (Fig. 4), which reveals the influence of either IOD or ENSO as independent factors on the distribution of winter rainfall in China.

Figure 4a reflects the partial correlation between the autumn IODI and China's winter rainfall excluding the ENSO effect. It shows that there is a negative correlation zone with the significance test of more than 0.1 in the northeast Inner Mongolia. Except for the area of weak negative correlation in the Yangtze-Huaihe River basins, the entire East China is basically positively correlated. The regions in Southwest China pass the 0.1 confidence test, and most of Inner Mongolia passes the 0.05 confidence test. This shows that excluding the influence of the ENSO, the winter precipitation in the regions along the Yangtze-Huaihe River valley and northeast Inner Mongolia will reduce in the typical years of IODI positive phase, while in the southwest, south, north China and northeast of China, precipitation will increase, and vice versa.

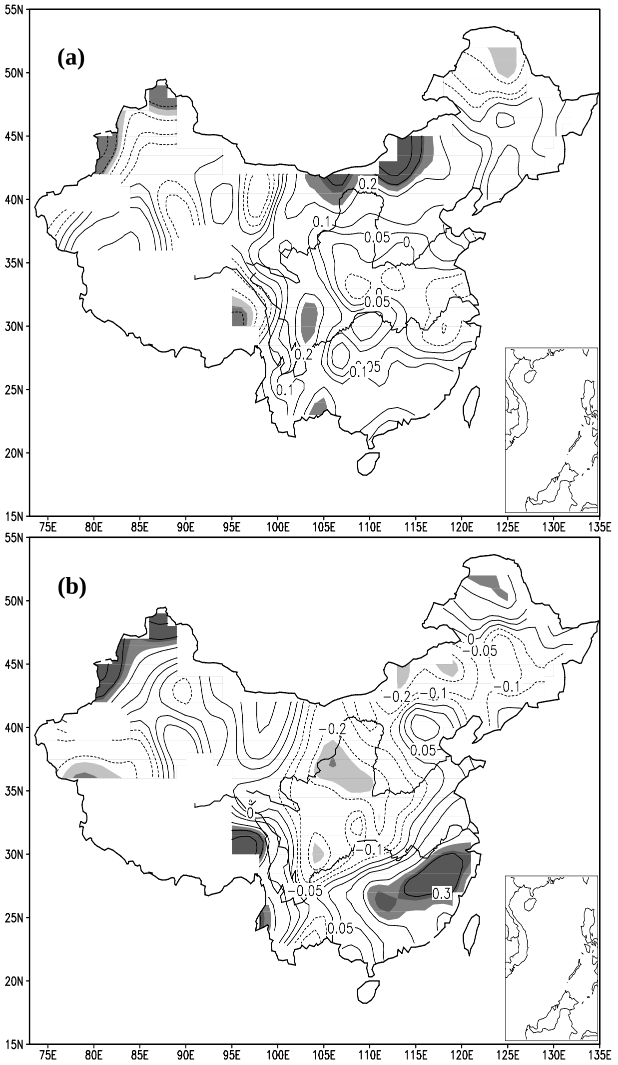


Figure 4. Partial correlation of IODI (a) and Nino3 index (b) with China's winter rainfall. Light and dark shadows are the regions that pass the 0.1 and 0.05 significance test, respectively.

Figure 4b shows that most of the regions in the area south of the Yangtze River are zones of positive correlation, especially in western Yunnan province and the southeast of China, whose positive correlation coefficient passes the 0.05 significance test. In addition, the eastern North China also manifests a positive correlation. Comparatively, some regions, including part of the southwest, the Yangtze-Huaihe River Valley and the Yellow River Basin, as well as Northeast China, are negatively correlated, and the negative correlation area near the Great Bend of the Yellow River passes the 0.1 significance test and some even more than 0.05 Therefore, the occurrence of El Niño is conducive to the increase in the winter precipitation of southern region of China and the decrease of rainfall in Yangtze-Huaihe River valley, the Yellow River basin and the northeast. This is also consistent with the conclusion by Gong and Wang[29]. In addition, the precipitation in the southwest (except the west of Yunnan province) also significantly reduces.

Comparing Fig. 4a with 4b, we found that the related area with the same trend are mainly concentrated in the area between the south of Yangtze river and the south of China, which indicates that the IOD and ENSO are exerting influence on winter rainfall in those areas. That is to say, the abnormal increase of SST in the western Indian Ocean and the eastern Pacific will lead to a significant increase of winter precipitation in the area from the south of Yangtze River to South China. The regions of negative correlation mainly include the area around the Great Bend of the Yellow River, Inner Mongolia and Northeast China. Besides, there is a good anti-phase relationship in the southwest region and the middle and lower reaches of the Yangtze river, which means the effects of the IOD and ENSO SSTA on winter rainfall are the opposite in these areas. The comparison between Fig. 4 and Fig. 3 shows that the influence of the IOD on winter rainfall in the area between the south of the Yangtze River to South China is similar to that of ENSO, and when IOD and ENSO are both in positive or negative phase work together, they will increase (decrease) precipitation more significantly. In other areas, however, they have almost the opposite effect on winter rainfall. When they work together, the regions from Inner Mongolia to the northern North China mainly present the influence of the IOD. That is, when the positive (negative) IOD phase occurs, the precipitation of the first winter after the year will increase (decrease) significantly in those regions. In general, ENSO mainly directly affects winter precipitation in the south of China and IOD mainly directly affects winter rainfall in the north, but the interaction between IOD and ENSO might strengthen the anomaly of winter precipitation in the south of China. In the following discussion, we will use the observed precipitation data of typical years to analyze the characteristics of winter precipitation anomaly in China under the influence of either IOD alone or ENSO alone, and the joint influence of IOD and ENSO together, so as to further verify and explore the relationship between winter rainfall and IOD.

4.3 *Impact of IOD and ENSO on the distribution of winter precipitation anomaly in China*

First of all, we choose the typical years to represent the occurrence of IOD alone, ENSO alone and IOD and ENSO combined, and these typical years are also selected based on the indexes of the autumn

IODI and autumn Niño3. Therefore, we employ the method of Saji and Yamagata[30] and followed the typical selection results by Saji and Yamagata[31] to select 22 cases of dipole abnormal events as the study cases, which include 11 cases of positive and negative dipole years each. Similarly, we use the method in Wang and Gong[32] to select 23 cases of abnormal ENSO events as the subjects of research, of which 11 are typical El Niño years and 12 are typical La Nina years. Thus, a table (Table 1) for typical years is formulated. Based on the characteristics of precipitation and circulation field in these typical years, we will discuss the influence of IOD on the winter rainfall, its variations and connection with ENSO climate.

Table 1. Typical years of IOD and ENSO independent occurrence and co-occurrence. The superscript 'a' represents the year with inconsistent IOD and ENSO phase.

Phase	Year of independent IOD occurrence	Year of independent ENSO occurrence	Year of IOD & ENSO co-occurrence
Positive	1961, 1967^a, 1977, 2007^a	1965, 1969, 1986, 2009	1963, 1972, 1982, 1987, 1997, 2002, 2006
negative	1960, 1968, 1980, 1992	1962, 1967^a, 1988, 1999, 2007^a	1964, 1971, 1975, 1984, 1996, 1998, 2005

Figure 5 shows the composite distribution of the anomaly percentage of the winter precipitation in the typical positive-phase years when IOD and El Niño co-occur and when IOD occurs independently. In the figure, the winter rainfall increases significantly in the co-occurrence year in central Inner Mongolia, northern part of North China and the south part of China, especially in the south of the Yangtze River and the coastal area, with maximum positive anomaly percentage value reaching 60%, while precipitation shows negative anomaly in the Yangtze-Huaihe River Valley and Yellow River basin and the northeast China. In the typical years of positive IOD phase when it occurs independently (Fig. 5b), the precipitation zone of positive anomaly covers North China and the southern and central part of Northeast China. The northern part of the northeast and most part of the middle and lower reaches of the Yangtze River are of negative anomaly in winter precipitation. It is notable that a significant abnormal precipitation center was located in the southwest of China. The existing research[33-35] suggested that the winter precipitation in coastal regions of the southeast China increase significantly in the years when El Niño events occurred in winter, while in the southwest part of China, Central China and North China, winter rainfall tend to decrease. Therefore, in the years when positive IOD phase and El Niño co-occurred, IOD mainly affected the winter rainfall in the regions of the southwest, Inner Mongolia and Northeast China, and the influence of ENSO is more significant in South China and the Yangtze-Huaihe River Valley. Both play a dominant role in their respective key area they influence, so that the southern and northern parts of East China were rainy but the center was comparatively dry. The results are basically consistent with the conclusion from Fig. 4a and 4b.

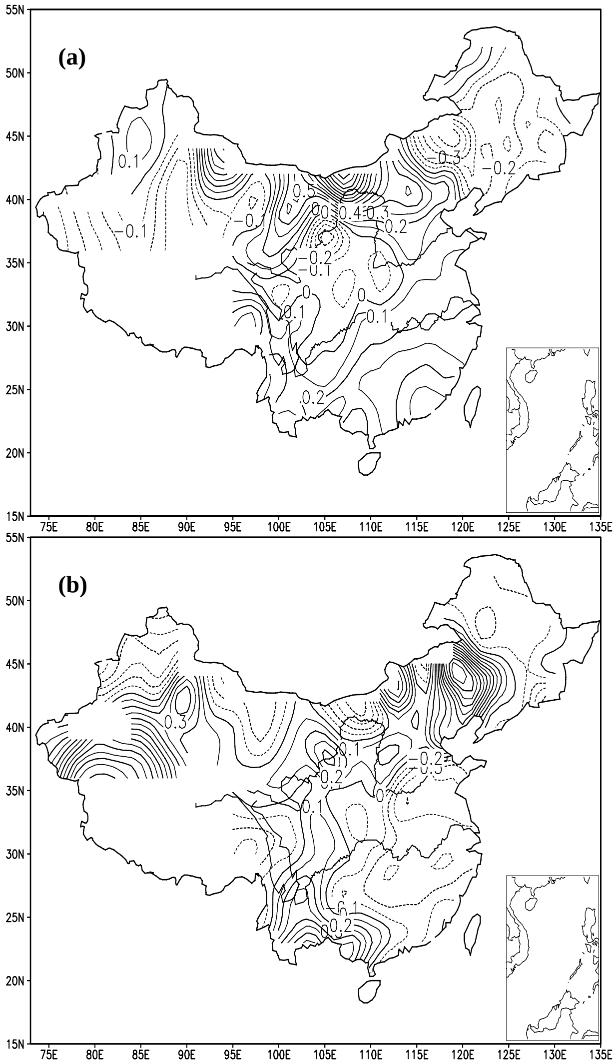


Figure 5. Composite distribution of winter precipitation anomaly percentage when the positive-phase IOD and El Niño co-occurs (a) and IOD occurrs independently (b). Units: 100%.

Similar results can be found in the analysis of winter precipitation anomaly in the typical years with negative phases of IOD and ENSO. When the negative IOD phase occurs together with a La Niña event (Fig. 6a), the abnormal precipitation distribution is basically opposite to that of Fig. 5, presenting a belt-shaped distribution in which there is less rain in the north and south than in the middle of East China. Besides, in the typical years of negative IOD phase (Fig. 6b), the winter precipitation increases significantly in the middle and lower reaches of the Yangtze River, and the precipitation significantly decreases in other regions, but the change in the north of Northeast China is not obvious. We also note that although the distribution pattern of abnormal precipitation in Fig. 6b is basically the opposite to that in Fig. 5b, the intensity of anomaly precipitation is relatively low. It means that the influence of the positive-phase IOD on winter precipitation in China is more obvious than the negative-phase IOD. This result is consistent with the conclusion of Xiao et al.[17]. Although the negative-phase IOD usually occurs simultaneously with the negative-phase ENSO SSTA, they caused different effects on winter precipitation in China, just like the effect of the positive-phase IOD on climate.

The equatorial eastern Pacific cold SSTA usually results in a decreasing trend of rainfall in the Yangtze-Huaihe River basins and areas south of the Yangtze River basin, and a significant increase in precipitation in the southwest, the area near the Great Bend of the Yellow River and the central Northeast China. The negative-phase IOD SSTA brings about a general decrease of winter rainfall in East China except for the middle and lower reaches of the Yangtze River. Under the effect of the negative-phase SSTA of IOD and ENSO, however, the winter precipitation decreases in the south of China but increases in the Yellow River basin and North China, which are consistent with the two key areas mentioned above.

5 ANALYSIS OF THE WATER VAPOR CIRCULATION CAUSES OF IOD’S INFLUENCE ON CHINA'S WINTER RAINFALL

From the perspective of the characteristics of circulation field, we will make a brief analysis of circulation causes of the impact of IOD with ENSO on the winter rainfall in China. We selected the 500 hPa height field and the 850 hPa flow field as the objects of analysis, and respectively used the positive and negative circulation fields of IOD and ENSO co-occurrence, independent IOD occurrence and independent ENSO occurrence to subtract the average climate circulation field in 50 years, so as to analyze the similarities and differences of the circulation status in the years of independent IOD occurrence and independent ENSO occurrence respectively.

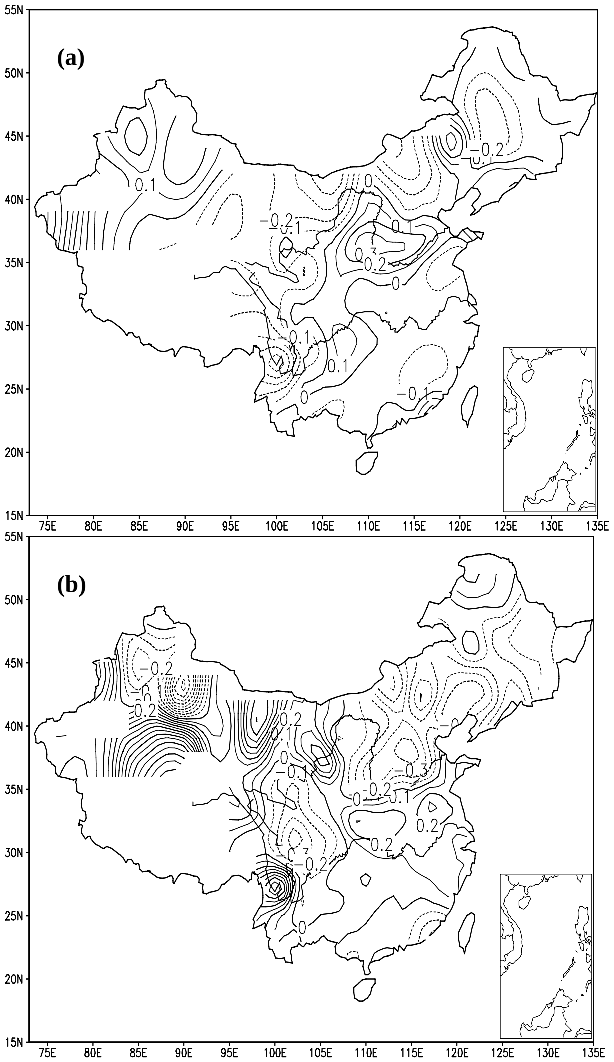
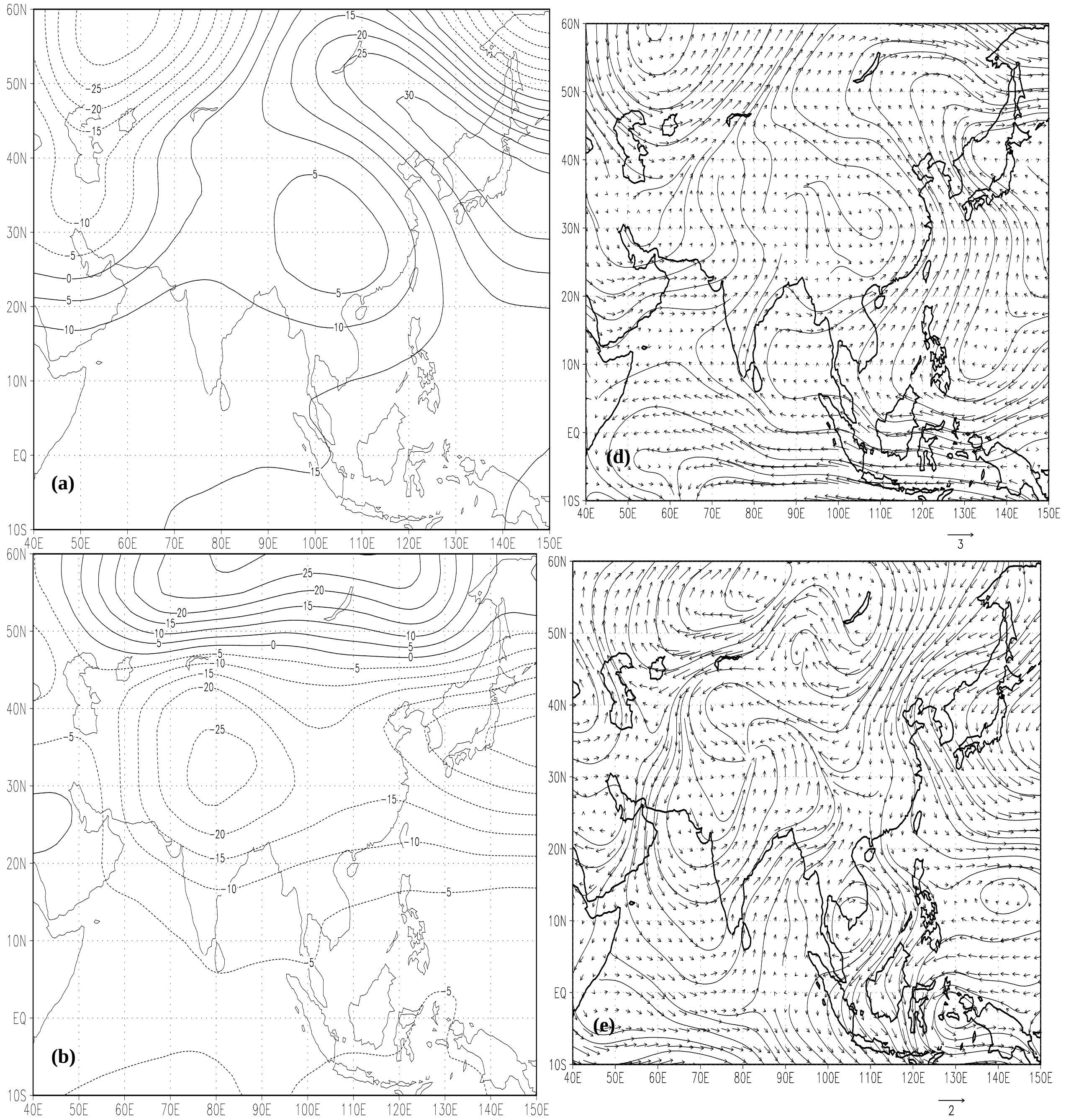


Figure 6. Composite distribution of winter precipitation anomaly percentage when the negative-phase IOD and La Niña co-occurs (a) and IOD occurs independently (b). Units: 100%.

Figure 7a shows that the 500 hPa abnormal height field presents a shape of two troughs and one ridge in the co-occurrence years of positive phase. In winter, East Asia is basically under the control of abnormal high pressure, whose center is located near the Sea of Japan. The position of a main East Asian trough is northward and eastward, and the subtropical high is northward. There is a similar height field structure in both El Niño years (Fig. 7c) and co-occurrence years. The Chinese mainland is under the control of an abnormal high pressure, and cold air enters China from a high-pressure to the east. This structure of height field is helpful for the delivery of warm moist air flows from southern China. However, the situation is very different in the positive-phase years of independent IOD occurrence. The abnormal height field is high in the north and low in the south, and the cold air passes through the middle and west path to control the mainland. It could be part of the reason for the increase of winter precipitation in the southwest in the years of positive IOD phase. From the perspective of circulation field, in the co-occurrence years (Fig. 7d), the mainland of China is under the control of southerly winds from south to north. Due to the blocking of cyclonic circulation near Lake Baikal in the middle and high latitudes in El Niño years, the cold air meets with the warm air in southern China, resulting in the increase of precipitation in the south. In the positive IOD years, however, the north-south air flow meeting takes place in the southwest, resulting in the increase of precipitation there.

Thus, when IOD and ENSO occur simultaneously, the participation of El Niño signal reverses the prevailing wind direction in the east of the Chinese mainland. However, the positive IOD anomaly in the El Niño years strengthens the southerly wind of southern China and pushes it northward continuously, and as a result, the precipitation in the southeast and north of China increases in the positive-phase co-occurrence years.



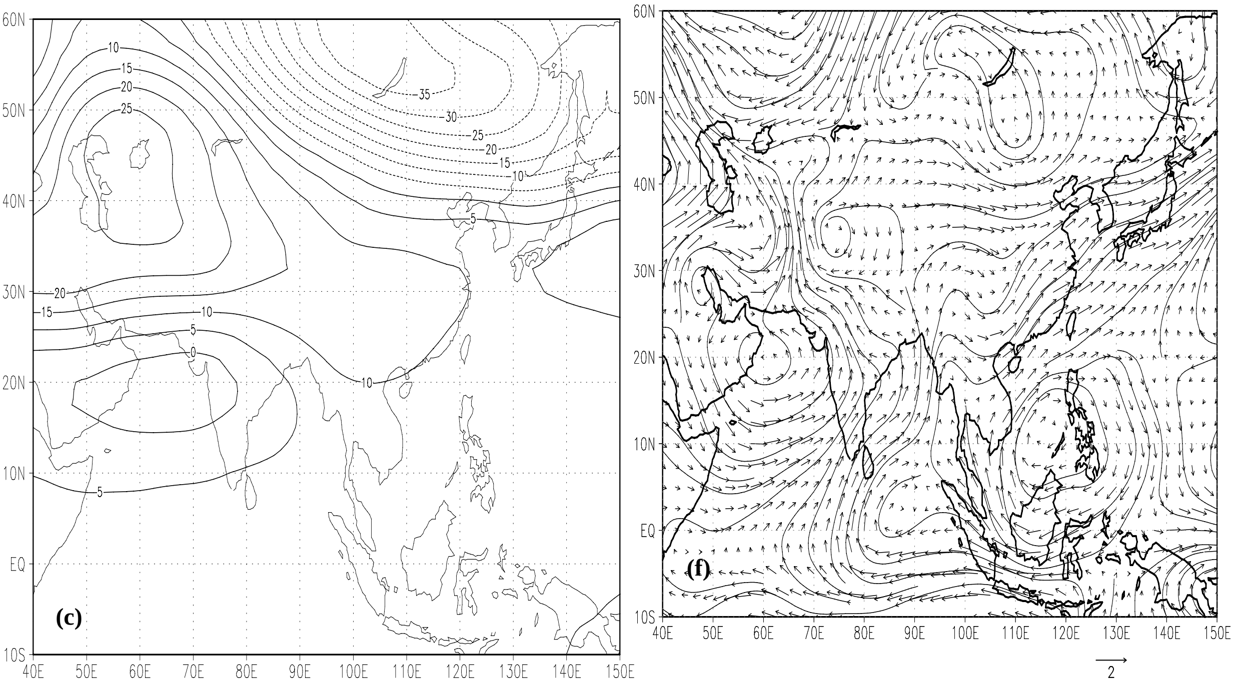


Figure 7. Difference between the 500 hPa geopotential height field (unit: dagpm) and 850 hPa circulation field (unit: m/s) and 50-year average climatological field in positive phase years of the co-occurrence and independent occurrence. (a and d): co-occurrence years; (b and e): IOD independent occurrence years; (c and f): El Niño independent occurrence years.

In the typical negative-phase co-occurrence years (Fig. 8a), the 500 hPa geopotential height field in the mainland is still controlled by abnormal high pressure, but its strength decreases significantly compared with that of the positive-phase years. The positive anomaly center of geopotential height moves eastward and northward in La Niña years (Fig. 8c), and its circulation status is similar to typical positive-phase IOD years. Likewise, China is still under the control of abnormal low pressure in the years of negative-phase IOD, but in combination with the surface pressure field (Figure omitted), China is under the control of abnormal high pressure in positive-phase IOD years, and the situation is completely the opposite in the years of negative phase. As a result, this configuration of unstable high- and low-layer pressure fields in positive-phase years also brings about the increase of winter precipitation compared with the negative phase years. From the perspective of circulation field, in the co-occurrence years, the northern and southern branches of the cyclonic circulation from the Philippines and south of Lake Baikal meet in the Yangtze-Huaihe River valley, causing the increase of precipitation in that region. In the La Niña years, the anticyclone located in the area from the Western Pacific to South China Sea disappears, and the northerly winds hold back the northward transport of warm moist air flows in the south. In the negative-phase IOD years (Fig. 8e), there is a significant southerly wind transporting warm and moist air flows to the coastal areas in the southeast. It is clear that the addition of La Niña signal will cover up the influence of IOD on winter rainfall in southern China, but it will increase precipitation in the Yangtze-Huaihe River valley, making the situation of precipitation in the south in the negative-phase co-occurrence years similar to that of ENSO years, i.e., a decrease in rainfall.

6 CONCLUSIONS

This work, by analyzing the winter precipitation anomaly in China in the years of independent IOD occurrence and co-occurrence of IOD and ENSO, discusses the impact of ENSO on the IOD mode with different phases of SSTA on winter precipitation in China.

(1) In the independent positive (negative) phase years of IOD, winter precipitation in the southwest (except western Yunnan), North China, and Northeast China significantly increases (decreases), while rainfall in the Yangtze-Huaihe River valley decreases (increases). The influence of IOD positive-phase SSTA on winter rainfall in China is bigger than that of the IOD negative phase.

(2) The influence of IOD and ENSO on winter rainfall in China is not the same. They impose opposite influence in regions including Southwest China, the middle and lower reaches of the Yangtze River, the area between the Great Bend of the Yellow River and Inner Mongolia, and Northeast China, which indicates that the influence of IOD and ENSO on winter rainfall in these areas offsets each other, but they have similar effects on precipitation in western Yunnan, South China and the Yangtze-Huaihe Rivers

valley.

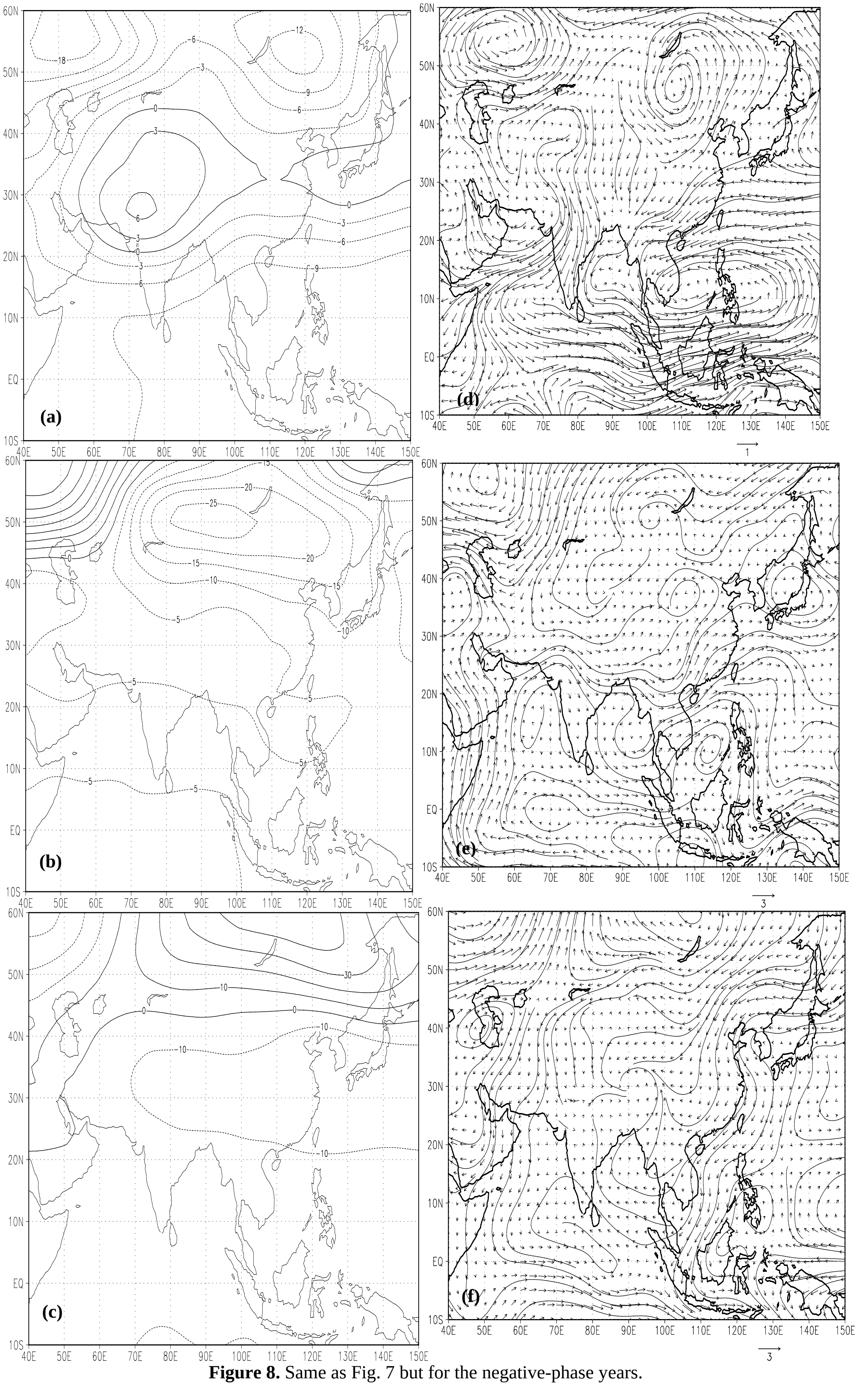


Figure 8. Same as Fig. 7 but for the negative-phase years.

(3) Compared with ENSO and IOD independent occurrence years, their joint effects are not a simple summation of individual effects. IOD SSTA has a more significant impact on winter precipitation in Southwest China (except for western Yunnan), Inner Mongolia and the northeast. Comparatively, ENSO SSTA mainly affects the precipitation in South China and the Yangtze-Huaihe Rivers valley.

(4) When IOD occurs independently, cold air enters Chinese mainland through the middle and west path, and when both IOD and ENSO occur simultaneously, East Asia is controlled by abnormal high pressure, and cold and warm air meets in a different area. This is the basic circulation cause of the difference in winter rainfall in the years of IOD independent occurrence and IOD-ENSO co-occurrence.

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