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Evolution mechanism of synoptic-scale EAP teleconnection pattern and its relationship to summer precipitation in China

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ABSTRACT

Using ERA-Interim reanalysis daily data and gridded precipitation dataset, the evolution mechanism of East Asia-Pacific (EAP) teleconnection pattern and its relationship to summer precipitation in China were investigated on synoptic timescales based on EOF analysis, composite analysis, and significance test. The results demonstrate that the evolution of synoptic-scale EAP pattern is identified as having a significant relationship with the energy propagation represented by the wave-activity flux (WAF). Such EAP-related WAFs show various features in different levels of the troposphere. In the lower troposphere, the WAF primarily points poleward from the Philippines, playing a vital role in triggering and maintaining the synoptic-scale EAP pattern. A middle tropospheric zonally distributed ridge/trough/ridge wave train provides a favorable westerly waveguide for the southeastward (eastward) energy propagation, converging with a relatively weak poleward WAF over mid-latitude (high-latitude) East Asia. Moreover, the upper-level EAP-related anomalies are partly influenced by two conspicuous eastward WAFs. One may favor the development of Okhotsk anticyclonic (positive) anomaly, and the other one related to the Silk-Road (SR) wave train along the Asian jet converges into the cyclonic (negative) anomaly to greatly strengthen it. Particularly, the highly efficient baroclinic energy conversion responsible for the self-maintenance of SR pattern is also crucial for reinforcing and maintaining this cyclonic anomaly for a prolonged period by extraction of available potential energy from basic flow. In addition, during EAP pattern lifetime, due to the strong moisture flux convergence and upper-level divergence, the long-lasting strong ascents of moist/warm air along a moist and thick layer, therefore induce the summer consecutive extreme precipitation in the middle and lower reaches of Yangtze River.

1. Introduction

East Asia-Pacific (EAP) teleconnection pattern also named as Pacific-Japan (PJ) teleconnection pattern is recognized as one of the dominant modes and the most influential patterns during boreal summer, with a north-south tripole structure between the equator and high-latitudes over East Asia, which reflects the concurrent behavior of the western Pacific subtropical high (WPSH), Mei-Yu front, and Okhotsk blocking high (Kawamura et al., 1996; Kosaka and Nakamura, 2006).

The evolution mechanism of this meridional pattern has attracted substantial scientific attentions on seasonal and interannual to interdecadal timescales (Nitta and Hu, 1996; Fujinami and Yasunari, 2009; Gong et al., 2017; Hu et al., 2018). Initially, Huang (1987) and Nitta (1987) revealed that EAP (PJ) pattern was largely triggered by the northward-propagating Rossby wave forced by the anomalous convective heating around the Philippine Sea. Recent studies emphasized the importance of upper-level quasi-stationary wave trains (Guan and Yamagata, 2003; Shi et al., 2009). Corresponding eastward propagating wave fluxes from Europe across Asia along the westerly jets play significant roles in the reinforcement and preservation of EAP pattern (Kosaka et al., 2012). For example, the eastward energy propagation along the Silk-Road (SR) wave train within the Asian jet areas contributes to the advance and intensification of the Mei-Yu front and the WPSH (Enomoto et al., 2003; Ding and Wang, 2005, 2007; Chen et al., 2008; Lu and Lin, 2009). With a more northern route, the energy propagation oriented eastward from the Ural blocking high along the subpolar jet can primarily strengthen the Okhotsk blocking high

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(Nakamura and Fukamachi, 2004; Wang and Zhang, 2015). Though many previous studies have documented these issues on monthly and interannual timescales, the role of energy propagation on the EAP evolution has received limited attentions on synoptic timescales (Shi et al., 2009; Li et al., 2017). Thus, a first goal of current study is to confirm the significance of different energy dispersions in the advance and maintenance of the synoptic-scale EAP pattern, clarifying the distinctions of EAP-related energy dispersions in different levels of the troposphere.

Additionally, various studies have revealed different climate impacts between the positive and negative EAP phases (Ambrizzi et al., 1995; Chen and Zhai, 2015). Accordingly, negative (positive) geopotential height anomalies over mid-latitude East Asia (the Sea of Okhotsk and the subtropical western Pacific) related to the positive EAP phase, result in severe floods in southern China and cool summers in Japan (Wang et al., 2000; Wakabayashi and Kawamura, 2004). In particular, the concurrent behavior and interaction between EAP pattern and other summer teleconnections may cause more extreme and consecutive rainfall in southern China (Wakabayashi and Kawamura, 2004; Wang and Wang, 2018). Thus, the EAP pattern has been widely considered as an effective predictor of East Asian summer monsoon climate anomalies on a seasonal timescale (Lau and Weng, 2002; Hsu and Lin, 2007). While negative EAP phase with less precipitation signals in China, is basically related to the Pacific typhoons or their remnants (Kawamura and Ogasawara, 2006; Choi et al., 2010). Few similarities between individual typhoon-induced precipitation cases lead to huge complexities and diversities of their mechanisms (Xu et al., 2014). Hence, negative EAP phase is not discussed in present article, EAP pattern refers in particular to positive EAP phase.

Although some attentions have been paid to the evolution and climate effects of EAP pattern on seasonal and interannual to inter-decadal timescales (Kosaka and Nakamura, 2006; Hsu and Lin, 2007), these issues have rarely been systematically discussed on synoptic timescales. Thus, the objective of this article is to illuminate the evolution mechanism of EAP pattern and its connection with summer precipitation in China on synoptic timescales. Quantifying the significance of the synoptic-scale EAP pattern in inducing summer precipitation is conducive to presenting a better understanding of the EAP-related anomalous circulation variations responsible for precipitation.

2. Data and methods

2.1. Data

Daily meteorological datasets utilized in present study are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA-Interim) during 1979–2015, including air temperature (K), horizontal wind field ($m\,s^{-1}$), geopotential height (gpm), vertical p-velocity ($Pa\,s^{-1}$), and specific humidity ($g\,kg^{-1}$), with 17 regular pressure levels vertically and a spatial resolution of $2.5^\circ \times 2.5^\circ$ (Dee et al., 2011; https://www.ecmwf.int/).

Daily outgoing long-wave radiation (OLR) data during 1979–2015 are also used to characterize the intensity and position variations of EAP-related convective activity near the Philippines (Liebmann, 1996; http://www.noaa.gov/), which are derived from the National Oceanic and Atmospheric Administration (NOAA) satellites, with a spatial resolution of $2.5^\circ \times 2.5^\circ$.

Daily precipitation dataset (Chinese Ground Precipitation $0.5^\circ \times 0.5^\circ$ Gridded Dataset, V2.0) employed in present study is released by the National Meteorological Information Center (NMIC) and China Meteorological Administration (CMA). More details of this gridded precipitation dataset are described in NMIC (National Meteorological Information Center, 2010; http://cdc.cma.gov.cn/).

2.2. Methods

The principal statistical methods used in present study include the empirical orthogonal function (EOF) analysis, composite analysis, and the ordinary Student's t-test. EOF analysis, which decomposes a space-time field into spatial modes and associated time series, provides an effective way to identify and extract the synoptic-scale EAP mode during East Asian summer based on daily geopotential height field (North et al., 1982; Loboda et al., 2005; Hatzaki and Wu, 2015). Composite analysis is a widely employed and simple yet effective tool in identifying typical synoptic to sub-monthly scale circulation patterns and their precursors related to extreme precipitation cases, and the purpose of ordinary Student's t-test is to achieve more rigorous statistical significance thresholds (Grotjahn and Faure, 2008; Chen and Zhai, 2016).

As suggested by Hart and Grumm (2001), for daily precipitation dataset, a 7-day binominal filter (3 days on either side of a particular day) is firstly used to highlight the daily variability. Accordingly, daily climatological mean value and standard deviation (σ) are calculated by use of the above smoothed daily precipitation data during 1979–2015. This unequal-weighed binominal filter is designed to dampen chaotic very-high-frequency signals and retain strong precipitation signals substantially (Chen and Zhai, 2015; Wang and Wang, 2018). For the other variables associated with the synoptic-scale EAP pattern, such as geopotential height and horizontal wind fields, a 21-day binominal filter seems more suitable (Grumm and Hart, 2001). The standard deviation and climatological mean value calculated by these smoothed data seem to be more stable compared with only using the unsmoothed single-day values. Hence, we can calculate the normalized anomaly of a variable on a particular day as follows: aiming to retain the synoptic signal mostly, corresponding climatological daily mean is firstly subtracted; then the value is divided by the corresponding climatological daily standard deviation.

Diabatic heating anomalies can cause the variations of vorticity in both the lower and upper troposphere, thereby affecting the circulation pattern (Hsu and Weng, 2001). To investigate the impact of atmospheric diabatic heating on EAP-related circulation variations, the apparent heat source (Q) is therefore calculated according to the widely-used scheme deduced by Yanai et al. (1973) based on ERA-Interim daily observational datasets; that is,

$$Q = c_p\left[\frac{\partial T}{\partial t} + \vec{V}\cdot\nabla_h T + \left(\frac{p}{p_0}\right)^{R/c_p}\omega\frac{\partial\theta}{\partial p}\right] \tag{1}$$

In Eq. (1), c_p, R, and T denote the specific heat of dry air at constant pressure, the gas constant for dry air, and the air temperature respectively, $p_0 = 1000$ hPa (Yanai et al., 1973). $\vec{V}$ is the horizontal vector winds, p the pressure, ω the vertical p-velocity, θ the potential temperature, and ∇ is the isobaric gradient operator.

The wave-activity flux (WAF) is calculated to describe the energy propagation characteristics of quasi-stationary waves and transient fluctuations in this study (Takaya and Nakamura, 1997, 2001). Concretely, the WAF is phase-independent under the assumption of the Wentzel–Kramers–Brillouin (WKB) approximation, which tends to be consistent with the local group velocity direction of quasi-stationary Rossby wave train. The two-dimensional formula can be expressed as:

$$W = \frac{p}{2000\,|\vec{U}|}\begin{Bmatrix} U({\psi'}_x^{2} - \psi'\psi'_{xx}) + V(\psi'_x\psi'_y - \psi'\psi'_{xy}) \\ U(\psi'_x\psi'_y - \psi'\psi'_{xy}) + V({\psi'}_y^{2} - \psi'\psi'_{yy}) \end{Bmatrix} \tag{2}$$

where ψ' denotes the stream function for quasi-geostrophic flow. $\vec{U} = (U, V)$ is the horizontal zonally varying basic flow, U and V represent the zonal and meridional wind components respectively, p signifies the pressure (hPa). The climatological daily mean flow during summer (June–August) from 1979 to 2015 is used as the basic flow, including zonal and meridional wind fields with zonal nonuniformity.