

Links between Western Pacific Subtropical High and vegetation growth in China

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Abstract: There is a lack of simple ways to predict the vegetation responses to the East Asian Monsoon (EAM) variability in China due to the complexity of the monsoon system. In this study, we found the variation of the Western Pacific Subtropical High (WPSH), which is one of the major components of the EAM, has a profound influence on the vegetation growth in China. When the WPSH is located more to the west of its climate average, the eastern and northwestern parts experience increased yearly-averaged normalized difference vegetation index (NDVI) and gross primary productivity (GPP) by 0.3%–2.2%, and 0.2%–2.2%, respectively. In contrast, when the WPSH is located more to the east of its climate average, the above areas experience decreased yearly-averaged NDVI and GPP by 0.4% to 1.6%, and 1.3% to 4.5%, respectively. The WPSH serves as a major circulation index to predict the response of vegetation to monsoon.

Keywords: East Asia monsoon; Western Pacific Subtropical High; normalized difference vegetation index (NDVI); gross primary productivity (GPP); China

1 Introduction

The Western Pacific Subtropical High (WPSH), which occupies about 20%–25% of the Northern Hemispheric surface, is a major permanent climate system (Zhou *et al.*, 2009). It controls the movement of weather systems and water vapor transportation in the subtropical areas and often cause large-scale weather extremes. It has obvious seasonal cycles and remarkable variations in location and intensity on various timescales (Liu and Wu, 2004). Its variations in intensity, structure, and location strongly influence the climate in China, as it is closely associated with the summer monsoon in East Asia and the winter monsoon in north-

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ern China (Huang *et al.*, 1985; Yang and Sun, 2003; Jiang *et al.*, 2011). The spatial and temporal pattern of precipitation over eastern China depends to a large degree on the lateral displacement of the WPSH (Huang and Wang, 1985). Many studies have investigated the mechanism of the WPSH and its relationship with the summer precipitation and temperature in China (Sun and Ying, 1999; Lu 2002; Yang and Sun, 2003; Liu and Wu, 2004; Zhou and Yu, 2005). However, fewer studies have considered its impacts on the vegetation growth in China.

The trend of vegetation growth in China is thought to be driven by monsoon. Fu and Wen (1999) found the spatial and temporal variations of NDVI in East Asia are highly correlated with the variations in monsoon rainfall. Zhang *et al.* (2002) found the abrupt transition of the monsoon precipitation causes the seasonal variations of leaf area index (LAI) in eastern China. Previous studies on the vegetation-monsoon relationship in China depend much on the monsoon index. As the EAM system involves complex interactions among tropical, subtropical, and mid-latitude weather and climate systems, as well as the land-atmosphere-ocean interactions at various spatial and temporal scales, it is difficult to quantify the monsoon and its variation. Some indices, such as Webster and Yang Index (Webster and Yang, 1992), Monsoon Hadley Circulation Index (Goswami *et al.*, 1999), Convection Index (Wang and Fan, 1999), Guo Index (Guo, 1983), Dynamical Normalized Seasonality Index (Li and Zeng, 2002), have notable differences which have led to discrepancies in the vegetation-monsoon relationship studies. For example, Jiang *et al.* (2013) reported a strong monsoon corresponds to positive net primary productivity (NPP) anomalies in southern China by using the Dynamical Normalized Seasonality Index while Li *et al.* (2015) found a strong monsoon corresponds to negative NPP anomalies in southern China by using the Guo Index. In general, there is a lack of simple methods for predicting the influences of the monsoon climate on vegetation growth. Due to the major influences of the WPSH on China's weather and climate over vast areas, it is important to better understand the links between the WPSH activities and vegetation growth in China, and to predict the vegetation responses to monsoon climate.

To quantify the spatial and temporal variations of vegetation growth, NDVI is used as a measure of the vegetation growth, greenness and cover (Tucker, 1979). NDVI has been widely used in studying the linkages between climate signals and vegetation dynamics, such as the relationships between El Niño/Southern Oscillation (Li and Kafatos, 2000; Anyamba *et al.*, 2002; Li *et al.*, 2016), North Atlantic Oscillation (Li *et al.*, 2015), sea surface temperature (Los *et al.*, 2001), West African monsoon (Jarlan *et al.*, 2005; Nicholson *et al.*, 2010) and regional NDVI. The changes of NDVI in China have been intensively studied before (Piao and Fang, 2003; Ding *et al.*, 2015). Previous studies show yearly and seasonal NDVI changes in China are closely correlated with precipitation and temperature change (Zhang *et al.*, 2006; Cui and Shi, 2010; Zhang *et al.*, 2013; Zhou *et al.*, 2014).

The strength of a WPSH is usually measured by the extent of the 5880 gpm contours. The China Meteorological Administration (CMA) has defined a series of indices for quantifying the WPSH activities, including the area (I_a), intension (I_i), position (I_r), west boundary (I_w) and north boundary (I_n) indices which are routinely used for weather forecast and climate projection. In this study, we investigate the link between the WPSH indices and NDVI over China and the responsible mechanisms, focusing on the influences of the WPSH intensity

and position anomalies. The objective of this study is to find a simple method for predicting and early warning the response of China's vegetation to the monsoon climate.

2 Data sources and methods

2.1 Data sources

The NDVI datasets used in this study are produced by the Global Inventory Monitoring and Modeling Studies (GIMMS) group using the AVHRR/NOAA series satellites (<http://glcf.umd.edu/data/gimms/>). The GIMMS NDVI datasets are at a spatial resolution of 8 km² and 15 day interval and have been corrected to minimize the effects of volcanic eruptions, solar angle and sensor errors and shifts and thus can be used as the indicators of vegetation growth (Piao *et al.*, 2003). We derive monthly NDVI from two images for each month using the maximum value composite (MVC) method (Holben, 1986). Pixels with average annual NDVI less than 0.05 were considered as non-vegetated areas and thus removed. We consider average NDVI from March to May, June to August and September to November, and December to February as the spring, summer, autumn and winter NDVI, respectively. The yearly averages of the NDVI is the average of monthly NDVI over a year. The yearly GPP data are the outputs of the atmospheric-vegetation interaction model (AVIM2) which is at a spatial resolution of 10 km² (Ji *et al.*, 2008; Li *et al.*, 2015).

The monthly air temperature and precipitation data of 670 meteorological stations are obtained from the CMA. The station data are interpolated to the 8 km² spatial resolution using ANUSPLINE (Hutchinson, 1989). The yearly water vapor flux data and the geopotential height at 500 hPa are from the NCEP/NCAR global reanalysis (Kalnay *et al.*, 1996).

The monthly WPSH indices, including I_i and I_w are obtained from the CMA. They are derived from the geopotential height of 500 hPa. I_i is defined by a weighted sum of the grid points at which the geopotential height greater than 5880 gpm within the above region, with a weighting coefficient of 1 for geopotential height of 5880 gpm, of 2 for 5890 gpm, of 3 for 5900 gpm etc. I_w is the longitude of the WPSH western boundary of the 5880 gpm isoline. I_a is defined as the sum of grid points in which the geopotential height greater than 5880 gpm within the region of 10°–50°N and 180°–110°E, and I_r is defined as the average latitude of the range from 110°E to 150°E. Yearly I_i and I_w are the averages of the monthly I_i and I_w . The growth season I_i and I_w are defined as averaged over the period of March to September.

2.2 Methods

We use 95% of the standard deviation as threshold to identify the high and low values for I_i and I_w . In Equations (1) and (2), I_x represents a growth season WPSH index, \bar{I}_x is the mean of I_x , n is the length of the I_x time series and i is year. If the growth season NDVI anomaly of year i is greater (less) than 95% of the standard deviation of the growth season NDVI time series, then the year is defined as a high (low) WPSH year.

$$I_{xi} - \bar{I}_x > 0.95 \sqrt{\frac{\sum_{i=1}^n (I_{xi} - \bar{I}_x)^2}{n}} \quad (1)$$

$$I_{xi} - \bar{I}_x < -0.95 \sqrt{\frac{\sum_{i=1}^n (I_{xi} - \bar{I}_x)^2}{n}} \quad (2)$$

Composite analysis is to average the variables, such as NDVI, air temperature, precipitation, 500 hPa geopotential height and water vapor fluxes, over high and low WPSH index years, respectively.

3 Results

3.1 Seasonal and annual variations of WPSH

Figure 1 shows the seasonal trajectory of WPSH, which exhibits a remarkable seasonal cycle. From January to April, the WPSH continues to extend westward, and then turns northeastward and reaches its northernmost position in August. After August, it turns southwestward and reaches its westernmost position in October. It then retreats southeastward to the sea. The WPSH intensity steadily increases from February to July and then decreases.

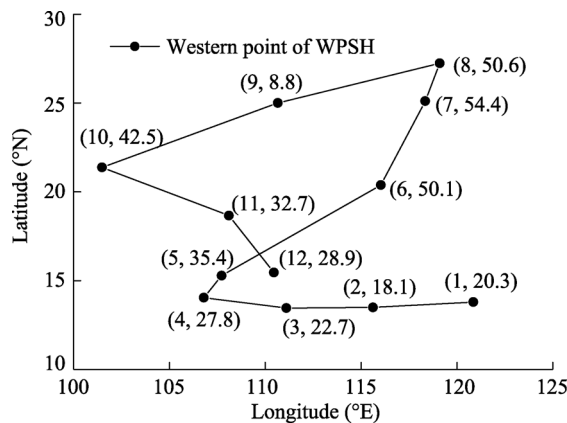


Figure 1 Seasonal trajectory of WPSH based on monthly means of I_w and I_i averaged over 1982–2010. The first number in the brackets denotes the number of month and the second number the monthly I_i averaged over the study period.

Yearly I_i is in the range of 13.2 and 68.5, and the year of 1994, 1995, 1998, 2005 and 2010 are identified as high I_i years, while 1984, 1985, 1986, 1999 and 2000 are identified as low I_i years. The high I_i year corresponds to a strong WPSH, while the low to a weak WPSH. Yearly I_w shifts between 93.3°E and 132.5°E with an average of 112.5°E. The detected high I_w years are 1984, 1985, 1986, 1989, 1999 and 2000, while the low I_w years are 1983, 1987, 1995, 1998, 2003 and 2010. The high I_w year corresponding to the WPSH is located in the east position, while the low to a west position.

3.2 Variation of China's NDVI

The spatial distribution of vegetation types in seven eco-regions and their regional mean yearly NDVI are shown in Figure 2. The seven eco-regions include Southwest China (SW), South China (SC), North China (NC), Inner Mongolia (IM), the Tibetan Plateau (TP) and North West China (NW). SW is dominated by tropical rain forest and subtropical evergreen forest, where the NDVI is the greatest. SC is mainly covered by subtropical evergreen forest and its NDVI is the second largest. NE is dominated by temperate forest and crops, while NC by crops with NDVI values of about 0.4. IM and the TP are dominated by grassland with NDVI values of around 0.2. NW mainly consists of desert, with sparse dry land vegetation

of NDVI of around 0.14. Significant increasing trends are detected in the NDVI times series for SW, SC, NC and NW ($P < 0.05$).

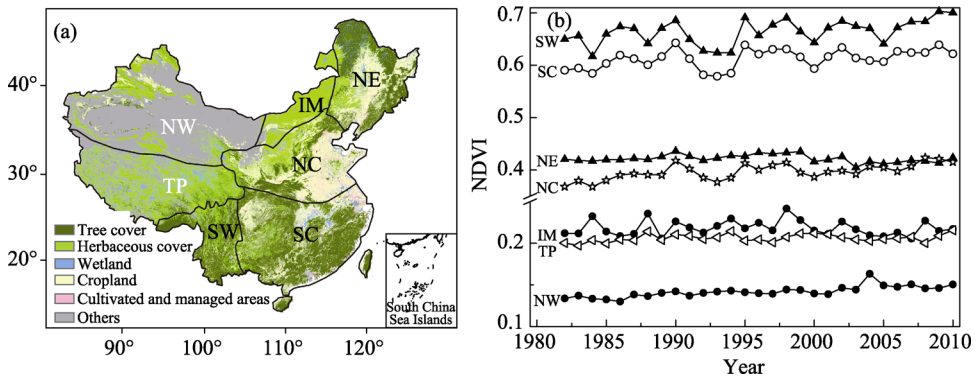


Figure 2 (a) Spatial distribution of vegetation types in the seven eco-regions of NE, IM, NW, NC, SC, TP and SW, representing Northeast China, Inner Mongolia, Northwest China, North China, Southeast China, Tibetan Plateau and Southwest China, respectively; (b) Regional mean yearly NDVI time series for eco-regions

3.3 Response of China's NDVI to intensity of WPSH

Figure 3a shows yearly I_i is positively correlated with NDVI in most areas of NC and SC, but negatively in most areas of NE, NW and TP. Composite analysis shows yearly NDVI anomalies have almost opposite spatial patterns in strong and weak WPSH years (Figures 3b and 3c). In strong WPSH years, regional average yearly NDVI anomalies are positive in all of the eco-regions except for SW, while in weak WPSH years, they are negative in most of the eco-regions except for NE and IM.

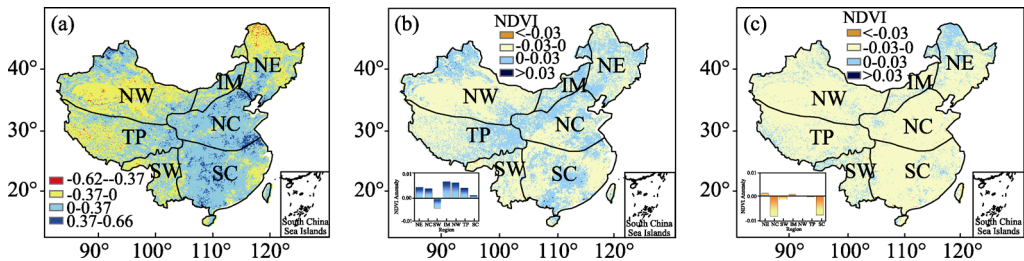


Figure 3 (a) Spatial distribution of correlation coefficient between yearly I_i and NDVI; (b) Spatial distribution of yearly NDVI anomalies composite for high I_i years; (c) As (b) but for low I_i years. All the anomalies in this research are relative to the average of 1982–2010.

3.4 Response of China's NDVI to zonal shifts of WPSH

The zonal shifts of the WPSH have profound influences on China's NDVI. The spatial pattern of NDVI anomalies for low I_w years are almost opposite to that for high I_w years. Most of China's yearly NDVI anomalies are positive in the low I_w years, but negative in the high I_w years (Figures 4a and 4b). Regional averaged NDVI for NC, IM, NW and SC are about 3%, 0.4%, 1.3% and 1.6% lower than the 1982–2010 average for high I_w years, respectively, but are 1.1%, 0.5%, 0.3% and 2.2% higher for low I_w years, respectively.

However, not all areas in China are influenced by the variations of the WPSH. For example, average NDVI anomalies are negative in SW and TP for both high and low I_w years,

indicating NDVI in SW and TP are not influenced by the zonal shifts of the WPSH. Figures 4a and 4b show NDVI anomalies are mostly negative in the southern part of NE in high I_w years, but mostly positive in low I_w years, which are consistent with NDVI anomalies in NC and IM during the two circulation patterns. However, the NDVI anomalies changes in the northern part of NE are opposite to that in the southern part of NE, indicating the northern part of NE may not be directly influenced by WPSH.

There is no simple one-to-one correspondence between the regional average NDVI and WPSH indices on annual time scale in most of the seven eco-regions. Only the regional NDVI average for NC and NW are significantly associated with I_a , with correlation coefficients of 0.38 and 0.48 ($P < 0.05$), which explains 14% to 23% of the NDVI variations, respectively. Previous studies on the NDVI-monsoon relationships find no significant correlation between annual NDVI and monsoon index (Fu and Wen, 1999).

To better understanding the impacts of WPSH on vegetation growth, we conducted composite analysis of the GPP difference in low and high I_w years (Figures 4c and 4d). GPP is the amount of carbon assimilated by plants via photosynthesis, the process is believed to be influenced by climate and other environmental factors. The spatial pattern of model simulated GPP anomalies composite for low and high I_w years agree well with the corresponding NDVI anomalies. Regional averaged GPP for NC, IM, NW and SC are about 1.8%, 3.3%, 4.5% and 1.3% lower than the 1982–2010 average for the high I_w years, respectively, but are 2.2%, 1.4%, 0.8% and 0.2% higher for the low I_w years, respectively. The regional average

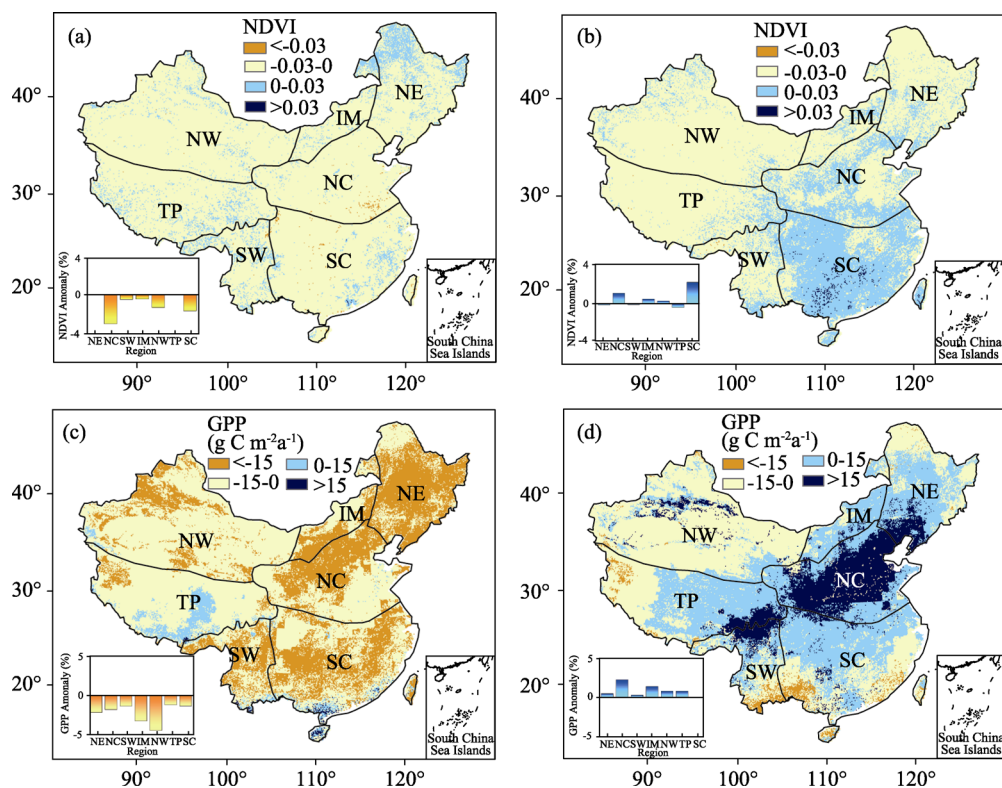


Figure 4 (a) Spatial distribution of yearly NDVI anomalies composite for high I_w years; (b) As (a) but for low I_w years; (c) Spatial distribution of yearly GPP anomalies composite for high I_w years; (d) As (c) but for low I_w years

GPP for NE, NC, IM and NW are significantly correlated with I_a , while for SW, TP and SC with I_r . Regional GPP average for NW is also significantly correlated with I_w . These correlation coefficients are between 0.37–0.40, indicating the variation of WPSH can explain 14%–16% GPP variations in China.

4 Discussion

4.1 Impacts of anomalous zonal location of WPSH on water vapor transportation

The NDVI pattern differences in the high and low I_w years are associated with anomalous large-scale circulations. When the WPSH is in west position, the anomalous circulation pattern benefits the northeastward transport of the warmer tropical water vapor from the Bay of Bengal and the South China Sea along the northwestern flank of the WPSH. As Figure 5a shows, large quantities of water vapor are carried from the adjacent oceans to China. The convergence of the warmer tropical water vapor with the colder subtropical water vapor often results in heavy rainfall in eastern China. When the WPSH is in east position, it is relatively weak (Figure 5b). This circulation pattern suppresses the warmer water vapor transportation to east China, such that the vertically integrated water vapor anomalies are mostly negative over China.

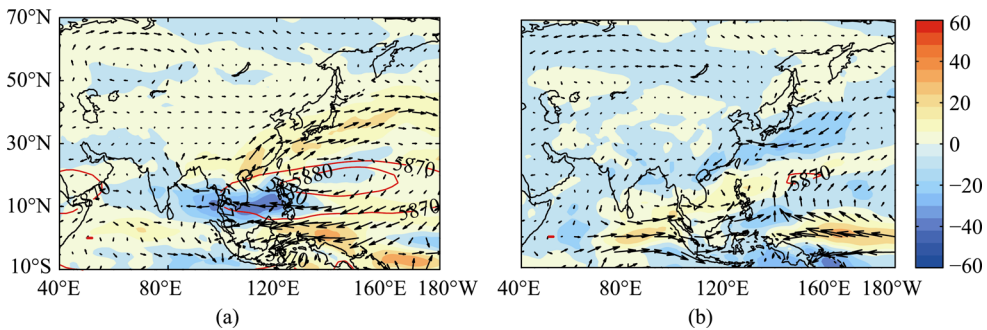


Figure 5 (a) The 500 hPa geopotential height and vertically integrated water fluxes anomalies composite for low I_w years; (b) As (a) but composite for high I_w years

4.2 Impacts of anomalous zonal location of WPSH on air temperature and precipitation

The spatial patterns of yearly precipitation anomalies are generally consistent with that of the yearly average vertically integrated water vapor flux. The yearly precipitation anomalies are positive in most areas of China in low I_w years, but negative in high I_w years (Figures 6a and 6b). Positive temperature anomalies occurred in most area of SC, NC, NW, IM and NE in low I_w years, while negative in high I_w years (Figures 6c and 6d).

Regional average precipitation is 10.0%, 8.7%, 12.3%, 9.1% and 3.7% higher than 1982–2010 average for NE, NC, IM, NW and SC in low I_w years, respectively, but are 0.9%, 3.0%, 5.9%, 5.4% and 2.4% lower than the average in high I_w years, respectively. Average temperature anomalies are in the range of -0.2°C to 0.1°C for NE, NC, IM, NW and SC in low I_w years, while in the range of -0.5°C to -0.6°C in high I_w years.

Figure 6e shows that NDVI is positively correlated with precipitation in IM and north-

western NW. Anomalous WPSH enhances precipitation which causes NDVI to increase in the low I_w years. However, it suppresses precipitation in the high I_w years, so the NDVI decreases. The NDVI-precipitation relationship in the above areas can generally explain the NDVI differences between the low and high I_w years.

NDVI is positively correlated with temperature in most areas of NC and SC (Figure 6f). The association of temperature and NDVI in the above regions can generally explain the

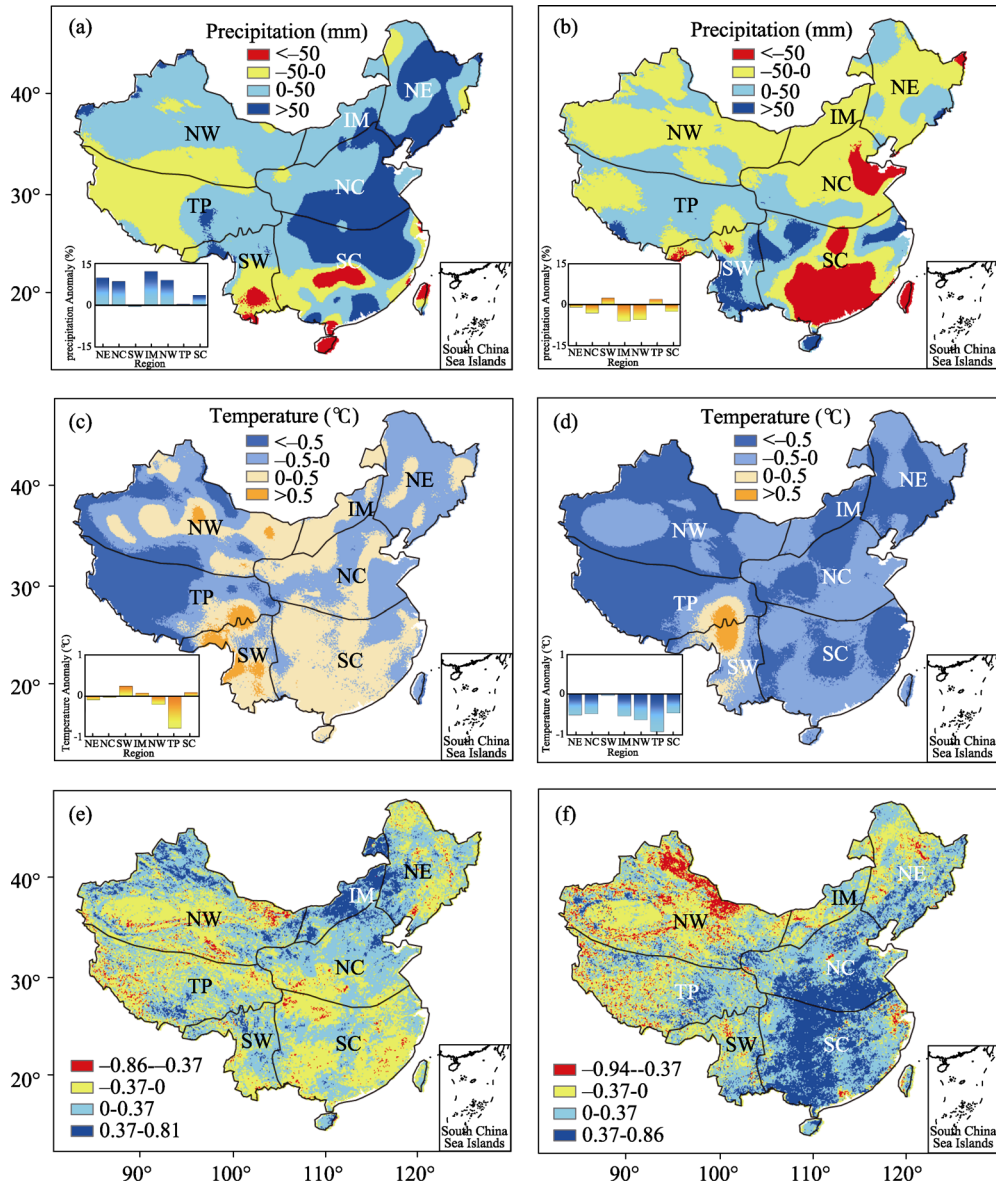


Figure 6 (a) Spatial pattern of yearly precipitation anomalies composite for low I_w years; (b) As (a) but for high I_w years; (c) Spatial pattern of yearly mean temperature anomalies composite for low I_w years; (d) As (c) but for high I_w years; (e) Spatial pattern of correlation coefficient between yearly NDVI and yearly precipitation; (f) As (e) but between yearly NDVI yearly mean temperature. 0.37 represents the threshold for 95% confidence level.

NDVI variations during the two circulation patterns. Average temperature for low I_w years is higher than that for high I_w years in NC and SC, which cause higher NDVI in low I_w years than in high I_w years.

4.3 Impacts of anomalous WPSH zonal location on seasonal NDVI

The influence of climate factors on vegetation growth is the combination of precipitation, air temperature and other factors, and their impacts are different in seasons. Figure 8 shows spatial pattern of the correlation coefficients between seasonal NDVI and seasonal average air temperature and precipitation. Spring precipitation is positively correlated with NDVI in some areas of IM and NC, but negatively correlated with NDVI in eastern SC (Figure 7a). The higher spring precipitation in eastern SC is often accompanied by lower temperature corresponding to lower NDVI, so the precipitation is negatively correlated with NDVI in eastern SC. Spring temperature is positively correlated with NDVI in NC, IM, SC and northern NW (Figure 7b). Higher spring temperature favors snow melting, high soil moisture and thus vegetation growth.

Summer precipitation is negatively correlated with NDVI in some area of SC but it is positively correlated with NDVI in IM and northern NW (Figure 7c). Higher summer temperature is often accompanied by drought and heat wave, so summer temperature is negatively correlated with NDVI in most areas of IM, NW and NC, but it is positively correlated with NDVI in some areas of SC (Figure 7d).

Autumn precipitation is negatively correlated with NDVI in NW, NC and SC. Autumn temperature is positively correlated with NDVI in most areas of IM, NC and SC (Figure 7f). Higher autumn temperature prolongs vegetation's growth season to increase NDVI.

Figure 8 shows seasonal NDVI composite for low I_w years is all greater than that composite for high I_w years in IM, NW, NC and SC. The seasonal relationships between NDVI and climate factors can generally explain the NDVI differences between low and high I_w years. For IM, higher spring and autumn temperature, as well as higher summer precipitation favors vegetation growth, so NDVI is greater in low I_w years. Although NW is not in the impact areas of the East Asian monsoon, its NDVI anomalies in low and high I_w years are consistent with those in IM. Higher spring and summer precipitation as well as higher autumn temperature can explain higher NDVI in low I_w years for NW and NC. Higher four seasons' temperature for low I_w years can explain the NDVI increase in SC.

5 Conclusions

East Asian monsoon controls the precipitation and temperature change in most areas of China, but our understanding of its relationship with vegetation is limited because of its complexity. In present study, we focus on the impacts of the WPSH which is one of the most important components of the East Asian monsoon system. We found a strong WPSH favors NDVI increase in eastern China, while a weak WPSH corresponds to a reduction in NDVI. The zonal shifts of WPSH has a profound influence on the vegetation growth in eastern and northwestern China. If WPSH is located in the west position, then the circulation pattern favors warm water vapor transportation to eastern China, which leads to significant precipitation. The westward expansion of WPSH also brings higher spring and autumn temperatures to east China, which favors vegetation growth. If WPSH is in the east position, then

precipitation greatly decreases in eastern and northwestern China and the spring and autumn temperature are lower than the average, accompanied by decreased NDVI.

Although the changes of climate factors in an area which control vegetation growth, yet they depend on the interaction of several climate systems. Our results show WPSH explains 14%–23% variations of the factors which affect NDVI in northern and northwestern China, and 14%–16% variations of the factors which affect GPP in China. The location and intensity of WPSH are easy to identify through 500 hPa geopotential height, and thus our results provide a simple way for the prediction of the vegetation growth trend in China.

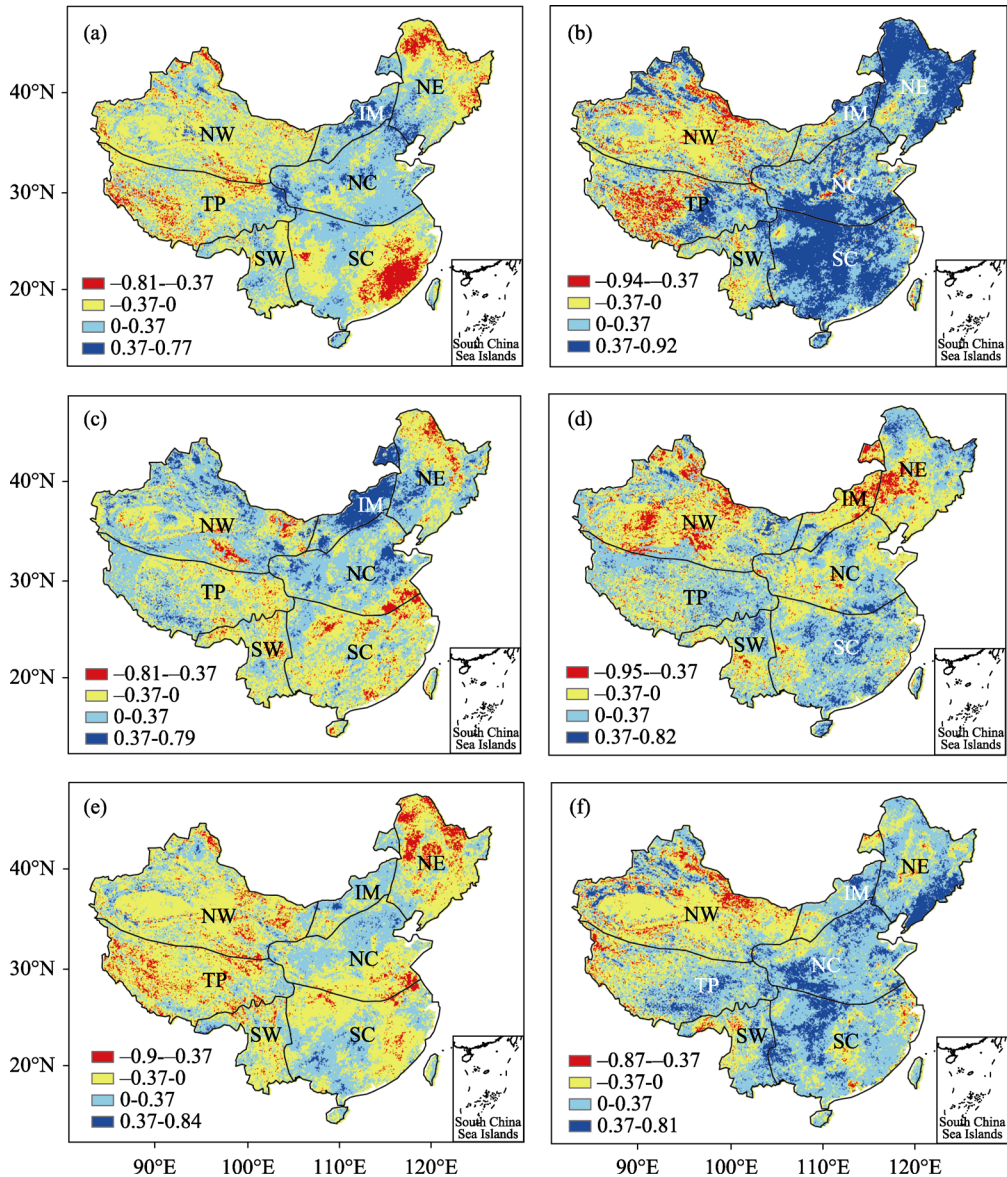


Figure 7 (a) Spatial pattern of correlation coefficient between spring precipitation and spring NDVI; (b) As (a) but for spring temperature; (c) Spatial pattern of correlation coefficient between summer precipitation and summer NDVI; (d) As (c) but for summer temperature; (e) Spatial pattern of correlation coefficient between autumn precipitation and autumn NDVI; (f) As (e) but for autumn temperature

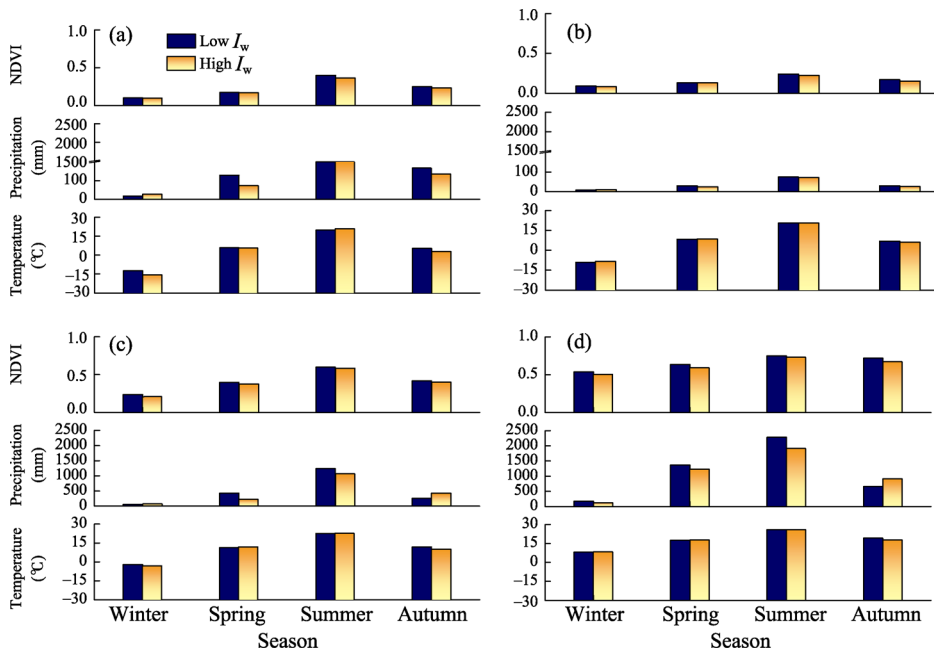


Figure 8 (a) Comparison of the seasonal mean NDVI, seasonal precipitation and seasonal mean temperature composite for low I_w and high I_w years for IM; (b) as (a) but for NW; (c) as (a) but for NC; and (d) as (a) but for SC

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