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INTERANNUAL VARIABILITY OF WINTER AND SPRING PRECIPITATION IN SOUTH CHINA AND ITS RELATION TO MOISTURE TRANSPORT

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Abstract: The interannual variability of winter and spring precipitation in South China (SC) and its relation to moisture transport are investigated by using the monthly precipitation data of NMIC, NCEP reanalysis datasets and NOAA ERSST analysis datasets from 1960 to 2008. The results show that winter and spring precipitation in SC is less than normal from the 1960s to the start of the 1970s and from the end of the 1990s to the present. Most of rainfall anomalies on the whole regional scale of SC is well in phase during winter and spring, and the frequency of persistent drought is higher than that of persistent flood. Seasonal variations of moisture transport differences of SC between persistent drought and flood events are observed: the differences in winter are characterized by moisture transport from Bay of Bangle (BOB) and South China Sea (SCS), while differences in spring are characterized by that from SCS and North China (NC). There are two types of Niño3.4 sea surface temperature anomaly (SSTA) related to persistent winter and spring drought (flood) events in SC, which are positive SSTA next to Niño4 (Niño3) and negative SSTA next to Niño3 (Niño4). Moreover, the variations of moisture transport from BOB and SC have important effects on persistent drought/flood in SC when the Niño3.4 index is in the positive phase, while those from western North Pacific (WNP)-SC in winter and those from Philippine Sea (PHS)-SC and NC in spring primarily contribute to persistent drought/flood events in SC when the Niño3.4 index is in the negative phase, and these stronger (weaker) moisture transports are observed in persistent flood (drought) during winter and spring regardless of the Niño3.4 index. In conclusion, with the correlation between variations and distributions of Niño3.4 SSTA and persistent drought/flood events in SC, moisture transport is responsible for the formation of precipitation anomalies. In addition, the moisture transport from SCS is most significantly correlated with persistent drought/flood events during winter and spring.

Key words: interannual variability; EEOF analysis; winter and spring precipitation; moisture transport; sea surface temperature anomaly

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1 INTRODUCTION

South China (SC), strongly influenced by the East Asia (EA) and the western North Pacific (WNP) monsoons[1], is one of the areas prone to natural disasters. SC has experienced several severe droughts since the 1990s, e.g., 1991 and 1999[2]. In 2003–2004, a persistent drought spread throughout the whole region; millions of residents and domestic animals had insufficient water supplies, and the economic losses from the agricultural sector alone reached more than 1.4 billion yuan (RMB). Recently, there is an increasing frequency of droughts during the winter half-year, which leads to intensive attention in the scientific community. In general, droughts can spread over the most part of SC and sustain for more than several months with distinct stages[2]. The interannual variations of seasonal precipitations are quite consistent in winter and spring, indicating that anomalous precipitation tends to prolong in winter and spring[3]. Most persistent droughts in winter and spring occur every 2 years and have severe impacts on societal and economic development in this region[4]. Due to the typical regional drought events, SC has become one of the five drought centers in China[5].

For a long time, much effort has been devoted to the analysis and monitoring of droughts in North and Northwest China[6-10]. In recent years, there have been attempts to develop techniques for analysis and

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monitoring of precipitation during the annually first and second rain seasons in SC[11-20]. However, due to lack of understanding of variations of rainfall during winter and spring, it is still difficult to objectively quantify the characteristics of drought in terms of intensity, magnitude, duration, and spatial extent. East Asian winter monsoon (EAWM) can greatly affect rainfall in SC during boreal winter (December to February). A biennial alternation of the summer and winter monsoons is observed and the possible relationship is in fact tied to the influence of the El Niño–southern oscillation (ENSO)[21]. A comparative analysis further demonstrated that the anomalous rainfall in SC during winter monsoons is closely related to the ENSO[22]. During boreal spring (March–May), the precipitation is considered as frontal rain[23]. One of the basic climate features of vertically integrated moisture transport (VIMT) from winter to summer is the occurrence of the prominent southerly VIMT over the Indochina Peninsula[24]. The variations of rainfall in SC during spring are affected by many factors. The positive rainfall anomalies in SC during the fall of an ENSO developing year through the following spring are related to an anomalous low-level anticyclone over the WNP[25]. Wen et al.[26] revealed that the contribution to the lower layer subsidence in SC is mainly from the forcing processes associated with the latent heat in the baroclinic troughs located to the north of SC. SST anomalies (SSTA) of Niño3 are the strongest precursor of Guangzhou spring rainfall[27]. The majority of previous work has focused mainly on the spatial and temporal variations of anomalous rainfall during winter or spring in SC, while less attention has been paid to persistent rainfall anomalies during winter through spring that are also of importance. Further, as is well known, the monsoon transports abundant water vapor from oceans to SC and greatly affects the rainfall and water budget in this region, which is crucial to the agricultural production and economy. So research on VIMT during the winter and spring has both scientific and social values.

2 DATA AND METHODOLOGY

The rainfall data used in this paper are the observed monthly mean precipitation data for 730 rain gauge stations from the National Meteorological Information Center (NMIC), and rainfall data from 47 stations in Guangdong and Guangxi is chosen to determine the total rainfall over SC. The National Centers for Environmental Prediction (NCEP, USA) reanalysis dataset[28] is chosen for calculating VIMT. The National Oceanic and Atmospheric Administration Extended Reconstructed Sea Surface Temperature (NOAA ERSST, USA) analysis dataset[29] is also used in this study. The present analysis basically covers the period from 1960 to 2008, unless specified otherwise.

Extended empirical orthogonal function (EEOF)[30], widely used in climate change research[31-32], is carried out to depict the interannual variation of winter-spring precipitation in SC. Then, correlation and composite analyses are applied to investigate the relationship between persistent drought/flood events and VIMT.

3 INTERANNUAL VARIATION OF WINTER AND SPRING PRECIPITATION IN SC

3.1 *Interannual variation*

Seasonal average rainfall in SC (20°–25.5°N, 105°–117°E) during winter, spring, summer and autumn is 122.9, 441.2, 706.9 and 291.2 mm, respectively. Percentage of winter-spring precipitation in total precipitation is close to 36%. EOF1 of anomalous precipitation during these seasons has the same-sign loading over the whole SC (figure not shown) and accounts for 55.6%, 40.9%, 34.2%, and 41.6% of the total variance, respectively. Hence, variations of seasonal rainfall in SC can be analyzed by area-averaged rainfall. It is obvious that both winter and spring precipitation exhibit three decadal changes. Both of them are below normal before 1970, above normal during 1970–1995, and below normal after the end of the 1990s (Fig. 1a). These precipitation anomalies exhibit significant interannual variations as well. The dominant 2-3-year periodicity tends to match that of EAWM[33] (Fig. 1b). In addition, the winter and spring precipitation anomalies are well in phase, with a correlation coefficient of 0.3, significant at the 95% confidence level, which is consistent with Jian et al.[3].

The correlation map obtained by winter and spring precipitation anomalies shows that most parts of SC have positive values (figure not shown). In fact, there are 29 (19) years for which winter and spring rainfall anomalies have the same (opposite) sign, with a probability of occurrence of 60.4% (39.6%). A persistent drought (flood) event can be defined as follows: normalized time series of both winter and spring rainfall anomalies are less (more) than -0.5 (0.5). Once winter and spring rainfall anomalies have the same sign, 82.7% of the years show abovementioned persistent drought/flood events. Overall, winter and spring precipitation anomalies spread over SC. Thus, it is worth investigating what are the reasons for the persistent rainfall anomalies during the winter-spring in SC.

3.2 *EEOF results*

Only the first two modes, which together explain over 51.3% of the total variance, are statistically significant. The first EEOF mode, which explains over 33.2% of the total variance, is shown in Fig. 2. Positive rainfall anomalies spread over SC in both winter and spring, displaying a persistent anomaly pattern, which is consistent with Jian et al.[3]. The correlation coefficients between its principal component (PC) and winter and spring rainfall anomalies are 0.91 and 0.58, respectively. Thus, PC1 can represent well the variations of rainfall in SC during winter and spring. A remarkable feature for the second EEOF mode is a synchronous change from winter to spring, with a positive anomaly during winter and a negative one during spring (figure now shown). In 70% of the years for which rainfall anomalies have the opposite sign, positive rainfall anomalies in winter are followed by negative rainfall anomalies in spring. Thus, drought in winter can be counteracted by increased rainfall in the following spring. Next, we will focus on EEOF1.

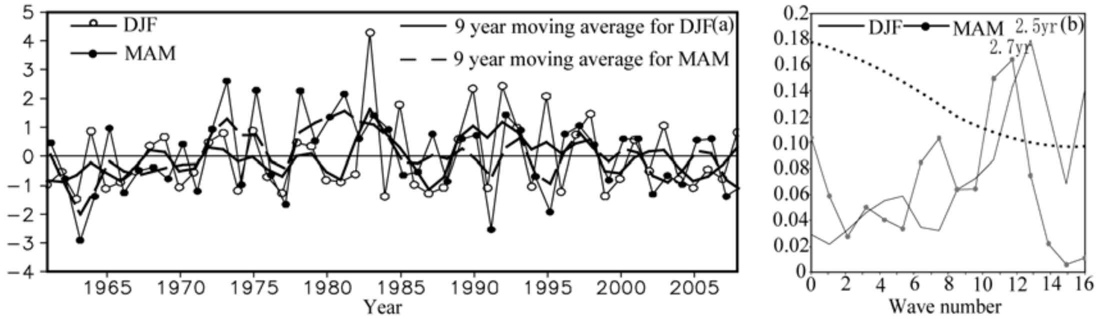

Figure 1. (a) The normalized time series of winter and spring precipitation anomalies averaged in SC. The solid and dashed lines indicate 9-year moving average for winter and spring, respectively. (b) Power spectrum for the winter and spring precipitation anomalies in SC. The dotted line indicates significant density at 5% level.

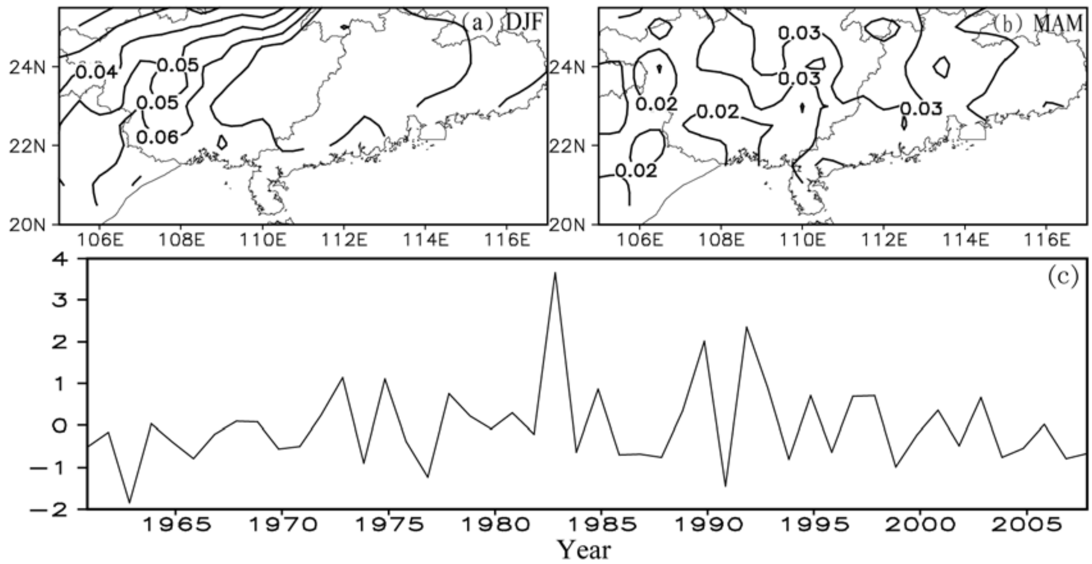

Figure 2. Spatial patterns of first EEOF mode associated with (a) winter and (b) spring precipitation anomalies in SC. (c) The normalized times series of corresponding PC.

4 RELATIONSHIP BETWEEN PERSISTENT RAINFALL ANOMALY AND VIMT

4.1 *Correlation between rainfall and VIMT*

Many previous studies have attempted to relate rainfall anomalies to atmospheric circulation, sea surface temperature (SST), and snow cover. These studies have revealed some relationships between rainfall anomaly and external forcing[34-36]. Precipitation, as a major component of water cycle, is generally influenced by source, path, and sink of VIMT[37-39]. Water evaporates as water vapor from the oceans. SST anomaly can affect not only atmospheric circulation, but also evaporation at the ocean surface. This will modulate the path of VIMT and distribution of rainfall which are responsible for the regional water balance. This process can be regarded as anomalous water vapor forcing.

VIMT and its flux divergence anomalies during winter-spring are obtained by regression against the PC1 (figure not shown). The most remarkable feature of zonal component is westerly anomalies over the Bay of Bengal (BOB) and the Philippine Sea (PHS), while that of meridional component is southerly anomalies over SC-WNP. Moreover, a negative flux divergence anomaly is observed over the whole SC. These results indicate that increased rainfall in SC is associated with stronger southwesterly VIMT and moisture convergence.

4.2 *Seasonal distribution of the VIMT*

The most prominent feature in winter is northeasterly or northerly prevailing over SC, which causes a cold and dry season. In spring, precipitation increases rapidly and varies greatly when a warm air mass and a cold air mass meet[27]. Since significant differences of VIMT over EA between winter and spring are observed in He et al.[24], further investigation on the seasonal distribution of the VIMT and its relation to precipitation is needed.

The seasonal distributions of the VIMT during winter and spring are presented in Fig. 3. During winter, a westerly VIMT originating from the northern part of Indochina Peninsula extends to WNP. Another very strong easterly VIMT moves across the PHS to the South China Sea (SCS) and converges over North Vietnam. During spring, abovementioned easterly VIMT weakens, while the westerly VIMT intensifies and spreads to the BOB. It is also noted that the southerly VIMT that exceeds 100 kg $m^{-1}s^{-1}$ over Indochina, with the establishment of a southern trough, acts as a linkage between tropical easterly VIMT and mid-latitude westerly VIMT.

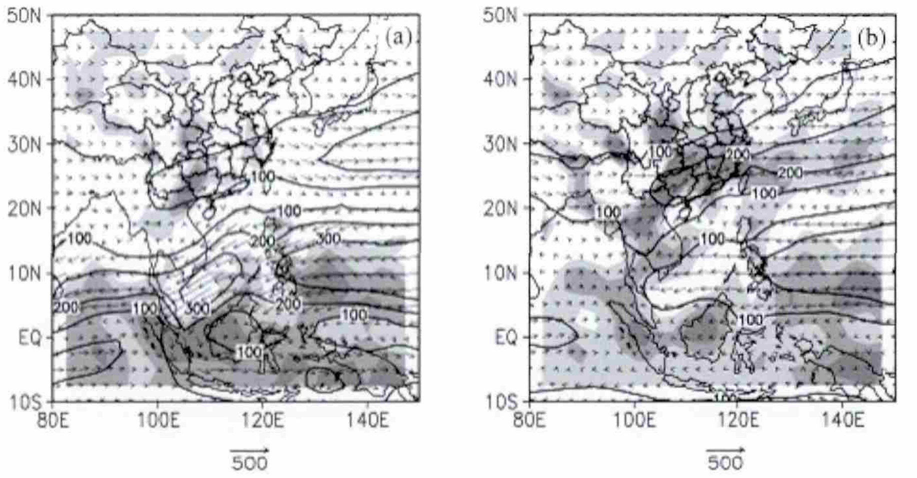

Figure 3. (a) The VIMT and flux divergence in winter from 1960 to 2008. (b) Same as (a) except for spring. The solid lines indicate moisture transport, unit is kg m^{-1} s^{-1}. Shading indicates moisture divergence, unit is 10^{-5}×kg m^{-2} s^{-1}.

4.3 *VIMT of persistent drought and flood*

There are 15 (9) persistent drought (flood) events in the 49-year period (Table 1). Differences of VIMT and flux divergence between persistent flood and drought events in SC are displayed in Fig. 4. Anomalous westerly VIMT differences from BOB and southerly VIMT differences from SCS converge and flow to SC in winter, which are associated with increased rainfall. In addition, southerly VIMT differences over subtropical WNP are observed. These southerly VIMT, however, cannot influence precipitation in SC. During spring, there is a massive anticyclonic difference over PHS-SCS. Southwesterly VIMT differences from the Indochina Peninsula and northerly VIMT differences from North China (NC) are responsible for increased rainfall. Persistent negative flux divergence differences are observed during winter and spring over SC, corresponding with the positive rainfall anomalies. Moreover, two positive flux divergence differences remain from winter to spring, indicating that sources of VIMT are mainly from the BOB and tropical western Pacific.

Table 1. Persistent drought/flood events in SC.

Flood	Drought
1972, 1974, 1982, 1988, 1989, 1991, 1992, 1996, 2000	1961, 1962, 1965, 1970, 1973, 1975, 1976, 1985, 1987, 1990, 1993, 1998, 2001, 2003, 2006

5 VIMT ANOMALIES AND SSTA

ENSO is one of the important subsystems for global climate change, which has been shown to be empirically linked to East Asian climate variations by air-sea interaction[43-48]. The positive rainfall anomalies in SC during the fall of an ENSO developing year through the following spring is related to an anomalous low-level anticyclone over WNP[25]. Characteristics related to persistent drought events during October to March in Guangdong has been revealed by Ji et al[49]. However, features of

VIMT of persistent drought and flood events with different phases of Niño3.4 index remain unknown.

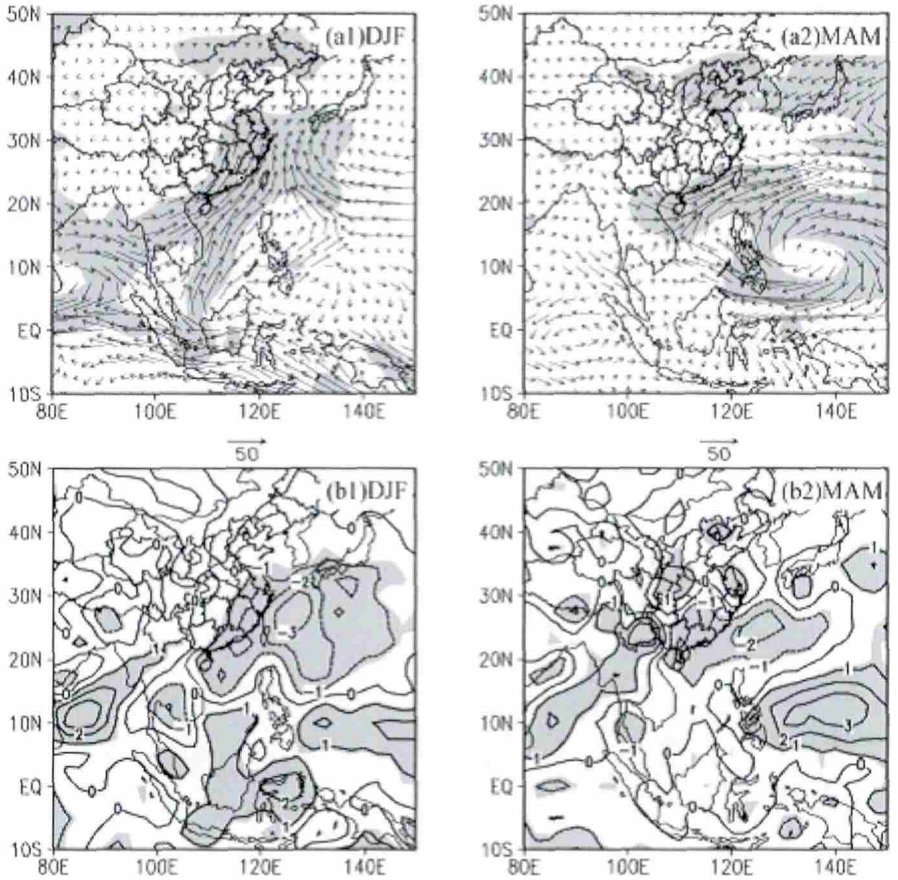

Figure 4. (a) The differences of VIMT and flux divergence between persistent flood and drought events in the winter (left panels) and spring (right panels) of SC, unit is kg $m^{-1} s^{-1}$. (b) Same as (a) except for flux divergence, unit is 10^{-5}×kg $m^{-2} s^{-1}$. Shading indicates where the area is significant at the 5% level.

5.1 *Correlation between rainfall anomalies and SSTA*

Correlation between PC1 and SSTA is shown in Fig. 5. There are two significant centers: a positive anomaly over tropical central and eastern Pacific, and a negative anomaly over WNP. These SSTA can affect rainfall anomalies in SC by the thermodynamic coupling between atmospheric Rossby waves and ocean mixed layer temperature variation, which are referred to as Pacific-East Asian teleconnection[46].

In fact, East Asian climate variations are not consistent with ENSO year by year. According to Climate Prediction Center, 16 (15) El Niño (La Niña) events are identified in the 49-year records. 9 (7) years of PC1 during 16 El Niño events are positive (negative), while 10 (5) years of it during 15 La Niña events are negative (positive). Hence, winter-spring rainfall anomaly in SC tends to be negative during La Niña events with 66.7% (10/15) probability of occurrence. However, during El Niño events, it is hard to conclude that winter-spring rainfall anomaly in SC tends to be positive with only 56.3% (9/16) probability of occurrence. This result is somewhat different from that documented by Tao et al[51].

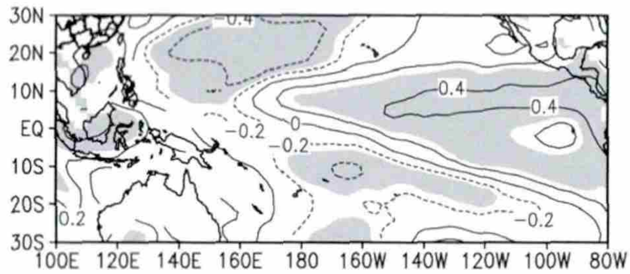

Figure 5. Correlation between the time series of precipitation associated with the EEOF1 and the SST from winter to spring. Shading indicates significant correlation at the 5% level.

We further focus on the relationship between persistent drought/flood events and Niño 3.4 index. In Table 2, 8 (7) years of Niño 3.4 index during persistent drought events are positive (negative), while 5 (4) years of that during persistent flood events are positive (negative). Thus, persistent drought/flood events occur in either positive or negative phase of Niño 3.4 index. Figure 6 displays the distribution of SSTA associated with persistent drought and flood events. Two types of SSTA associated with persistent drought events are exhibited: the positive SSTA is close to Niño 4 in the positive phase of Niño 3.4 index, and the negative SSTA is close to Niño 3 in the negative phase of Niño 3.4 index. This finding is consistent with Lin et al.[52]. Another two types of SSTA associated with persistent flood events are also exhibited: the positive SSTA is close to Niño 3 in the positive phase of Niño 3.4 index, and the negative SSTA is close to Niño 4 in the negative phase of Niño 3.4 index. Therefore, persistent drought/flood events are related to not only the phase of Niño 3.4 index, but also the location of SSTA. In other words, it is unreasonable for the prediction of winter-spring persistent drought/flood events to be only on the basis of the phase of tropical central and eastern Pacific SSTA.

Table 2. Persistent winter and spring drought/flood events in SC and Niño3.4 SSTA.

Flood	1972	1974	1982	1988	1989	1991	1992	1996	2000
SSTA/℃	1.17	−0.63	1.93	−1.43	0.17	1.63	0.43	−0.23	−0.5

Drought	1961	1962	1965	1970	1973	1975	1976	1985	1987	1990	1993	1998	2001	2003	2006
SSTA/℃	−0.4	−0.3	1.0	−1.3	−1.63	−0.6	0.43	−0.37	0.43	0.33	0.23	−1.17	0.07	0.3	0.4

Notes: Dark (shallow) shaded cell refers to El Niño (La Niña) event.

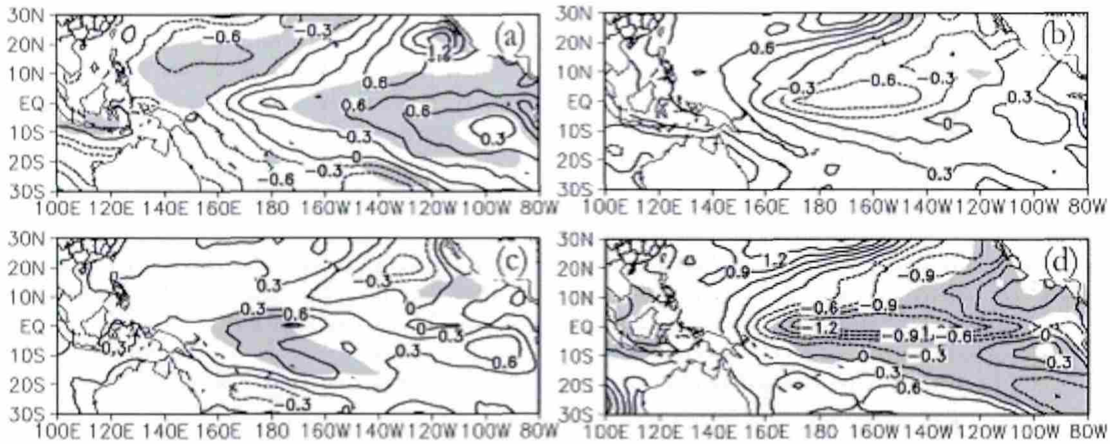

Figure 6. Composite SSTA related to persistent drought/flood events during winter-spring in SC. a, b represent the positive and negative SSTA in persistent flood events, respectively; c, d are the same as a, b, but for persistent drought events. Shading indicates significant correlation at the 5% level.

5.2 *Distribution of VIMT differences between persistent drought and flood events in different phases of Niño 3.4 index*

To help understand the characteristics of VIMT differences between persistent drought and flood events in different phases of Niño 3.4 index, the composite analysis is applied in this subsection and presented in Figs. 7 & 8. In the positive phase of Niño 3.4 index, an anomalous anticyclonic VIMT difference maintained over PHS during winter and spring (Fig. 7a1 & 7a2). Anomalous westerly VIMT difference from the BOB and anomalous southerly VIMT difference from the SCS converge over the northern part of SCS and flow to SC, which leads to the increased rainfall in this region. Sources of anomalous VIMT difference are mainly located in the BOB and WNP (Fig. 7b1 & 7b2). In the negative phase, an anomalous anticyclonic VIMT difference exits over subtropical WNP during winter, and anomalous southerly VIMT difference prevails over the SCS (Fig. 8a1). During spring, anomalous northerly VIMT difference from NC and anomalous southerly VIMT difference from the western branch of the anomalous anticyclonic VIMT difference over PHS contribute to the above-normal rainfall in SC (Fig. 8a2). Sources of anomalous VIMT difference are located in NC and WNP (Fig. 8b1 & 8b2). Hence, during different phases of Niño 3.4 index, anomalous VIMT differences related to persistent drought/flood events in SC are quite distinct. In addition, anomalous southerly VIMT differences over SCS are observed in both the positive and negative phases of Niño 3.4 index, indicating that VIMT over SCS is most significantly correlated with persistent drought/flood events during winter and spring.

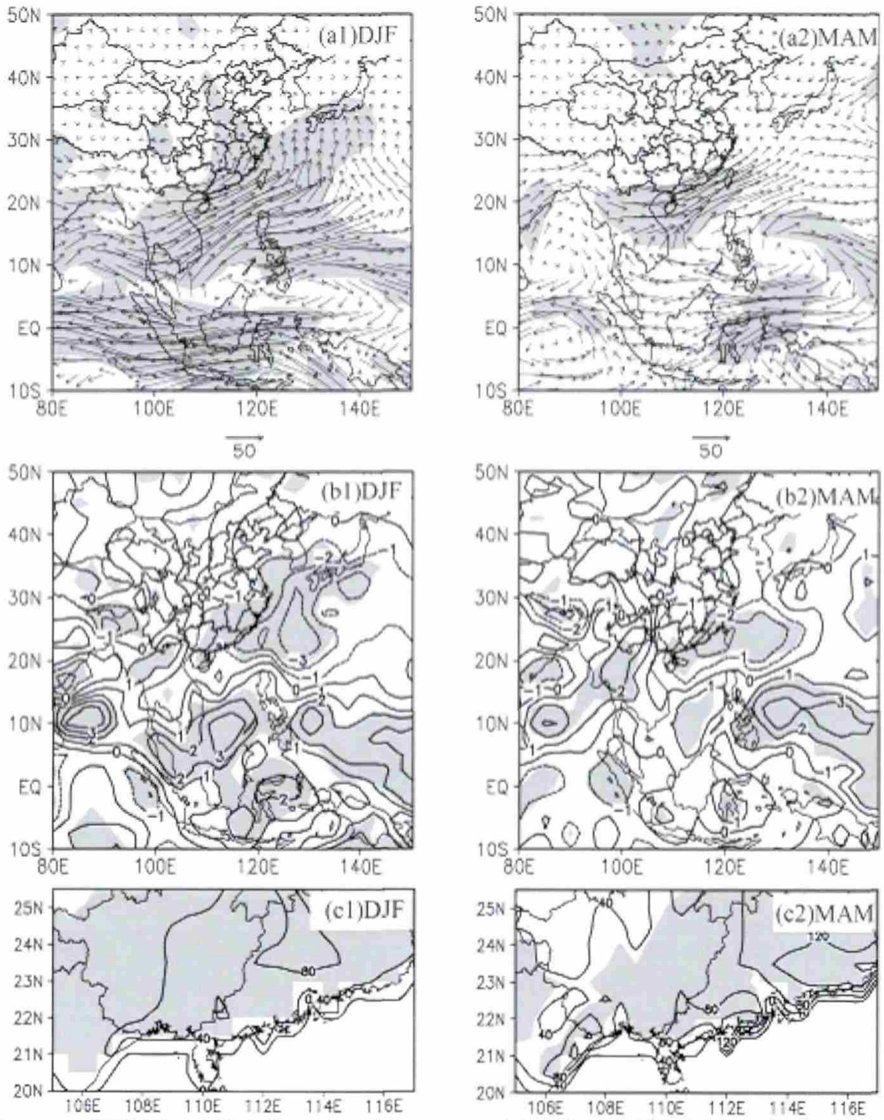

Figure 7. (a) The differences of VIMT and flux divergence between persistent drought/flood events in the winter (left panels) and spring (right panels) of SC with the positive phase of Niño3.4 index, unit is kg m^{-1} s^{-1}. (b) Same as (a) except for moisture divergence, unit is 10^{-5}×kg m^{-2} s^{-1}. (c) Same as (a) except for precipitation, unit is mm/month. Shading indicates where the area is significant at the 5% level.

6 SUMMARY AND DISCUSSION

(1) With dominant 2-3-year periodicity, winter and spring precipitation in SC exhibit significant interannual variations during 1960–2008. Winter and spring precipitation in SC is less than normal from the 1960s to the start of the 1970s and from the end of the 1990s to the present. The precipitation variations in these two seasons tend to be in phase, and the frequency of persistent drought is higher than that of persistent flood.

(2) Generally, there is a significant positive correlation between persistent winter-spring precipitation anomaly in SC and VIMT anomaly over BOB and SCS. Additionally, significant difference of VIMT anomaly between winter and spring is also found: variations of VIMT are mainly over BOB and SCS during winter, but over NC and SCS during spring.

(3) Two types of SSTA associated with persistent drought (flood) events are identified: the positive SSTA is close to Niño 4 (Niño 3) in the positive phase of Niño 3.4 index, and the negative SSTA is close to Niño 3 (Niño 4) in the negative phase of Niño 3.4 index. Hence, persistent drought/flood events are related to not only the phase of Niño 3.4 index, but also the location of SSTA.

(4) In the positive phase of Niño 3.4 index, VIMT anomalies over BOB and SCS sustain from winter to spring and lead to the persistent drought/flood events. In contrast, in the negative phase of Niño 3.4 index, southerly VIMT from the WNP during winter, and northerly VIMT from NC and southerly VIMT from PHS contribute to variations of rainfall in SC.

Regardless of the phase of Niño 3.4 index, the abovementioned VIMT are weaker (stronger) associated with persistent drought (flood) events. In addition, VIMT over SCS is most significantly correlated with persistent drought/flood events from winter to spring.

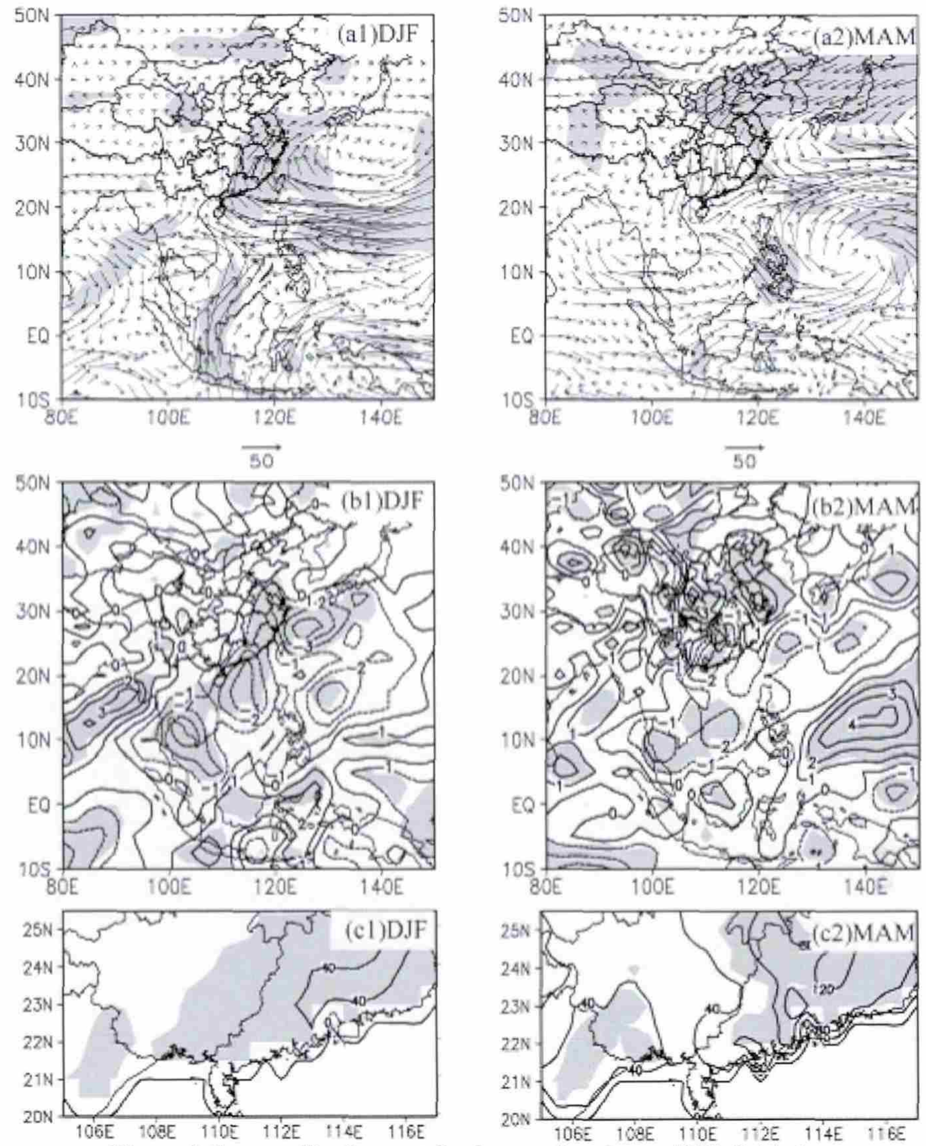

Figure 8. Same as Fig. 7 except for the negative phase of Niño3.4 index.

Consequently, SCS acts as an important gateway through which warm and moist air flows to SC. The VIMT over this region is an important factor that influences the water cycle over SC. But how much does it contribute to the winter-spring precipitation in numerical models? Besides, the physical process of persistent drought events in SC corresponding to SSTA in tropical Pacific has been proposed by Lin et al.[52], while that of persistent flood events in response to SSTA remains unknown. These issues deserve further observational and modeling studies.

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