Stationary Wave Activity Associated with the East Asian Winter Monsoon Pathway

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Abstract The pathway of the East Asian winter monsoon (EAWM) that usually leads to the out-of-phase pattern of surface air temperature between northern and southern East Asia is an important feature in the variability of the EAWM besides its strength. Using the European Centre for Medium-Range Weather Forecasts 40-year (ERA40) reanalysis dataset, this study investigates the pathway-related stationary wave activity to explore the mechanism of the interannual variations in the EAWM pathway. It reveals that when the southern pathway of the EAWM is strong, the phase of the climatological stationary wave tends to be shifted westward significantly in both the horizontal and vertical directions by an anomalous wavenumber 2 pattern at mid-latitudes, whereas the changes are relatively small in the subtropics. The horizontal changes in the stationary wave phase facilitate a north-south-oriented East Asian trough in the middle troposphere that eventually produces the strong southern pathway of the EAWM. The vertical changes in the stationary wave, in contrast, feature a westward-tilted phase line with height over the North Pacific, indicating enhanced upward propagation of waves into the stratosphere. This result suggests that the phase of stationary waves at mid-latitudes dominate the interannual variations in the EAWM pathway. Moreover, it supports our previous interpretation of the possible role of the North Pacific sea surface temperature (SST) in the EAWM pathway variability. It also implies that the excitation of anomalous mid-latitude stationary waves may be the key in the response of the EAWM pathway to the North Pacific SST.

Keywords: East Asian winter monsoon, pathway, stationary wave, phase


1 Introduction

The East Asian winter monsoon (EAWM) is a distinct and active component of the global climate system. It dominates the wintertime weather and climate of East Asia and significantly influences human lives there (Chang et al., 2006; Huang et al., 2012; Wang and Lu, 2013). Among the many aspects of the EAWM, its strength is possibly the most interesting to both researchers and weather forecasters because a strong EAWM is usually associated with damaging snowstorms or low temperatures, whereas a weak EAWM is not. The consensus is that the seasonal mean surface air temperature is below (above) normal over most parts of East Asia in strong (weak) EAWM winters. This may be why so many indices have been proposed to reveal the variability in and mechanism of the strength of the EAWM (Wang and Chen, 2010).

Despite the importance of the strength of the EAWM in the East Asian winter climate, it has been noticed that the EAWM also varies in other important characteristics in addition to the strength, as observed in both the circulation (Wu et al., 2006; Wang et al., 2009) and temperature (Kang et al., 2006, 2009; Wang et al., 2010) fields. For example, Kang et al. (2006, 2009) proposed for the first time that the winter mean surface air temperature in China is characterized by two major modes on both interannual and interdecadal timescales on the basis of observational data from 160 Chinese stations. The first leading mode reflects the variability of the surface air temperature in all of China, and it is related to the strength of the EAWM. The second leading mode, in contrast, describes an oscillation of the surface air temperature between the northern and southern parts of China (“oscillation mode” hereafter). Two similar modes were also obtained by analyzing reanalysis data in a larger domain over East Asia (Wang et al., 2010; Sohn et al., 2011). Although the oscillation mode explains a smaller variance than the first leading mode does, its effect could be important during certain years. For example, the 2007/08 winter featured a weak EAWM, but the southern part of China experienced severe and persistent snowstorms and freezing weather, with higher temperatures in the northern part of China (Wen et al., 2009; Zhou et al., 2009). This temperature pattern resembles the oscillation mode and suggests that it is important to explore the related mechanism.

Recently, Wang et al. (2009) proposed the concept of the EAWM pathway in the winter mean sense and suggested that the variations in the EAWM pathway could lead to out-of-phase oscillations of surface air temperature between northern and southern East Asia. When the southern pathway is strong, the main cold air flow is along the coast of China and penetrates into the deep tropics. Accordingly, significant cooling is observed in southern China, the South China Sea, and Southeast Asia, whereas warming is observed in the northern part of East Asia (Wang et al., 2009). The climate anomalies approximately reverse signs when the eastern pathway is strong. This pattern resembles the oscillation mode, and it suggests that the latter could be accounted for in part by the variations in the EAWM pathway. Furthermore, Wang
et al. (2009) suggested that the EAWM pathway may be caused by the horizontal tilt of the East Asian trough, a quasi-stationary trough in the middle troposphere. Their results imply an active role of the stationary waves in the variations in the EAWM pathway and suggest the need to analyze the associated stationary wave activities. However, analyses of this aspect were not performed in Wang et al. (2009). Hence, in this study we will briefly delineate the three-dimensional stationary wave activities associated with the interannual variations in the EAWM pathway.

2 Data and methods

The data used in this study are from the European Centre for Medium-Range Weather Forecasts 40-year (ERA40) monthly mean reanalysis dataset. It has a $2.5^\circ \times 2.5^\circ$ horizontal resolution and extends from 1900 to 1 hPa with 23 vertical pressure levels, spanning 45 years from September 1957 to August 2002 (Uppala et al., 2005). Seasonal means are considered throughout this paper; they are constructed from the monthly means by averaging the data for December, January, and February (DJF), yielding results for 45 winters (1957–2001). Here the winter of 1957 refers to the 1957/58 winter.

The interannual variations in the EAWM pathway are determined by the trough axis index (TAI) proposed in Wang et al. (2009). It is defined as the normalized time series of the second principal component via empirical orthogonal function analysis of the normalized winter mean 500-hPa geopotential height in the region (25–50$^\circ$N, 100–180$^\circ$E). Using the criterion of $\pm 0.5$ standard deviations, 15 (15) high- (low-) TAI winters are selected (Table 1), consistent with Wang et al. (2009). The winters with high- (low-) TAI correspond to strong southern (eastern) EAWM pathway (Wang et al., 2009). In this study, we focus on the composite difference between high- and low- TAI winters. The significance of the results is evaluated with the two-sided Student’s t-test.

Table 1 High- and low-TAI winters used in this study.

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<tr>
<th>Year</th>
<th>High TAI</th>
<th>Low TAI</th>
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As a diagnostic tool, the three-dimensional Eliassen-Palm (EP) flux defined by Plumb (1985) is used to indicate the stationary wave activities associated with the EAWM pathway. The quasi-geostrophic version of the EP flux in spherical geometry with a log-pressure vertical coordinate is defined as follows:

$$F_x = \left( \frac{F_x}{F_y} \right) = \frac{p \cos \phi \left\{ \begin{array}{l} \frac{1}{2a^2 \cos^2 \phi} \left[ \left( \frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi'' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] \\
\frac{1}{2a^2 \sin^2 \phi} \left[ \frac{\psi'}{\partial \phi} \frac{\partial \psi'}{\partial \phi} - \psi'' \frac{\partial^2 \psi'}{\partial \phi^2} \right] \\
\frac{2\Omega^2 \sin^2 \phi}{N^2 a \cos \phi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial z} - \psi'' \frac{\partial^2 \psi'}{\partial \lambda \partial z} \right] \end{array} \right\}}{p \cos \phi},$$

where $F_x$, $F_y$, and $F_z$ denote the longitudinal, latitudinal, and vertical components of the EP flux, respectively, and $p$, $a$, $\Omega$, $\lambda$, $\phi$, $z$, $\psi'$, and $N$ denote the pressure, radius of the earth, rotation rate of the earth, longitude, latitude, log-pressure vertical coordinate, perturbed quasi-geostrophic stream function, and buoyancy frequency, respectively.

3 Results

Figure 1a shows the composite difference in the 500-hPa geopotential height (H500) between high- and low- TAI winters, which features a Eurasian (EU)-like pattern and Pacific-North America (PNA)-like pattern (Wallace and Gutzler, 1981) over Eurasia and North America respectively. The associated dipole over the North Pacific is almost identical to those in the high- and low- TAI phases except for the polarity (Figs. 6b and 8b of Wang et al., 2009), implying that it is reasonable to apply quasi-linear analysis to the variability of the EAWM pathway. The strong positive center around the Aleutian Islands strengthens the climatological ridge over Northwest America and weakens the climatological trough over East Asia, hence shifting the mid-latitude (40–70$^\circ$N) horizontal quasi-stationary trough-ridge system westward in the East Asia-North Pacific region. At subtropical latitudes (15–35$^\circ$N), in contrast, the negative H500 anomalies along the coasts of East Asia tend to enhance the climatological trough, although the changes in H500 are relatively small and not easily recognized solely from Fig. 1a. This configuration indicates a horizontal westward shift of the stationary wave phases in the middle troposphere, especially at mid-latitudes. It facilitates a more north-south oriented East Asian trough at 500-hPa (i.e., high TAI), which in turn leads to a warm north-cold south temperature pattern (i.e., a strong southern EAWM pathway, Wang et al., 2009) by steering cold air equatorward to the southern part of East Asia.

To further delineate the three-dimensional characteristics of stationary waves associated with the variability of the EAWM pathway, two vertical profiles are plotted along 50$^\circ$N and 25$^\circ$N (Figs. 1b and 1c, respectively). At 50$^\circ$N, both the climatological and the anomalous stationary waves feature clear wavenumber 2 structures (Fig. 1b). The anomalous troughs and ridges are located west of their climatological mean locations, indicating a $\sim 90^\circ$ westward shift of the climatological stationary waves. This suggests that the variability of the EAWM pathway is associated with significant changes in the phase of the stationary waves in both the horizontal and vertical directions. In addition, we notice that the anomalous ridge over the North Pacific tilts westward with height from near the surface into the lower stratosphere, whereas the other anomalous ridges and troughs are almost barotropic (Fig. 1b). The vertically westward tilt of the wave structure corresponds to a poleward eddy heat flux; hence, the anomalous tilted ridge over the North Pacific indicates enhanced upward propagation of stationary waves in this region.
Figure 1 (a) Composite difference (shading) of winter (December, January, and February (DJF)) mean 500-hPa geopotential height between high- and low-TAI years overlaid on the climatology of 500-hPa geopotential height (contours). Composite difference (shading) of winter (DJF) mean geopotential height between high- and low-TAI years overlaid on the climatology of geopotential height departures from zonal means (contours) at (b) 50°N and (c) 25°N. Contour and shading intervals are 50 gpm and 20 gpm, respectively. Zero contour lines are bold. Stippling indicates at the 95% confidence level.

The climatological stationary waves at 25°N also feature a wavenumber 2 pattern (Fig. 1c), similar to that at 50°N (Fig. 1b) but with a 180° phase difference. The amplitude at 25°N, in contrast, is at least 50% smaller than that at 50°N. Accompanying the enhanced southern EAWM pathway, the geopotential height anomalies at 25°N are negative over most longitudes except the North American longitude (Fig. 1c). This anomalous wavenumber 1 pattern is equivalent-barotropic and is mainly confined below 50-hPa. From the vertical profile, it is evident that the anomalous stationary wave enhances its mid-tropospheric climatological trough at the longitude of the East Asian coast (around 120°E) and weakens its climatological ridge over the North Pacific. The former clarifies the related analysis on Fig. 1a and suggests that the horizontal tilt of the mid-tropospheric East Asian trough is induced mainly by the changes in mid-latitude (e.g., 50°N) stationary waves.

The EP flux is a convenient and useful tool in stationary-wave-related diagnostics because it is parallel to the group velocity (Plumb, 1985). Figure 2 shows the three-dimensional EP flux associated with the variability of the EAWM pathway at different pressure levels. The most dominant feature is the upward and northeastward propagation of stationary waves around the North Pacific when the southern pathway of the EAWM is strong. The upward propagation of stationary waves is observed mainly from the Sea of Okhotsk to northern North America (Fig. 2), consistent with the analysis of Fig. 1b. Moreover, it is noteworthy that Wang et al. (2009) suggested that the interannual variability of the EAWM pathway is driven by the North Pacific sea surface temperature (SST) anomalies. Here the enhanced upward propagation of stationary waves is observed just to the north of the SST anomalies indicated by Wang et al. (2009). This suggests that the response of the stationary waves is the likely mechanism by which the North Pacific SST influences the EAWM pathway.

4 Summary and discussions

Using the ERA40 reanalysis dataset, this study investigates the three-dimensional activity of stationary waves associated with the interannual variations in the EAWM pathway. It reveals that when the southern EAWM pathway is strong, the 500-hPa geopotential height field features a combination of EU-like and PNA-like anomalies. The anomalous stationary waves take on a wavenumber 2 pattern at mid-latitudes, which shifts the climatological stationary waves westward over the East Asia-North Pacific region. In the subtropics, in contrast, the anomalous stationary waves feature a wavenumber 1 pattern, which deepens the climatological East Asian trough and weakens the climatological North Pacific ridge in the tropo-
sphere. Accordingly, the horizontal East Asian trough axis is oriented more in the north-south direction, which in turn leads to a warm north-cold south temperature pattern by steering cold air equatorward to the southern part of East Asia. In this process, the mid-latitude stationary waves are the dominant contributor to the changes in the tilt of the East Asian trough.

Inspections of the vertical profiles at different latitudes suggest that the anomalous stationary waves feature a clear westward tilt with height at mid-latitudes (e.g., at 50°N). This configuration shifts the climatological stationary waves westward and facilitates more upward propagation of waves into the stratosphere. The diagnostics of the three-dimensional EP flux confirms this interpretation. It further indicates that the associated upward propagation of anomalous stationary waves occurs mainly in the region stretching from the Sea of Okhotsk to northern North America, just to the north of the SST anomalies indicated by Wang et al. (2009). Hence, it confirms the argument of Wang et al. (2009) that the North Pacific SST is the likely driver for the interannual variability in the EAWM pathway. Moreover, it suggests that the responses of the stationary waves may be the key process by which the North Pacific SST influences the EAWM pathway.

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References