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Relationship between the Asian Westerly Jet Stream and Summer Rainfall over Central Asia and North China: Roles of the Indian Monsoon and the South Asian High

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1. Introduction

Over the Eurasian continent, the summertime upper-tropospheric westerlies are located around 40ºN where the Asian westerly jet stream (AWJS) exists. Diagnostic analyses are performed to investigate the relationship between the AWJS and the associated rainfall pattern over the AWJS region in boreal summer on interannual time scales. The physical mechanisms on the relationship between the AWJS and the rainfall pattern are revealed by exploring the effects of the Indian summer monsoon (ISM) and the South Asian high (SAH).

The interannual variation of the AWJS is depicted by the principal component of the first EOF mode of the 200-hPa zonal wind over the AWJS region (u200_PC1). It indicates the significant southeast-northwest (SE-NW) fluctuation of the AWJS. The South Asian high index (SAHI: $Z200_{(20^o\text{-}27.5^oN,\ 85^o\text{-}115^oE)}$ minus $Z200_{(27.5^o\text{-}35^oN,\ 50^o\text{-}80^oE)}$) defined by Wei et al. (2015) provides an accurate depiction of the SE-NW displacement of the SAH. And we also use the all-India rainfall index (AIRI) to measure the intensity of the ISM. These indices are employed to analyze the relationships of the SAH, AWJS and ISM with the rainfall over the AWJS region.

2. Summer rainfall over the AWJS region

A regression analysis of summer rainfall against the SAHI shows a pronounced inverse relationship between the arid region in central Asia (CA) and the monsoon region in North China (NC) (Fig. 1). Such a relationship indicates that when the SAH moves to the southeast, rainfall increases to the northwest of the Tibetan Plateau (TP) over CA and decreases in the monsoon region of the same latitudes over NC (Fig. 1a). Figure 1b provides a zonal distribution of regressed rainfall anomalies along 36º-41ºN. It illustrates that positive anomalies

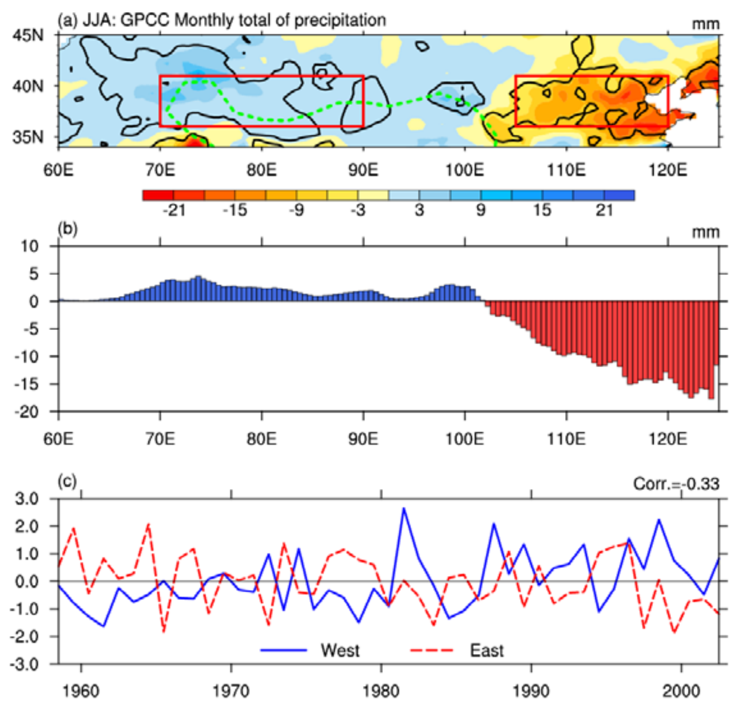

Fig. 1 (a) Regressed JJA rainfall anomalies against the SAHI (shadings; unit: mm). Areas exceeding the 0.05 significance level are highlighted by thick contours. Mid-latitude CA (36º-41ºN, 70º-90ºE) and NC (36º-41ºN, 105º-120ºE) regions are indicated by red boxes. (b) Zonal distribution of regressed JJA rainfall anomalies along 36º-41ºN. (c) Standardized time series of CA rainfall (blue solid line) and NC rainfall (red dashed line) from 1958 to 2002.

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consistently appear to the west of about 102ºE, with the maximum value at approximately 70º-80ºE. To the east of about 102ºE, negative rainfall anomalies enhance from the west to the east. Affected by the EASM, the rainfall anomalies over NC is much larger than those over CA. Figure 1c shows the time series for standardized summer rainfall over CA (36º-41ºN, 70º-90ºE) and NC (36º-41ºN, 105º-120ºE). The out-of-phase relationship of the summer rainfall over these two regions is obvious on interannual time scale. The coefficient of correlation between the rainfalls over CA and NC is -0.33, which exceeds the 0.05 significance level.

The out-of-phase variations in the rainfall over the AWJS region are significantly related to the fluctuations of the AWJS, the SAH, and the ISM (see Table 1). When the ISM is weak, the AWJS and the SAH shift to the southeast, and the summer rainfall increases in the arid CA region and decreases in NC of the EASM region. Moreover, the significant correlation (see Table 1) among these three systems indicates that the fluctuations of these three systems may be interdependent from each other.

Table 1 Correlation coefficients among rainfall over CA, NC, SAHI, u200_PC1, and AIRI

	CA_Rainfall	NC_Rainfall	SAHI	u200_PC1	AIRI
CA_Rainfall	1.00				
NC_Rainfall	-0.33**	1.00			
SAHI	**0.63***	**-0.53***	1.00		
u200_PC1	**0.68***	**-0.47***	**0.73***	1.00	
AIRI	-0.37**	**0.47***	**-0.64***	**-0.52***	1.00

Note: * and ** indicate correlation coefficients exceeding the 0.01 and 0.05 significance level, respectively.

3. Physical links among the SAH, AWJS and ISM

3.1 Effect of SAH on the AWJS rainfall

A regression analysis of the circulation anomalies at 200 hPa against the SAHI shows that when the SAH moves to the southeast, the anomalous cyclone to the northwest of TP strengthens the westerlies to the south of the AWJS and causes a southward movement of the AWJS (Fig. 2). In the eastern portion of the AWJS over the EASM region, strong anomalous northwesterlies are generated between the anomalous cyclone over northeastern Asia and the anomalous anticyclone to the southeast of the TP, and move the AWJS to the southeast. Therefore, the anomalous circulation associated with the SE-NW fluctuation of the SAH is responsible for the SE-NW variation of the AWJS. When the SAH moves to the southeast, the southeastward located AWJ will intensify the upper-level divergence over CA and the upper-level convergence over NC. As a result, there are more rainfall in CA and less rainfall in NC.

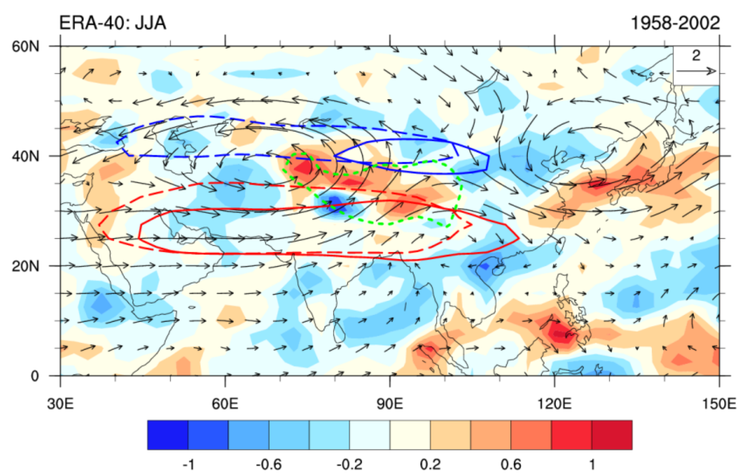

Fig. 2 Regressed circulation (vectors; unit: m s^{-1}) and divergence (shadings; unit: 10^{-6} s^{-1}) anomalies against the SAHI at 200 hPa. Westerly jet stream (blue contours) and SAH (red contours) are represented by the composited values of 30 m s^{-1} and 12520 gpm (contours), respectively, for SAHI larger than 1 (solid line) and smaller than -1 (dashed line). Contours in green indicate the TP region with elevations exceeding 3000 m.

3.2 Effect of ISM on the AWJS rainfall

Regression of the divergent wind anomalies at 200 hPa against the SAHI shows that a southward branch of anomalous divergent winds stretches from CA to the ISM region, and another eastward branch of anomalous divergent winds originates from CA to NC in the mid-latitudes (Fig. 3). The latitude-altitude cross section of the regressed divergent winds against the SAHI along the 70º–85ºE band of the ISM region shows a pronounced meridional circulation that connects the ISM region to the AWJS region (Fig. 4 Left). Thus, the variations in the intensity of ISM may exert an effect on the AWJS at mid-latitudes via meridional divergent wind circulation. From Fig. 4 (Right), a notable zonal vertical circulation is observed in the mid-latitude AWJS region. It connects the arid region in the west with the monsoon region in the east, and couples the meridional divergent wind circulation with the common ascending branch in the CA arid region. The result indicates that a weak ISM results in a southeast shift of the SAH (Wei et al. 2014, 2015), which further influences the mid-latitude AWJS through meridional divergent wind circulation, leading to the formation of a zonal divergent wind circulation with an updraft in the arid CA region and a downdraft in the monsoon region to the east. These anomalous vertical motions favor increased rainfall over CA and decreased rainfall over NC.

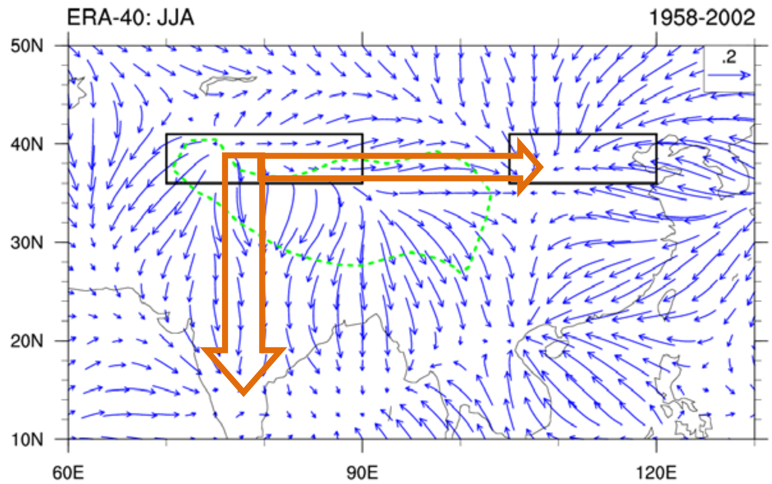

Fig. 3 Regression of 200 hPa divergent winds against the SAHI (vectors; unit: m s^{-1}). Black boxes indicate CA (36º-41ºN, 70º-90ºE) and NC (36º-41ºN, 105º-120ºE), respectively. Contours in green indicate the TP region with elevations exceeding 3000 m.

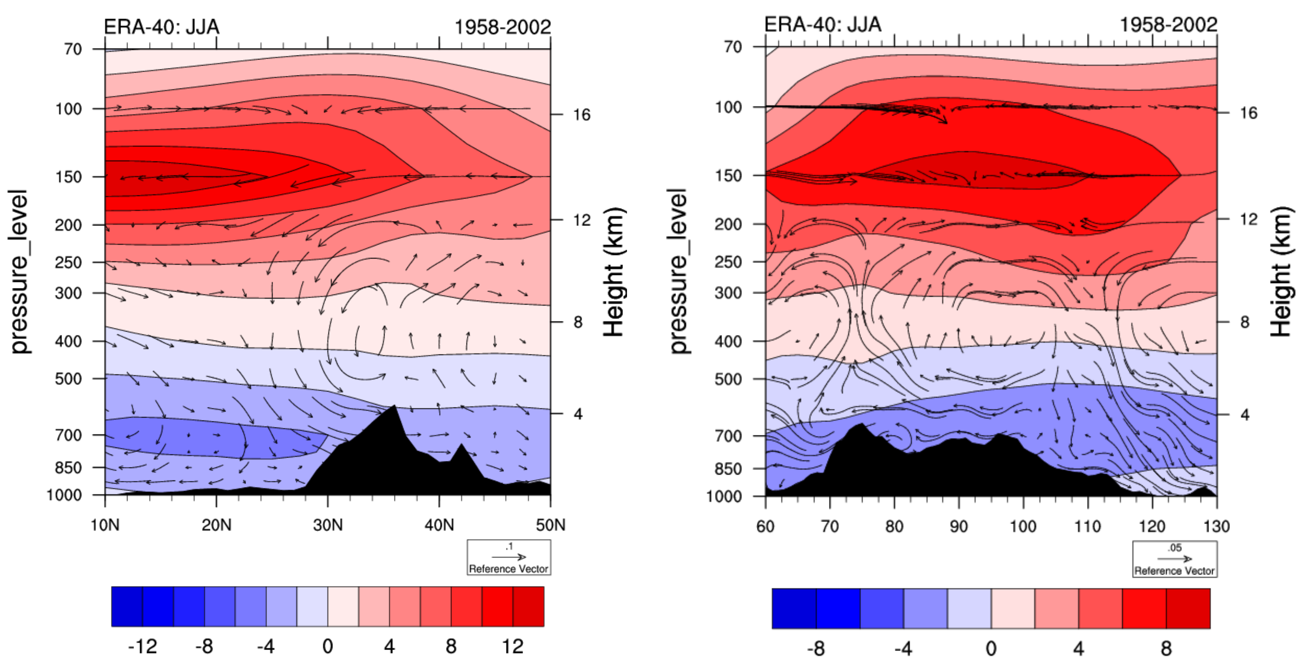

Fig. 4 (Left) Latitude-altitude cross section along 70º-85ºE and (Right) longitude-altitude cross section along 35º-42.5ºN for regressed velocity potential (shadings; unit: 10^5 m^2 s^{-1}) and vertical circulations (vectors; unit: m s^{-1} and -0.1 pa s^{-1} for meridional and vertical components, respectively) against the SAHI. The black area indicates the averaged elevation.

4. Conclusions and discussions

The out-of-phase rainfall variation between CA and NC is closely related to the SE-NW movements of the SAH and the AWJS, and the SE-NW variation of the AWJS is closely related to that of the SAH. Furthermore, the fluctuation of the ISM influences the atmospheric circulation over the AWJS region through an anomalous meridional vertical divergent wind circulation, which connects the anomalous circulation of zonal vertical divergent wind in the mid-latitudes. When the ISM is weaker than normal, the SAH and the AWJS shift to the southeast, the arid region in CA becomes wetter, and the monsoon region over NC becomes drier. When the AWJS and the SAH are located to the southeast, both the divergence over CA and the convergence over NC at the upper troposphere intensify. The inverse upper-level divergence anomalies associated with the location of the AWJS are responsible for the opposing rainfall anomalies over the AWJS region.

In this study, we have proposed a possible physical process that connects the ISM with two upper-level systems, the SAH and the AWJS. We have also revealed the main causes of the inverse rainfall anomalies over CA and NC and showed that the upper-level SAH can connect the ISM with summer rainfall in the AWJS region.

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