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MULTI–TIMESCALE VARIATIONS OF SOMALI JET AND ITS RELATION WITH PRECIPITATION IN CHINA

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Abstract: Based on the ERA reanalysis winds data, the multi-time scale variations of Somali jet are analyzed synthetically. The jet's influences on rainfall in China on interannual, interdecadal and sub-monthly scales are also studied using correlation and composite analyses. The results demonstrate that the interdecadal variations of the jet are significant. The Somali jet became weaker in the 1960s and became the weakest in the early 1970s before enhancing slowly in the late 1970s. Moreover, the relation between the Somali jet and summer precipitation in China is close, but varies on different timescales. Preliminary analysis shows that the intensity variations in May and June during the early days of establishment are well correlated with summer precipitation in China. The Somali jet intensity on the interdecadal scale is closely related with interdecadal variations of the precipitation in China. Regardless of leading or contemporaneous correlation, the correlations between the Somali jet intensity and the rainfall in northern and southern China show obvious interdecadal variations. Moreover, the link between the anomalies of the jet intensity in May-August and precipitation evolution on synoptic scale in China is further studied. China has more rainfall with positive anomalies of the Somali jet but less rainfall with negative anomalies during the active period of the jet. The influence of positive Somali jet anomalies on China precipitation is more evident.

Key words: multi-timescale variations; Somali jet intensity; precipitation in China

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1 INTRODUCTION

As one of the strongest cross-equatorial flows in the Northern Hemisphere during boreal summer, Somali jet plays an important role in the moisture transportation in the Asian monsoon (Xue and Zeng [1]; Xu et al. [2]). The variations of Somali jet exert significant impacts on weather and climate change in Asia, e.g. drought or flood (Huang et al.[3]; He et al.[4]; Li and Wu [5]), which have attracted much attention recently. The concept of cross-equatorial flow was first proposed by Simpson[6] in the 1920s. Tao et al.[7] pointed out that there is a close relationship between the atmospheric circulation of the Northern and Southern Hemispheres (Tao et al.[7]). After the Somali low-level jet was found by Findlater [8], dynamic and numerical simulations of the jet were carried out in order to study its role in atmospheric mass exchange between the two hemispheres (Bannon[9]; Krishnamurti et al.[10]). It was found that multi-timescale variations are one of the most important characteristics of the Somali jet. Its variations are distinct from other flows on interannual, interdecadal and sub-monthly scales. Although the Somali jet is the strongest cross-equatorial flow in the Northern Hemisphere in summer, the contribution of its interannual variation to the global cross-equatorial flow is small (Lei and Yang[11]). The interannual variation of the Somali jet is weaker than other cross-equatorial flows in the East Asia, but its interdecadal variation intensifying before the 1980s and weakening after that is evident (Tang et al. [12]). There is significant interdecadal variation and an abrupt change of the Somali jet in the Eastern Hemisphere in summer, and the jet has increased significantly since 1980 (Shi et al. [13]). Numerical simulations also showed that the Somali jet features obvious interdecadal variations and varies from weak to strong in the mid and late 1970s (Zeng et al.[14]).

The Somali jet plays an important role in the East Asian monsoon on different time scales. The strength of Somali cross-equatorial flow has vital impact on the onset of the South China Sea Summer Monsoon (SCSSM) (Shi et al. [15]). Li and Wu argued that the obvious enhancement of westerlies in the equatorial Indian Ocean and the occurrence of the Somali jet northward flow happen just before the onset of the SCSSM[5]. The interannual variation of the Somali jet is closely related with the South Asian summer monsoon, the East Asian subtropical summer monsoon and the SCSSM (Cong et al. [16]). Besides, its effects on the Indian monsoon and the

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East Asian monsoon are different from each other. The interdecadal variation of the Somali jet is highly related to the South Asia high and atmospheric circulation anomalies of the East Asia (Wang and Xue[17]). The correlations between the Somali jet and the strength of East Asian summer monsoon on interannual and interdecadal time scales are positive and negative, respectively (Wang and Yang[18]). In addition, the Somali jet strongly influences the spatial patterns of precipitation in China. Li et al. showed that the extreme flood in China's Yangtze river and Northeast China in 1998 was closely linked to the strong cross-equatorial flow in Somalia in May (Li et al.[19]). The enhancement of meridional winds near Somalia in the 105°E equatorial area occurred before rainstorms happened in the South China (Li et al.[20]). Thus, the Somali jet is an important factor for background circulation which affects the summer precipitation in the east of Northwest China (Li et al.[21]).

The Somali jet intensity index is defined in order to analyze its multi-time scale variations. Gao and Xue suggested that the vertical center of low-level cross-equatorial flow is located at 925 hPa rather than 850 hPa using NCEP/NCAR reanalysis (Gao and Xue[22]). Zhao found that wind speed is generally the largest at 925 hPa in longitude-height sections (Zhao[23]). The areas for calculating the Somali jet intensity index in different studies are not consistent. Li et al. took 40°-55°E, 5°S-5°N as the central zone of the jet (Li et al.[24]), while Wang and Xue chose 37.5-62.5°E, 15°S-10°N as the area of intensity index[17].

The Somali jet shows obvious multi-time scale variations, but previous studies mainly focused on the interannual and interdecadal variations and paid little attention on other scales, especially on sub-monthly scale. The Somali jet strongly influences the onset, development and decay of the East Asian monsoon, but the investigation of the jet's effects on the climate in China especially in terms of drought and flood distributions on different timescales is rare. The present study is to establish the Somali jet index and analyze its variations on interannual, interdecadal and interseasonal scales. We also explore its influence on rainfall in China in rainy seasons as well as spatial patterns of drought and flood. Our study could be served as reference for climate prediction in the East Asia.

2 DATA AND METHODS

The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) is more reasonable compared with the NCEP/NCAR and JRA-25 in regard to atmospheric quality transmission (Zhao[23]). The ERA-40 zonal, meridional winds and geopotential height (total 23 levels) are used on 2.5°×2.5° horizontal grids. We use monthly and 6-hourly ERA-40 reanalysis between 1958-2001, 44 years in total. In order to extend our analysis to 2010, we use the ERA-Interim with the same horizontal resolution between 1979-2010 as a supplement to ERA-40. The values between 1979-2010 when both ERA-Interim and ERA-40 are available are defined as the average of them. In addition, we use daily precipitation of 717 stations and precipitation of 160 stations provided by the National Meteorological Information Center and the National Climate Center, respectively.

We process daily data into pentad in order to investigate the Somali jet variations on sub-monthly time scale. We use JJA mean as summer mean. Wavelet analysis, filtering, correlation analysis, composite analysis and running correlation analysis are employed for data analysis.

3 TEMPORAL AND SPATIAL VARIATIONS OF SOMALI JET

3.1 *Definition of Somali jet intensity index*

Firstly, the temporal and spatial variations of the Somali jet are analyzed. Fig.1a shows the annual mean equatorial meridional winds at 925 hPa as a function of time and longitude. The Somali jet is obvious in both boreal winter and summer. The jet flow is northward in summer and reaches its maximum at 41°E between pentad 34 and 44. The jet reverses its direction in winter and the maximum wind speed moves eastward by 7°. Therefore the Somali cross-equatorial flow resembles the monsoon in physical nature. The wind direction shifts to southerly on pentad 18 and to northerly on pentad 66. Fig. 1b shows meridional wind in summer as a function of longitude and height. The Somali jet with its peak at 41°E is the strongest low-level cross-equatorial jet, and it can reach 700 hPa.

Previous studies suggest that the Somali jet intensity index is defined according to the altitude (pressure layer) and area of the jet. It is generally believed that 925 hPa is the representative pressure layer and different studies select different area when considering the area of the Somali jet (Wang and Xue[17]; Gao and Xue[22]; Zhao [22]; Li et al.[24]). The multi-year averaged horizontal winds show the onset progress of the Somali jet (Fig. 2). Large wind speed appears at 10°S and expands to the equator on pentad 21, but the cross-equatorial flow is weak and contains the component of easterly wind that points to the mainland. The wind speed becomes larger and the southerly winds develop to 5°N on pentad 25 at the beginning of the jet's establishment. The whole region (40°E to 55°E, 10°S to 5°N) shows large meridional wind and a complete circulation system forms between the Somali jet and the monsoon, with the center of the jet spanning from 40°E to 55°E at the same time. In general, the regional average of 40° to 55°E, 10°S to 5°N depicts the development process of the Somali jet and therefore is used as area of the Somali jet in the present study.

From above, we consider the averaged meridional winds over 40°E to 55°E, 10°S to 5°N at 925 hPa as the Somali jet index. Then the time series of the Somali

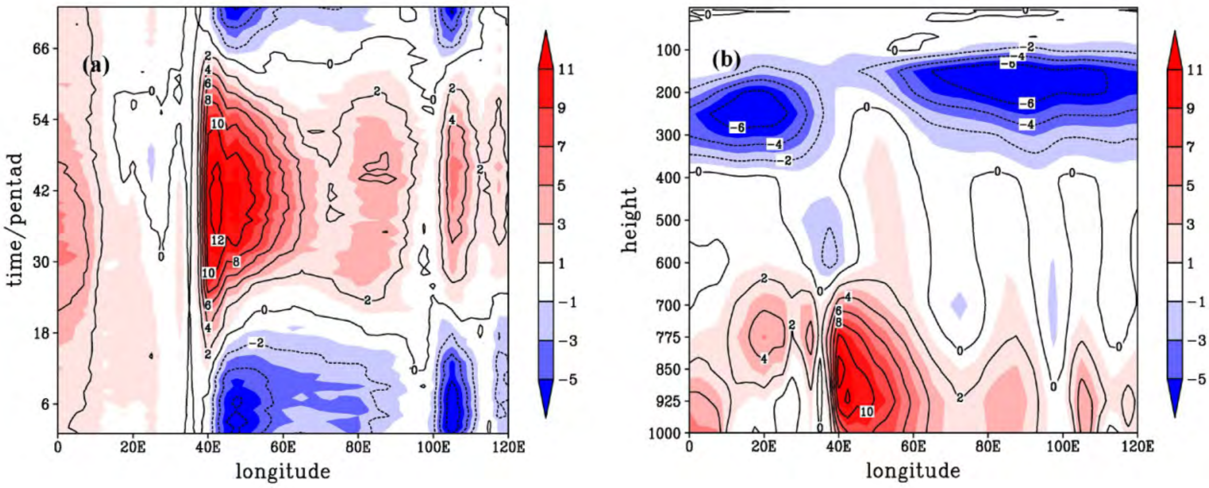

Figure 1. (a) Multi-year averaged equatorial meridional winds at 925 hPa between 1958-2010 as a function of time and longitude; (b) the meridional winds in summer as a function of longitude and height. Red represents the southerly winds and blue represents the northerly winds in unit of m/s.

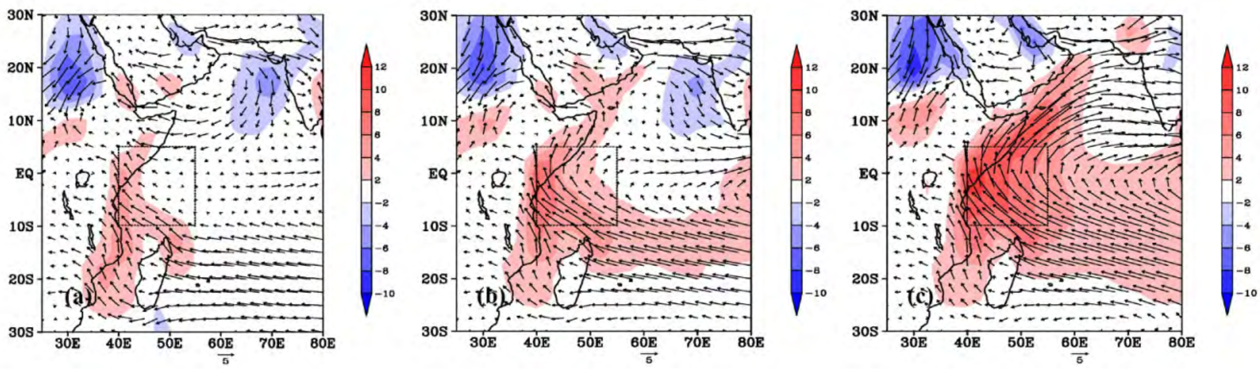

Figure 2. The multi-year averaged horizontal winds at 925 hPa in pentad 21 (a), pentad 25 (b) and pentad 30 (c). The area included in the box is 40°-55°E, 10°S-5°N. Red represents the southerly winds and blue represents the northerly winds in unit of m/s.

jet index are standardized to analyze the multi-scale variations of the Somali jet.

3.2 *Multi-timescale variations of Somali jet*

The pentad series of the Somali jet intensity index is analyzed using Morlet wavelet analysis and the significant period of oscillation is also studied. Fig.3a shows that the wavelet power is highest at the 9-pentad period. The 2-year period is significant from the mid-1960s to the early 1970s and from the mid-1980s to the mid-1990s. The 6-year period is significant from the late 1960s to the early 1970s and in the mid-1980s. The period between 10-15 years is significant from the

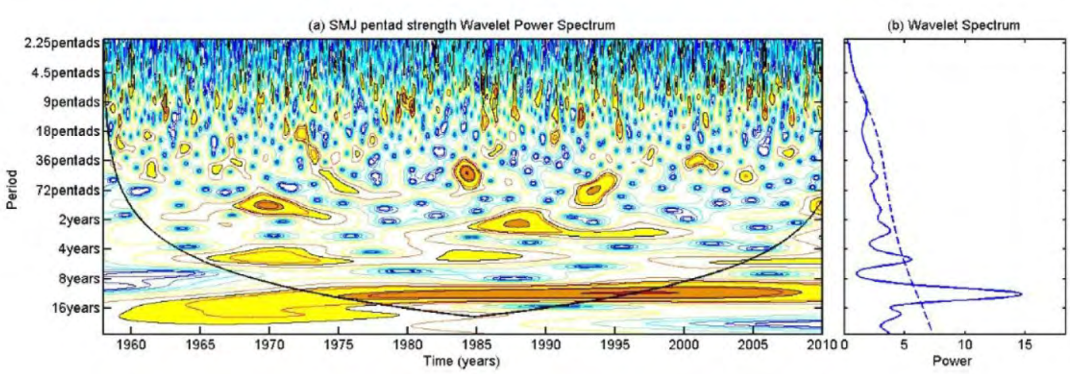

Figure 3. Morlet wavelet analysis results of Somali jet intensity. (a) Wavelet power spectrum; the value decrease as the contour color changes from red to blue and the color shade indicates the passage of the 0.05 significance level; (b) global wavelet spectrum corresponding to (a) with dashed line indicating the 0.05 significance level.

mid-1970s to the mid-1980s. Though the period of 32 years passes the significance level, we do not take it into account because it appears in the area of head influence. In the global wavelet spectrum (Fig.3b), the periods of quasi-9 pentads (45 days), quasi-6 years and 10 to 15 years all pass the 95% confidence level, and the interdecadal variation period of 10 to 15 years is more significant.

Figure 4 shows the seasonal variation of the Somali jet intensity index. The index reverses its sign from negative to positive on pentad 17, suggesting that the meridional winds change from northerly to southerly. The jet strengthens gradually and reaches its maximum of 8.7 m/s on pentad 37 (in early June). Then the jet weakens and changes into northerly winds on pentad 66. The climatological seasonal variations of the Somali jet index shows that the Somali jet is strongest in summer and exhibits seasonal cycle as the monsoon.

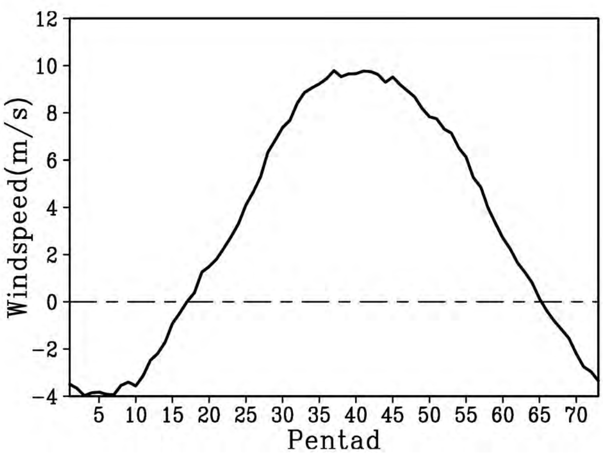

Figure 4. The seasonal variation of Somali jet multi-year averaged intensity index.

Figure 5 shows the annual intensity index series of the Somali jet in summer and an 11-year moving average curve. The intensity has obvious interannual and interdecadal variations and the innterdecadal variation is the most significant. The Somali jet gradually became weaker in the 1960s and reached the weakest in the early 1970s, and then began to enhance slowly in the late 1970s.

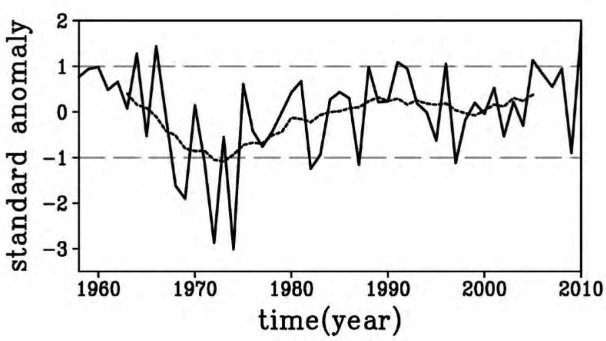

Figure 5. The annual intensity index series of Somali jet in summer (solid line) and 11-year moving average curve (dotted line).

4 INTERDECADAL AND INTERANNUAL VARIATIONS OF SOMALI JET AND THEIR LINK TO PRECIPITATION IN CHINA

4.1 *Relationship between the Somali jet and precipitation in China on interannual scale*

We checked the contemporaneous and leading correlations of monthly Somali jet index in summer with rainfall in China (not shown), and found that their relationship varies significantly with different months. We focus on the east of China (in the east of 92°E) where meteorological stations are densely distributed. The contemporaneous correlation shows that the intensity of the Somali jet is closely correlated with the precipitation in China in June (Fig.6a). The correlation is positive in the Huang-Huai Rivers plain and North China, and negative correlation is prevalent in the east of the Northeast China and the south of China. We omit the west region due to the sparse observations. The leading correlation shows that the intensity of the Somali jet in May is closely related to July precipitation in China (Fig.6b). The positive correlation in North and Central China is significant, while the negative correlation appears in the middle and lower reaches of Yangtze River. In general, there is a close relationship between the jet intensity and summer rainfall in China. The intensity of the Somali jet at onset has a close correlation with summer rainfall in China. Because rainfall in China is influenced indirectly by the Somali jet on the interannual scale, the onset of the jet plays a more important role in the anomalous atmospheric circulation later on. The process and mechanism of how the Somali jet influences China' s rainfall need further investigation.

According to the contemporaneous correlation distribution of the jet intensity and June precipitation in China (Fig.6a), we calculated the 11-year running correlation series between jet and precipitation in North China. Likewise, according to the correlation of the jet intensity in May and July precipitation in China (Fig.6b), we calculated the 11-year running correlation series between jet and precipitation in the middle and lower reaches of the Yangtze River. We explored the correlation variations of the Somali jet and precipitation in northern and southern China by means of running correlation of jet and rainfall in China.

Figure 7b shows that the running correlation of jet intensity and precipitation in North China in June is significantly positive from the early 1960s to the late 1990s. During this period, the rainfall in the northern region in June was greatly affected by the variation of the Somali jet. The precipitation in the northern region became more (less) when the jet was stronger (weaker), but their correlation weakened after the late 1990s. Fig. 7b shows the running correlation between jet in May and precipitation in July in the middle and lower reaches of Yangtze River. Their correlatio n is significantly negative from the mid-1970s to the mid-1980s, indicating that the rainfall in the southern region became less (more) when the jet was stronger (weaker). No significant correlation was found during other periods. From the analysis above, it is known that regardless of leading or contemporaneous correlation, the correlation between the Somali jet and the rainfall in northern and southern China show obvious interdecadal variations. This suggests that the influence of the jet on the precipitation in China exhibits strong interdecadal variations. It also reflects the complexity of the relationship between the Somali jet and the East Asian monsoon activities, especially the precipitation in China.

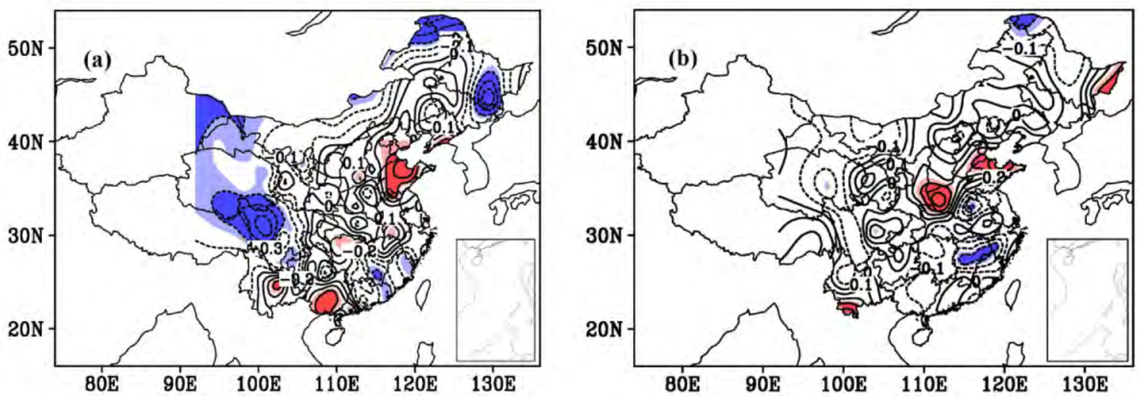

Figure 6. The correlation coefficient between Somali jet intensity and precipitation in China during 1958-2010 on interannual time scale. (a) Jet and precipitation in June; (b) jet intensity in May and precipitation in July. Dark (light) red area presents positive correlation passing the 0.95 (0.90) significance level and dark (light) blue area presents negative correlation passing the 0.95 (0.90) significance level.

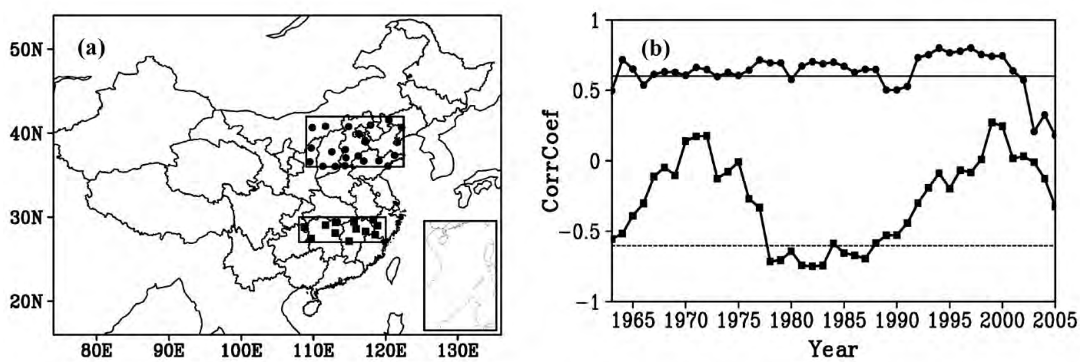

Figure 7. The correlation areas in China (a). Round dots: stations in North China. Square boxes: stations in the middle and lower reaches of the Yangtze River. Running correlation of the jet intensity and rainfall in North China in June (b, curve of round dots) and running correlation of the jet intensity in May and rainfall in the middle and lower reaches of Yangtze River (b, curve of square dots). ± 0.602 line represents the 0.95 significance level.

4.2 *Relationship between the Somali jet and precipitation in China on interdecadal scale*

The above analysis suggests that the correlation between the Somali jet intensity and the precipitation in China varies with space and time, which is probably caused by the complexity of their relationship on multiple timescales. Therefore, we further investigate the response of the precipitation in China to the evident jet variation on the interdecadal scale. Fig.8a shows the correlation between the jet intensity and precipitation in China both on interdecadal scales in June. There is negative relationship between the jet and precipitation in northern Inner Mongolia on the interdecadal scale in June. The rainfall in the eastern part of China is positively correlated with the jet intensity on the interdecadal scale in addition to Huang-Huai Rivers and part of South China. The correlation distribution of the jet intensity in May and China precipitation in July (Fig.8b) shows that a significantly positive correlation area appears in Inner Mongolia and Central China, and a negative correlation region appears in Northeast and North China. The above analysis indicates that in both the leading and contemporaneous correlation, the intensity variation of the Somali jet has a close relationship with the precipitation in China on the interdecadal scale.

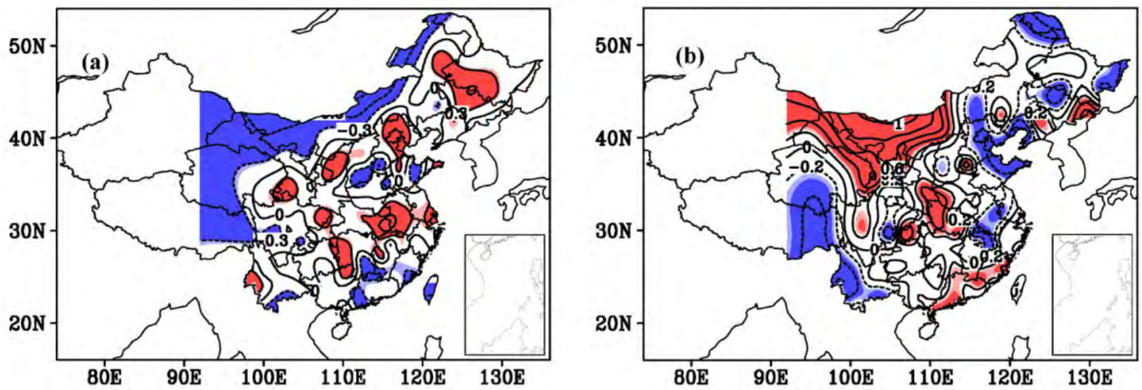

Figure 8. The correlation coefficient between Somali jet intensity and precipitation in China during 1958-2010 on interdecadal scale. (a) Jet and precipitation in June; (b) jet intensity in May and precipitation in July. Dark (light) red area presents positive correlation passing the 0.95 (0.90) significance level and dark (light) blue area presents negative correlation passing 0.95 (0.90) significant level.

5 RELATIONSHIP BETWEEN SOMALI JET INTENSITY AND THE PRECIPITATION IN CHINA ON INTRASEASONAL SCALE

This section investigates the relationship between the Somali jet and the precipitation in China on the intraseasonal scale. We calculated the pentad intensity series of the Somali jet during its active period (May to August) by subtracting the climatological pentad mean from the original time series. We took nine pentads with maximum and minimum intensity respectively for composite analysis. The precipitation in China and its related atmospheric circulation are composed to study the link between the Somali jet and precipitation in China on the synoptic timescale. The anomalous winds on 850 hPa show that the anomalous southerly wind of the Somali jet is large in the pentad when the Somali jet intensity is large (Fig.9a). Anomalous southerly winds occur in the east of China and strong abnormal southeasterly winds appear in the west of North China. Anomalous precipitation in percentage (Fig.9b) in China shows that there is more precipitation in most parts of the northern region except in Northeast China, and the precipitation increases significantly in central China, western Xinjiang and central Qinghai. There is also more precipitation in most parts of southern region except Zhejiang and Anhui, and positive anomalous precipitation is significant in Yunnan. This suggests that the China rainfall increases with positive anomalies of the Somali jet intensity.

The 850-hPa anomalous winds show that the anomalous northerly wind of the Somali jet is large in the pentad when the Somali jet intensity is weak (Fig. 9c). Strong anomalous southerly winds occur in North China and strong easterly anomalous winds from the South China Sea appear in South China. Compared with the precipitation in positive anomalies of the jet, the degree of less rainfall in Northeast China is significantly increased, and the degree of more rainfall in other parts of northern region is significantly decreased. The rainfall also decreases in the southern region. The rainfall in China becomes less but with a less obvious degree. Overall, rainfall decreases in China with negative anomalies of the Somali jet intensity, but the influence is not significant.

From the analysis above, it is found that the atmospheric circulations corresponding to the positive and negative intensity anomalies are nearly opposite with different precipitation pattern in China when the Somali jet is active. The rainfall in China increases (decreases) when the jet intensity is high (low). The influence of the positive anomalous jet on China precipitation seems to be more important. As one of the factors influencing the precipitation in China, the Somali jet has significant positive contribution when its intensity is stronger than in the same period on the intraseasonal scale. Instead of significant negative contribution, the jet's impact on the precipitation is weak when the intensity is low, which indicates that the jet's contribution to the precipitation in China is asymmetric.

The wind lagging the pentad of maximum and minimum intensity of jet is also studied. The temporal evolutions of circulation differences between positive and negative anomalous jet intensity reveal that the circulation presents some regularity in the East and South Asia as the time lag becomes longer. The 850-hPa wind differences (Fig.10a) show that there are strong anomalous southerly winds in Somalia and they turn westerly after crossing the equator in the pentads with anomalous jet intensity. The westerlies spread to the south of the India Peninsula and the westerlies in equatorial regions reach the island of Sumatra. With a lagging of 1 pentad, the cross-equatorial westerlies move to the west coast of the Philippines. The westerlies on the equator in 60° to 90°E over the Indian Ocean are weaker but strong westerlies appear in the Indonesian region. With a lagging of 2 pentads, the westerlies strengthen and run through the eastern Philippines from the Somalia region. The strong

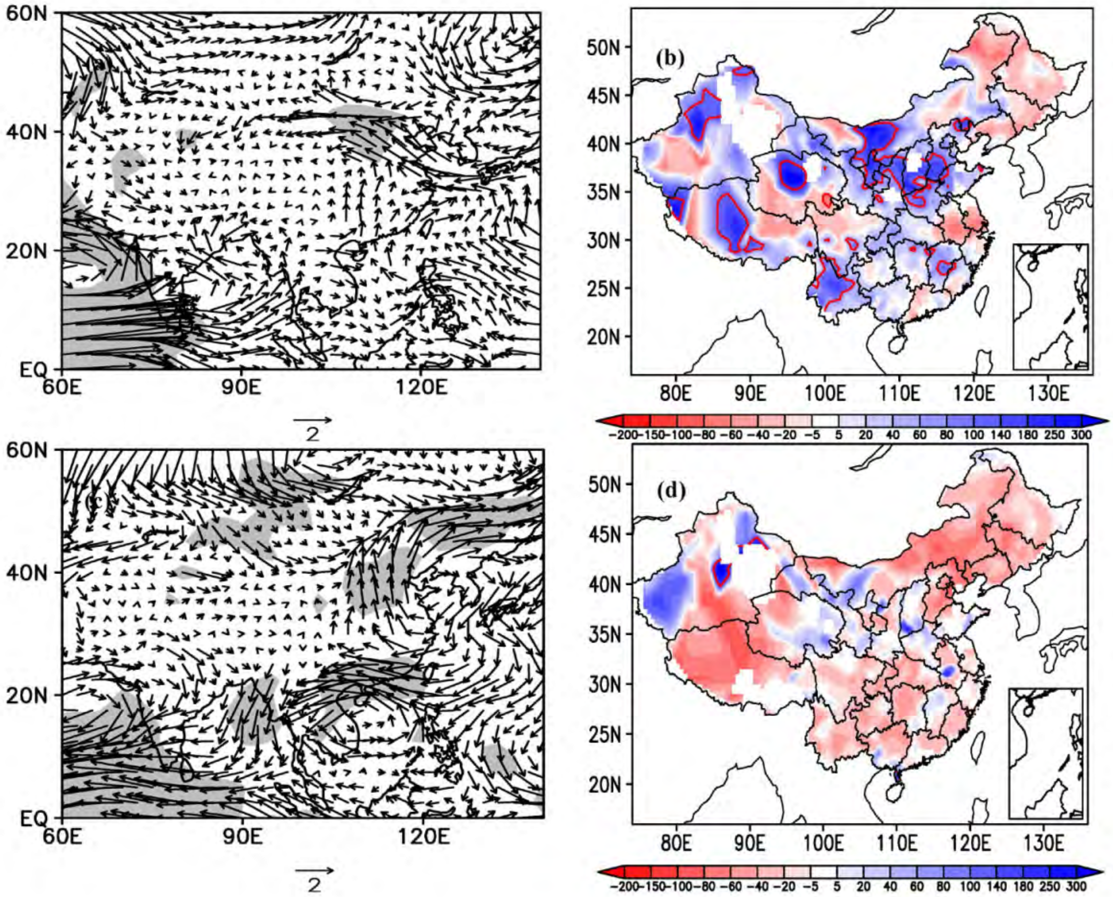

Figure 9. Composite anomalies: 850-hPa anomalous winds (a) and the percentage of anomalous precipitation in China (b) for the nine pentads with maximum intensity of Somali jet. (c) and (d) are the same but for the nine pentads with minimum intensity of the jet. Red contour indicates the 0.95 significance level.

westerlies disappear in the equator and a strong anomalous cyclonic circulation appears over the South China Sea. With a lagging of 3 pentads, the westerlies at the north of the equator are still present but slightly reduce in the Indian Peninsula. The abnormal cyclonic circulation over the South China Sea strengthens continually. With a lagging of 4 pentads, the westerlies disappear and the cyclone over the South China Sea maintains.

As discussed above, the circulation variations in the East and South Asia have some regularity on the intraseasonal scale with temporal evolution and the influence lasts 4 pentads. However, the evolution of the atmospheric circulation, especially the relationship between anomalous cyclonic circulation over the South China Sea and the precipitation in China, needs further investigation.

6 SUMMARY AND DISCUSSION

(1) The Somali jet exhibits significant variations on the intraseasonal, interannual and interdecadal scales. The interdecadal variations are more significant compared with the interannual variations. The intensity of the Somali jet became weaker gradually in the 1960s, reached the weakest in the early 1970s, and then enhanced slowly in the late 1970s.

(2) The correlation between the intensity of the Somali jet and summer precipitation in China varies on the interannual scale. The jet intensity variations in May and June during the early days of establishment are well correlated with summer precipitation, indicative of an indirect influence on summer rainfall in China on the interannual scale. The running correlations between the Somali jet intensity and rainfall in northern and southern China show obvious interdecadal variations, and the Somali jet intensity on the interdecadal scale is closely related to interdecadal variations of the precipitation in China.

(3) The Somali jet is connected with precipitation evolution in China on intraseasonal scale. When the positive anomalous the Somali jet intensity appears in May to August, there are anomalous southerly winds in east region and strong southeasterlies in the west of the North China. When the negatively anomalous intensity appears, there are southerly anomalous winds in North China and strong easterly anomalies in South China. There are more precipitation in China in the pentad of

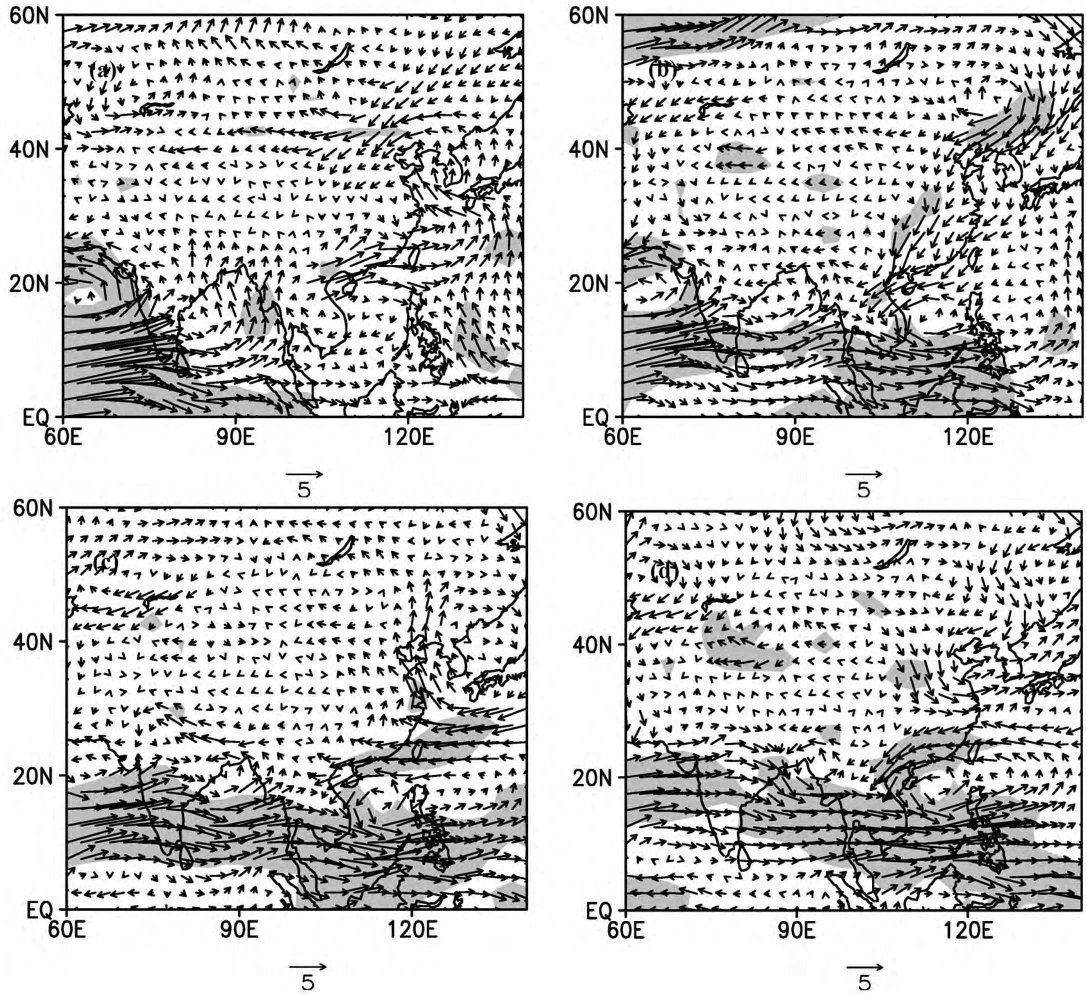

Figure 10. Winds difference at 850 hPa between the extreme positive and negative anomalies of Somali jet intensity on pentads of abnormal intensity (a) and 1, 2 and 3 pentads lagging (b, c and d).

positive anomalous jet intensity and less precipitation in the pentad of negative anomalous jet intensity. The influence of the jet on the rainfall in China is more significant when the positive anomalies appear. The circulation variations in the East and South Asia have some regularity on the intraseasonal scale with obvious temporal evolution.

It is noted that the results about the relationship between the Somali jet and precipitation in China in the present study are mainly based on phenomenon and need to be further confirmed in other ways. We plan to study the mechanisms of the connection between the Somali jet and the rainfall in China on different timescales. In addition, the influences on the East Asian monsoon (especially the precipitation in China during the onset of the Somali jet) also need further investigation.

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