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The modulation of Tibetan Plateau heating on the multi-scale northernmost margin activity of East Asia summer monsoon in northern China

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ABSTRACT

The northernmost margin of East Asian summer monsoon (EASM) could well reflect wet/dry climate variability in the EASM marginal zone (northern China). The study shows that EASM occurs in northern China from Meiyu period to midsummer, and it is also the advancing period of the northern margin of EASM (NMEASM) before the 43rd pentad. NMEASM activity exhibits multi-scale variability, at cycles of 2–3-yr, 4–6-yr and 9–12-yr, which respond not only to EASM intensity but also to westerly circulation anomaly, exhibiting the mid-latitude Eurasian waves and the high-latitude Eurasian teleconnection (EU) patterns.

The positive anomalies of Silk Road pattern and EU pattern in recent two decades contribute to the enhanced west-ridge and east-trough anomaly around 120°E over northern China, leading to divergence of moisture flux and north wind anomaly, which is helpful for southward western pacific subtropical high (WPSH) and southward NMEASM. Negative Eurasian pattern along subtropical Jet leads to anticyclone anomaly over south of the Yangtze River, deep trough and north wind anomaly along the west coast of the subtropical Pacific, contributing to southward WPSH and NMEASM at the cycle of 4–6-yr. Remote forcing sources of these anomalous Eurasian waves include North Europe, north of Caspian Sea, Central Asia, Tibetan Plateau and the west of Lake Baikal; the south of Lake Baikal is a local forcing region. The Tibetan Plateau heating and snow cover could modulate Eurasian wave pattern at multi-scale, which could be used as prediction reference of multi-scale NMEASM.

1. Introduction

The northernmost margin of East Asian summer monsoon (NMEASM) is the most northern position where the East Asian summer monsoon (EASM) could reach (Qian et al., 2009). Due to multi-scale variation of EASM intensity and other factors, the NMEASM exhibits obvious activity. Which was defined as EASM marginal zone (Fu, 2003; Qian et al., 2007), a climate sensitivity zone. The EASM marginal zone just lies in northern China (Yang et al., 2005), thus some obvious nature disasters including flooding, droughts, heat waves, duststorms, and other consequent natural hazards are significant in northern China (Shi and Zhu, 1996), which are closely related to the NMEASM activity (e.g., Gao and Yang, 2009; Waliser, 2006; Yang and Lau, 2006; Chen and Bordoni, 2014). Therefore, it is essential to predict multi-scale NMEASM.

The variability of the NMEASM is close related to EASM intensity. Weakening EASM intensity after 1970s has contributed to decreased monsoon rainfall in northern China (Wang, 2001) and the "southern flood–northern drought" pattern in China (Wang, 2002; Yu et al., 2004; Ding et al., 2009), which exhibits the important effect of EASM intensity on the climate in the EASM marginal zone and the NMEASM. Qian et al. (2012) further show that dry/wet variability in northern China strongly depends upon whether summer monsoon flow reaches northern China, emphasizing the significance of the NMEASM on the climate in the EASM marginal zone, meanwhile, it also exhibits incomplete consistent variability between EASM intensity and the NMEASM activity, as well as climate anomaly in the EASM marginal zone (Huang et al., 2009; Lv et al., 2011; Zhang et al., 2015). Zhang et al. (2016) also prove that EASM intensity and the NMEASM are inconsistent with each other, and the latter is superior to the former on drought evaluation in northern China. Therefore, the multi-scale variability of the NMEASM and its impact on climate in northern China has become a hotspot topic (Hu and Qian, 2007).

Besides EASM intensity, both subtropical circulation and westerly circulation are significant for NMEASM variability. The position of western Pacific subtropical high (WPSH), exhibited by the west-extending ridge and the ridge line of WPSH, determines the route of water vapor transport to the EASM marginal zone and precipitation position

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in northern China and Japan (Tao and Chen, 1987; Wu and Zhou, 2008). WPSH acts as baton effect for the water vapor transport of EASM to northern China, because EASM marginal zone is far from tropical Pacific and Indian Ocean, which leads to consuming of water vapor and energy transfer in a long-distance transport via South China, the Yangtze River, and other regions. In addition, other circulation systems also result in vorticity anomaly, that indirectly disturbs EASM moisture supply, especially, a meridional Pacific–Japan teleconnection pattern (PJ, found by Nitta, 1987) exerts modulation on EASM activity in the EASM marginal zone (Wang and He, 2015). As for westerly circulation, a quasi-stationary Eurasian teleconnection (EU-like pattern; found by Wallace and Gutzler, 1981) appeared in the summer drought events of 1999 and 2000 in northern China (Wei et al., 2004); EU-like pattern and Silk Road patterns (defined by Lu, 2002) were also responsible for 2014 drought in northern China through changing WPSH and East Asian trough (Wang and He, 2015); Similar to Silk Road pattern, an Eurasian wave pattern in the mid-latitude is the prominent factor resulting in 1994 drought in central China, southern Korea and Japan (Park and Schubert, 2010). Studies showed that EU pattern, Eurasian wave pattern and PJ pattern occurred over the EASM marginal zone. How do they affect NMEASM variability? It is meaningful to predict monthly and longer monsoon rests, the occurrence of these waves, as well as their simulation in the model.

To find the forcing sources of anomalous Eurasian wave pattern and how Eurasian wave pattern affects the climate in the EASM marginal zone, some key regions are investigated. Long soil moisture memory acts as a "bridge" for remote forcing. Higher land surface temperature and sensible heat flux in Europe, due to decrease in sea ice extent in spring leading to decrease in wave energy sinking, exert enhanced EU-like pattern and precipitation in summer, which links the spring sea ice anomalies with EASM (Zhao et al., 2004). Winter North Atlantic Oscillation (NAO) has an in-phase correlation with summer precipitation in eastern China at 2–3-yr cycle (Fu and Zeng, 2005), also relying on a "bridge" over the Eurasian continent. The continent thermal around the Mediterranean Sea and Caspian Sea exerts wave energy on the quasi-stationary Rossby wave pattern along the subtropical jets (JS, Wang and He, 2015). As the highest land, the Tibetan Plateau (TP) surface heating provides the major heat source in maintaining the stationary waves for EASM in the later spring and early summer (Yanai et al., 1992; Ting, 1994; Yanai and Li, 1994; Halder and Dirmeyer, 2016). However, weakening trend in TP sensible heat flux in recent decades has no significantly stable correlation with EASM (Duan et al., 2011), which exhibits uncertainty of TP heating effect on EASM. The reason is worth exploring. Zhang et al. (2017) show that TP heating has double-mode adjustment to the circumglobal teleconnection and Eurasian wave, due to zonal heating difference, including sensible heat flux in the east of TP and snow cover in the west of TP. Besides, TP snow cover exerts positive correlation with the west-extension of WPSH at inter-decadal scale (Zhang et al., 2004), and the TP orographic forcing is responsible for the extra tropical equivalent barotropic stationary wave features (Ting, 1994). How does this force influence the climate in the EASM marginal zone? What cycle do these forces affect Eurasian wave pattern? These questions are uncertainty.

In this study, the NMEASM variability during the Meiyu period and midsummer is contrasted; and the effect mechanism is discussed. The data and methods are described in Section 2. The temporal and spatial variability of NMEASM and Eurasian wave patterns are shown in Section 3, and the possible mechanism that TP heating and Eurasian wave pattern affecting NMEASM is shown in Section 4. The conclusions are presented in Section 5.

2. Data and methods

The datasets are used here: the reanalysis dataset of the European Center Medium-Range Weather Forecasting (ECMWF) Interim (ERA-Interim) monthly data (http://apps.ecmwf.int/datasets/) from 1979 to 2016 with a horizontal resolution of 0.75° × 0.75° (Dee et al., 2011); ERA40 data with a horizontal resolution of 0.75° × 0.75° is used to obtain the data before 1978. Because both ECMWF datasets have the same resolution, therefore the v-wind anomalies from both datasets are used for exhibiting wave patterns. *Re*-analysis dataset is used for analyzing of atmospheric circulation, the northernmost margin index (NMI) of EASM. West-extending ridge index from 74 circulation indexes dataset (http://ncc.cma.gov.cn) is used for exhibiting the west-extending position of WPSH (Lu, 2002). The monthly MAM snow cover data over the west of the TP (70–80°E, 31–41°N) and the east of the TP (80–105°E, 35–41°N) from 1966 to 2015 were obtained from the Global Snow Lab at Rutgers University (http://climate.rutgers.edu/snowcover), with a polar stereographic projection of the Northern Hemisphere and an 89° × 89° grid (Robinson and Frei, 2000; Estilow et al., 2015).

A highly relevant EASM index, the shear vorticity index defined by Wang and Fan (1999, WF index hereafter), is calculated and used for reflecting EASM intensity, because it was well correlated with the leading principal component of EASM. The WF index was defined by the U850 in (5°–15°N, 90°–130°E) minus U850 in (22.5°–32.5°N, 110°–140°E), described by Wang et al. (2008). In addition, the East Asia summer monsoon indexes defined by Shi and Zhu (1996) and Guo (1983) are also analyzed. EU-like pattern defined by Wang and He (2015) is also used for cycle analysis. The NMI of EASM is defined according to the pentad factors as below: 1) 850-hPa $u > 0, v > 0$; 2) 850-hPa pseudo-equivalent potential temperature larger than 335 K; and 3) mean precipitation > 4 mm/day (Hu and Qian, 2007; Zhang et al., 2015).

The multi-scale variability is indicated with the application of an adaptive and temporally local filter tool, known as the ensemble empirical mode decomposition (EEMD), a method developed in recent years (Wu and Huang, 2009; Huang and Wu, 2008). An empirical orthogonal function (EOF) analysis method is executed for displaying spatial and temporal pattern of Eurasian wave pattern. The wave activity fluxes (WAF) method from Takaya and Nakamura (2001, TN-flux hereafter) is used, so as to verify the wave pattern propagating over the Eurasian continent, and the relation with EASM activity. The power spectrum is used for cycle analysis. So as to find multi-scale and keep weak cycle information, alpha is defined as 0.1 in the method.

3. Results analysis

3.1. Spatial and temporal distribution of the northernmost margin of EASM

Fig. 1(a) shows annual NMEASM during Meiyu period (June 10th to July 15th) and midsummer (July 16th to August 31st) from 1979 to 2015. The reason to separate summer into Meiyu period and midsummer is that the moisture supply of EASM during Meiyu period could reach northern China and part of EASM marginal zone, with rain belt along the Yangtze River to Japan; however, the NMEASM activates in the EASM marginal zone during midsummer with rain belt occurring in northern China. Thus, the critical difference is NMEASM and rain belt position during two periods. Fig. 1(a) clearly shows the large variability of NMEASM not only during Meiyu period but also during midsummer, with amplitude > 8–10 latitudes from 110°E to 120°E, respectively. Such large variability of NMEASM corresponds to the large variability of dry/wet climate, and precipitation in northern China.

Fig. 1(b) exhibits advancing in NMEASM with time along three longitudes, which shows that EASM reaching the north of 30°N occurs between the 33th pentad and the 48th pentad, and it reaches the northmost margin at the 42nd pentad on average. Therefore, it is the advancing period before 43rd pentad and maintaining and retreating period after 43rd pentad. The same as Fig. 1(a), the NAEASM exhibits southwest to northeast distribution, and EASM could extend more north in the northeast than that in the central China.

To contrast the difference of NAEASM activities during the