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The 10–30-day oscillation of winter zonal wind in the entrance region of the East Asian subtropical jet and its relationship with precipitation in southern China

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ABSTRACT

Using ECMWF ERA-Interim 6-h reanalysis data, zonal wind intra-seasonal oscillations (ISOs) in the entrance region of the East Asian subtropical westerly jet (EASWJ) in winter from 1979/1980 to 2012/2013 are studied. The results first show that there is an area with large ISO strength in the northwest of the EASWJ; in the key region, zonal wind has a dominant period of 10–30 days. The composite analysis reveals that zonal wind at 200 hPa in this key region has 10–30-day oscillation characteristics. On the 10–30-day time scale, the center of zonal wind anomaly moves eastward. The propagation of zonal wind oscillation relates to temperature tendencies at different latitudes. The remarkable increase (or decrease) in zonal wind in the key region is mostly determined by temperature anomalies to the north. The 10–30-day filtered temperature advection to the north of the key region leads to either a decrease or an increase in temperature; on the other hand, temperature variations south of the key region have trends opposite of the northern trends, which changes the temperature gradient. On the 10–30-day time scale, zonal wind anomalies are associated with precipitation in southern China. When there are easterly wind anomalies over the key region, precipitation occurs over the Yangtze River basin and its south. Diabatic heating during precipitation corresponds with warming to the south of the key region, which combines with the temperature advection to weaken the easterly wind and strengths the westerly wind. Then, the intra-seasonal precipitation moves to southwest China with warm advection and the enhanced westerly wind, which brings the positive relative vorticity advection there.

1. Introduction

In the 1970s, Madden and Julian discovered that there is a 40–50-day oscillation in tropical circulation and defined it as the ISO, or the Madden-Julian oscillation (MJO) (Madden and Julian, 1971, 1972). Many scholars have studied the tropical ISO, and there are certain understandings of the structural characteristics and active regulars of the tropical ISO (Krishnamurti and Subrahmanyam, 1982; Murakami et al., 1984; Lau and Chan, 1986; Knutson and Weickmann, 1987; Li, 1990; Li and Zhou, 1991; Madden and Julian, 1994; Jiang et al., 2004; Li et al., 2015; Feng et al., 2015; Wang et al., 2017; Hsu et al., 2014). However, studies of the extratropical ISO began late. Some studies have shown that the ISO of different meteorological fields, such as meridional wind and zonal wind, are

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totally different from the ISO of geopotential height (Han et al., 2010). The ISO in the northeast Pacific is the strongest in winter and the weakest in summer, but the ISO in East Asia and the northwest Pacific is the strongest in summer and the weakest in winter. The ISO in the northwest Pacific in summer will cause anomalously persistent droughts and floods in the Yangtze-Huaihe River basin (Zhu et al., 2003; Gao et al., 2016). In recent years, continuous freezing rain and snow events occurred frequently in winter in southern China, which had significant ISO characteristics (Wu et al., 2009). A case study also shows that the persistent precipitation anomaly in southern China in winter is closely related to the intra-seasonal variation of EASWJ (Yao et al., 2014). Thus, it is of important theoretical significance to analyze intra-seasonal variation characteristics of the EASWJ in winter.

The EASWJ is a large and stable system in the upper troposphere of the subtropical frontal zone; it is a strong westerly wind belt, where the wind speed is over 30 m s^{-1}. The horizontal length is approximately ten thousand kilometers, the horizontal width is approximately several hundred kilometers, and it is approximately several kilometers thick (Kuang and Zhang, 2006). It maintains the upper branch of the Hadley cell (i.e., the northward branch) and carries Earth's angular momentum from the equator to subtropical regions (Holton, 2004). Thermal anomalies also have an influence on the EASWJ (Kuang et al., 2014; Guo et al., 2015). The EASWJ is strongest in winter. Generally, there is a strong divergence south of the jet entrance, which effects precipitation in southern China; therefore, it is commonly considered as one of the control systems for precipitation in China (Zhang et al., 2006).

In the past, due to the limitation of observed data, scholars have studied the EASWJ at seasonal, inter-annual and inter-decadal time scales (Yang and Webster, 1990; Liao et al., 2004; Zhang et al., 2006; Yang et al., 2000; Ren et al., 2010; Ren et al., 2011; Shi et al., 2014; Xiang and Yang, 2012; Xue and Zhang, 2017). In recent years, observed data, reanalysis data and simulation data have been very abundant, allowing sub-seasonal study to be realized. Jin et al. (2012) studied intra-seasonal characteristics, such as location and intensity, of the EASWJ in summer and noted that the feature of the position index of westerly jet not only has a synoptic scale of one week, but also has a quasi-biweekly dominant period. Other studies (Lin and Lu, 2005; Lin, 2010) showed that after the onset of the summer monsoon, there is a remarkable increase in the intra-seasonal phenomenon north of the EASWJ, which may be closely related to eddies that propagate from upstream regions in the jet; these studies also noted that the study of intra-seasonal characteristics and mutation mechanisms of the EASWJ is not deep enough. Many scholars have studied the relationship between the EASWJ and precipitation in East Asia and concluded that variations in the location and intensity of the EASWJ have an important effect on precipitation intensity and the distribution of precipitation in East Asia (Lin and Lu, 2009). However, it was found in other case studies that latent heat during the rainy period can also influence zonal wind on a sub-seasonal time scale (Yao et al., 2014; Jin et al., 2012).

In summary, the study of intra-seasonal variations in the EASWJ is insufficient. In addition, analyses have generally regarded characteristics in summer, and there has been little research about the winter EASWJ ISO. Therefore, using the ECMWF ERA-Interim 6-h reanalysis data in this paper, the ISO of zonal wind at the entrance of the EASWJ is studied, and intra-seasonal evolution characteristics, thermal propagation mechanisms, and relationships with precipitation in southern China are also studied. The rest of the paper is arranged as follows: Section 2 is for data and methods, Section 3 describes the characteristics of the intra-seasonal zonal wind, Section 4 explains the thermodynamic mechanism of the zonal wind 10–30-day oscillation, Section 5 gives the relationship between precipitation and the zonal wind 10–30-day oscillation, and Section 6 is the conclusion.

2. Data and methods

The data used in this paper are ECMWF ERA-Interim 6-h reanalysis data, which includes zonal wind, meridional wind, vertical velocity, precipitation and temperature. The horizontal resolution of the data is 1.5° × 1.5°. Observation station rainfall data are also used in the paper. The station data we used are provided by China Meteorological Administration (CMA), and the website of the data is http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html

In this paper, winter is actually the winter-half year; that is, winter is defined from November 1st to April 30th of the following year. From 1979/1980 to 2012/2013, there are a total of 34 winters and 6163 days. Before using the 6-h reanalysis data, the data are processed into daily data, with an average of 4 data in one day.

The methods used in this paper include a power spectrum analysis (to achieve a typical period of zonal wind), a Butterworth bandpass filter (to obtain a sub-seasonal scale of meteorological elements), a Gaussian low-pass filter and synthetic analysis.

To explain the propagation of the zonal wind ISO, this study takes into account the thermal wind theorem (Holton, 2004):

$$\frac{\partial u}{\partial p} = \left(\frac{R}{fp}\right)\frac{\partial T}{\partial y} \tag{1}$$

where u is the zonal wind, p is the pressure, R is the gas constant, f is the Coriolis parameter, and T is the air temperature.

Further analysis on local temperature tendencies in the key region are performed using the first law of thermodynamics (Holton, 2004):

$$\left(\frac{\partial T}{\partial t}\right)' = \left(-\vec{V}\cdot\nabla \mathrm{T}\right)' - \left(\omega\left(\frac{\partial T}{\partial p} - \frac{R}{C_p}\frac{T}{P}\right)\right)' + \left(\frac{1}{C_p}\frac{dQ}{dt}\right)' \tag{2}$$

Among these variables, the left term, $\left(\frac{\partial T}{\partial t}\right)'$, is the local temperature tendency. The first item on the right side of the equation, $(-\vec{V}\cdot\nabla T)'$, is the horizontal temperature advection. The second item on the right side of the equation, $-\left(\omega\left(\frac{\partial T}{\partial p} - \frac{R}{C_p}\frac{T}{P}\right)\right)'$, is adiabatic