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Impact of East Asian winter monsoon on the Pacific storm track

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ABSTRACT: The storm track plays an important role in modulating the variability of atmosphere circulations such as day-to-day weather variability and teleconnection patterns. The variation in amplitude of the storm track is usually related to the midlatitude basic flow. Recent studies show that a strong (weak) East Asian winter monsoon (EAWM) and weak (strong) synoptic eddy activity lead to the weakening (enhancement) of the Pacific storm track. Two empirical orthogonal function (EOF) modes of the EAWM were identified recently. However, their different impacts on the position and intensity of the Pacific storm track are not clear. Based on the ECMWF 40 Year Re-analysis (ERA40) data, the different responses of the Pacific storm track to these two EOF modes of EAWM are investigated in this study. The results imply that the first EOF mode (i.e., the northern mode) of EAWM, characterized by a northward-shifted westerly jet tends to lead to a northward shift of the Pacific storm track. The second EOF mode (i.e., the southern mode) of EAWM, featured by a more southward located westerly jet stream, tends to cause a southward shift of the Pacific storm track. Moreover, the amplitude of the Pacific storm track associated with the southern mode is considerably weaker than the amplitude associated with the northern mode. It is also demonstrated that the westerly jet associated with the EAWM may play an important role in transporting the upstream synoptic waves to the Pacific Ocean and contributing to the development of the Pacific storm track.

KEY WORDS storm track; monsoon; EAWM

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1. Introduction

Teleconnection patterns play an important role in influencing the climate and weather variability. Numerous studies have investigated the mechanisms responsible for teleconnection patterns since the last century, but the formation mechanisms are still subject to debate (Bliss and Walker, 1932; Lorenz, 1951; Hoskins and Karoly, 1981; Lau, 1988; Rodwell *et al.*, 1999). Some studies show that boundary forcing (for example, sea surface temperature (SST) anomalies, topography) can yield low frequency variability of the atmospheric circulation and generate teleconnection patterns such as the Pacific-North American (PNA) and the North Atlantic Oscillation (NAO) (Horel and Wallace, 1981; Wallace and Gutzler, 1981; Held *et al.*, 1989; Czaja and Frankignoul, 1999; Rodwell *et al.*, 1999) but such conclusions are still questioned (e.g., Frankignoul, 1985; Robinson, 2000). Other studies have pointed out that the fundamental cause of teleconnection patterns is an internal dynamic process of the atmosphere (Lau, 1981, 1988; James and James, 1989; Cai and Mak, 1990; Robinson, 1991; Branstator, 1992, 1995; Feldstein, 1998, 2003; Song *et al.*, 2011). Lau (1988) first demonstrated that the teleconnection patterns, such as the PNA and Eastern Atlantic pattern (EA), are accompanied by a meridional shift of the storm track (defined as the regions with preferred synoptic eddy activity). Such a conclusion is corroborated by some subsequent modelling and observational studies (e.g., Branstator, 1992, 1995; Song *et al.*, 2011). Jin (2010) showed that the energy needed for the growth of teleconnection patterns comes from the background storm track activity. This appears to play a very important role in modulating the teleconnection patterns.

The middle latitudes atmosphere is baroclinicity unstable due to the north–south contrast of radiative heating. This instability is considered to be the most important factor in generating synoptic eddies and storm tracks (Charney, 1947; Eady, 1949). However, Nakamura *et al.* (2002) found that the interannual variations of storm track intensity do not always follow the variations of baroclinic instability. Many studies about the suppression of the winter storm track have focused on the upstream effects induced by the winter monsoon (Orlanski, 2005; Robinson *et al.*, 2006). Interaction between the winter monsoon and the upper level jet stream is thus of particular interest (Zhang *et al.*, 2006). Nakamura (1992) detected an out of phase relationship between the Pacific storm track and the upstream jet, where the jet stream is defined by intense wind at upper troposphere with speed exceeding 40 m s^{-1}. When the strength of the winter upper tropospheric jet exceeds 45 m s^{-1}, the baroclinic wave activity is suppressed over the storm track region and the jet strength shows a negative correlation with the strength of the storm track. Harnik and Chang (2004) found that a narrower and faster jet stream always enhances the group velocity and reduces the eddy activity along the jet, which leads to a further suppression of the downstream storm track in winter (December, January and February, DJF). According to the evolution of Rossby wave packets, Robinson *et al.* (2006) emphasized that downstream changes of the Pacific storm track are likely related to the

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intraseasonal variations of the East Asian winter monsoon (EAWM). These synoptic waves traverse East Asia through the upper level jet and 'seed' the Pacific storm track (Robinson *et al.*, 2006). Hereafter, this is referred to as the 'upstream seeding effect'.

Different methods have been used to measure the intensity of the EAWM. Most previous studies adopted direct circulation variables (e.g., zonal wind, sea surface pressure) to estimate the strength of the EAWM (Wen *et al.*, 2000; Gong *et al.*, 2001; Jhun and Lee, 2004). Jhun and Lee (2004) (hereafter referred to as JL2004) defined the EAWM index as the difference in area-averaged zonal wind between the boxed regions 27.5–37.5 °N, 110–170 °E and 50–60 °N, 80–140 °E at 300 hPa. However, the EAWM can also be characterized by strong northerly winds that transport intense cold air from high latitudes to low latitudes, resulting in a sudden change of air temperature, snow and rainfall over East Asia (Gong *et al.*, 2001; Jhun and Lee, 2004; Wang *et al.*, 2010). Using empirical orthogonal function (EOF) analysis of the 2 m air temperature, Wang *et al.* (2010) found that there are two distinct modes of variability over East Asia in winter. However, the two EAWM modes are generated by different circulations and are independent. The first EOF mode shows a northern mode featured by uniform cooling throughout the whole East Asian continent. The second EOF mode indicates a southern mode with opposite sign temperature changes between southern and northern East Asia. Northerly wind can penetrate further south during the southern mode than during the northern mode (Wang *et al.*, 2010). Since most of the previous studies adopt direct circulation variables to estimate the EAWM, only one kind of the EAWM was discussed in their studies (Wen *et al.*, 2000; Jhun and Lee, 2004). However, the difference between the circulation variables defined the EAWM index (i.e., JL2004) and the two main EAWM statistical modes (Wang *et al.*, 2010) have never been investigated.

In this study the impacts of the EAWM on the storm track over the Pacific Ocean are investigated, based on the two statistical EAWM modes. The purpose of this study is to demonstrate whether either or both of these modes of the EAWM can influence the Pacific storm track. The paper is organized as follows. Data and methods are introduced in Section 2. In Section 3, the linkage between the EAWM and the upper level jet stream will be discussed. The relationship between the jet stream, the winter monsoon modes and the storm track is then derived. Conclusions and discussions are given in Section 4.

2. Data and methods

The analysis in this study uses the 40 year European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data (ERA40) for the period from 1957 to 2002 (Uppala *et al.*, 2005). The daily mean zonal and meridional winds are band-pass filtered with a period of 2–8 days using a Lanczos filter with 41 weights following Duchon (1979) to extract the synoptic-eddy component. To describe the intensity of the synoptic eddy activity over the storm track region, the variance of the daily mean eddy meridional wind at 300 hPa for each winter season (i.e., December, January and February) is used. The winter monsoon index of Wang *et al.* (2010) is chosen to quantify the intensity of the EAWM. In order to investigate the different responses of two EAWM modes, linear regression is applied using the principal component (PC) time series.

3. Results

3.1. Overview of two East Asian winter monsoon modes

During the EAWM, strong northerly winds bring intense cold air from high to low latitudes. The onset of the EAWM and its subsequent propagation are often characterized by a decrease in surface temperature. Wang *et al.* (2010) chose 2 m air temperatures as an index and identified two leading modes of variability for the EAWM, which are referred to as the northern mode and the southern mode. These two distinct modes are independent from each other. To investigate the two EAWM modes further, the relationship between the EOF modes with the circulation variable defined index (for instance, JL2004 EAWM index) is examined first (Figure 1). The second PC (southern mode) is highly correlated with the JL2004 EAWM index ($r = 0.54$, statistical significant above 99%). In contrast, the PC1 (northern mode) and the JL2004 EAWM index are not well correlated ($r = 0.23$, as shown in Figure 1). This indicates that the southern mode is more closely related to the EAWM index discussed in prior studies (i.e. Jhun and Lee, 2004). Since most EAWM indices are based on the definition of a specified domain averaged zonal wind, they only identify one type of EWAM mode variability. The first EOF mode (northern mode) is not captured in the study by JL2004.

In general, the jet stream is closely related to the EAWM. In order to identify the different responses of the jet stream and the associated air temperatures during the two EAWM modes, linear regressions of the zonal wind with respect to the air temperatures were applied on the PC time series of the two modes. It is evident that low level air temperatures (from 1000 to 400 hPa) represent the two EAWM modes well (Figure 2), consistent with 2 m air temperatures in Wang *et al.* (2010). The apparent difference between two modes is that westerly anomalies in conjunction with low level cold air mass spreads further south during the southern mode than during the northern mode. The air temperatures show an opposite sign between aloft and underneath in both modes. Moreover, the northern mode exhibits a meridional dipolar structure, yet the southern mode represents a tripolar distribution of the zonal wind anomalies over 20–80 °N. The maxima of the southmost westerly anomalies (referred to as the jet stream core) of both modes are located at the upper level at about 300 hPa.

3.2. Two East Asian winter monsoon modes with associated jet stream and circulation anomalies

As shown in the previous section, the two EAWM modes can be distinguished. The associated zonal winds and the low level cold air mass tend to extend further south during the southern mode than during the northern mode. Furthermore, the interannual variability of each mode originates from different systems. An anomalous cyclonic circulation at 300 hPa over Siberia–Mongolia (45–55 °N, 90–120 °E) relative to the climatological flow is found during the northern mode (Figure 3(b)) whereas the southern mode is characterized by anomalous anticyclonic circulation associated with the Mongolian high (60 °N, 102 °E) and the Okhotsk high (60 °N, 150 °E), as well as anomalous cyclonic circulation related to the mid-Pacific low (30–40 °N, 120–150 °W, as shown in Figure 3(c)) at the 300 hPa level.

As mentioned in previous studies, the EAWM is closely related to the upper level jet stream, it modulates the large-scale circulation not only over East Asia, but also over the North Pacific. The westerly anomalies arise from the anomalous

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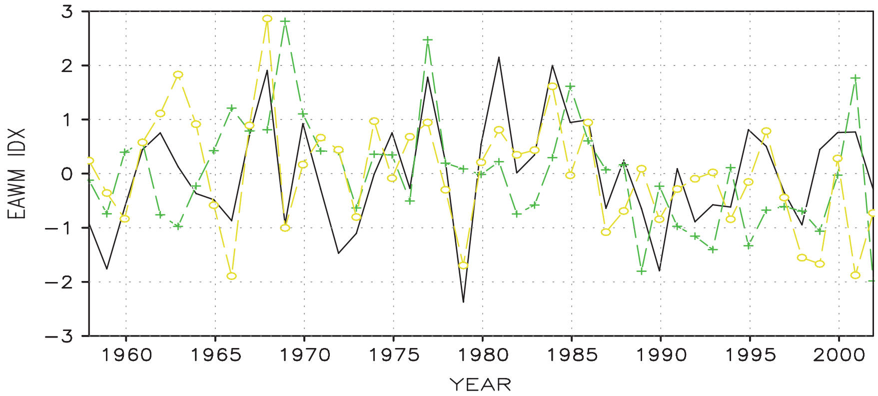

Figure 1. Normalized principal component time series for the first (dotted line, marked as a cross) and second EOF modes (dotted line, marked as a circle) for the winter mean 2 m air temperatures, as well as the normalized JL2004 EAWM index (solid line) defined by zonal wind at 300 hPa. This figure is available in colour online at wileyonlinelibrary.com/journal/met

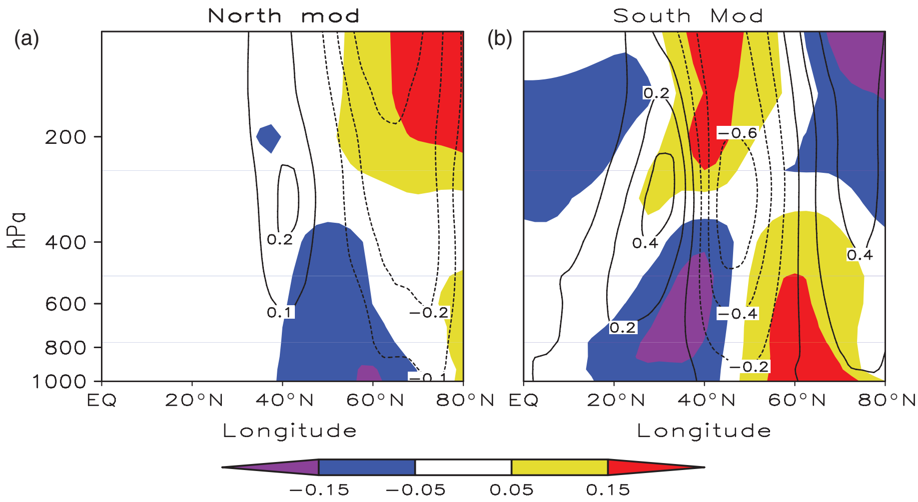

Figure 2. Height-latitude cross sections of the zonal wind (contour) and temperature anomalies (shading) over 45 winters from 1957/1958 to 2001/2002. (a) Regressed on the northern mode (contour interval is 0.1). (b) Regressed on the southern mode (contour interval is 0.2). Zonal wind and air temperature are calculated by zonal average of EAWM area coverage extending from 100 $^\circ$ E to 140 $^\circ$ E. This figure is available in colour online at wileyonlinelibrary.com/journal/met

cyclonic circulation due to the northern mode (Figure 3(b)), which may favour the transport of cold air mass and synoptic waves from high-latitude Russia toward northeast Asia. During the southern mode, the westerly jet anomalies generated by the elongated cyclonic anomalies can extend toward the middle Pacific Ocean. Moreover, the westerly anomalies associated with the southern mode can penetrate further south than those during the northern mode. Thus, the two EAWM modes both reflect the variability of the westerly jet stream well. Since synoptic eddies migrate along the westerly flow, the westerly jet stream is conductive to the enhancement of the downstream storm track (Robinson *et al.*, 2006; Lee *et al.*, 2010). It is expected that the downstream Pacific storm activity has a different response to the EAWM induced anomalous jet stream.

3.3. Upstream jet with downstream synoptic eddy activity

As first identified by Nakamura (1992), the upstream disturbances play an important role in suppressing the storminess over the western Pacific. Some previous studies have also shown that the storm track activity over the Pacific Ocean is primarily generated by synoptic waves that originated from northeast Asia. The 'seeds' traverse Asia through a waveguide provided by the jet stream (Nakamura, 1992; Hakim, 2003), and influence the downstream storm track. To investigate the linkage between the jet stream with respect to the EAWM and the downstream synoptic eddy activity further, a linear regression analysis of the respective EAWM PC time series was applied.

Figure 4(a) displays the climatological mean jet stream position and the Pacific storm track. The westerly jet is meridionally narrower and zonally elongated from East Asia to the northwest Pacific during the winter. Furthermore, the location of the westerly jet core ranges from 130 to 160 $^\circ$ E around the Sea of Japan. Moreover, the significant storm track activity is located downstream of the westerly jet, which is zonally extended to the entire north Pacific region. Still, the zonal axis of the Pacific storm track is located 5° north over the jet stream. Relative to the climatological jet stream location, during the northern mode (Figure 4(b)), the notable westerly anomalies are located at the middle latitudes (28–50 $^\circ$ N) and the easterly anomalies are on the equator (0–28 $^\circ$ N) and polar (50–80 $^\circ$ N) side. The striking feature of the storm track activity is the enhancement (suppression) at the middle (low/high) latitudes, which

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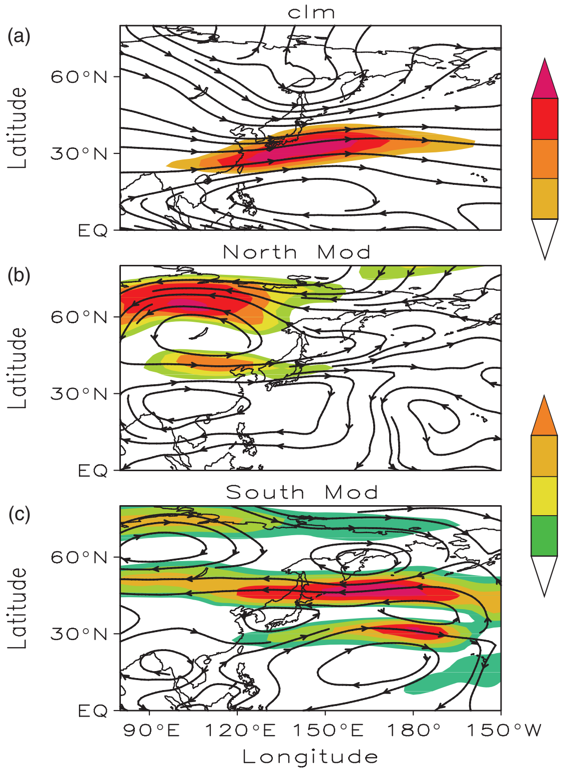

Figure 3. Stream field at 300 hPa (contours with arrow, unit: $m\,s^{-1}$), the climatological jet stream is characterized by wind speeds larger than 40 $m\,s^{-1}$ and the regressed anomalous jet is featured by the wind speeds exceed 0.15 (shaded). (a) Climatological winter mean; (b) Regressed on the northern mode; (c) Regressed on the southern mode. This figure is available in colour online at wileyonlinelibrary.com/journal/met

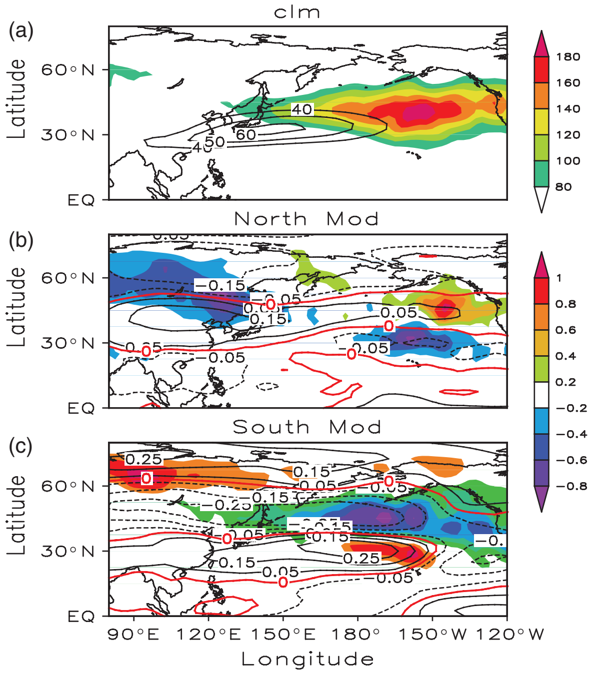

Figure 4. The 300 hPa zonal wind (contours, unit: $m\,s^{-1}$) and the Pacific storm track (represented as the variance of the 300 hPa meridional wind perturbations, shaded, unit: $m^2\,s^{-2}$). (a) Climatological winter mean; (b) Regressed on the northern mode; (c) Regressed on the southern mode. This figure is available in colour online at wileyonlinelibrary.com/journal/met

coexists with the jet stream anomaly. The westerly (easterly) anomalies seem to be responsible for the downstream intensified (relaxed) storm track, resulting in a northward-shifted (southward-shifted) storm track. On the other hand, during the southern mode, the zonal wind anomalies indicate an opposite sign change between southern and northern East Asia. The further southward penetration of the EAWM causes the jet stream to shift southward and leads to a meridionally tripolar pattern of the zonal wind anomalies. As mentioned above, the anomalous westerly flow favours the transport of synoptic waves toward the downstream storm track area. In consequence, the downstream storm track is enhanced (weakened) in the southern (northern) part. Furthermore, the westerly anomalies are weaker than the easterly anomalies, which may result in the amplitude of the Pacific storm track being weaker than that of the climatological mean. Therefore, the Pacific storm track is suppressed and moves southward. These conclusions are in good agreement with previous studies (i.e., Nakamura, 1992).

3.4. Role of local baroclinicity

In order to investigate the upstream seeding effect of the two EAWM modes on the Pacific storm track further, the Eady growth rate, which is regarded as an indicator of baroclinicity, was calculated. Since synoptic eddies are created by baroclinic instability (Eady, 1949), the Eady growth rate can represent the activity of the synoptic eddies. The growth rate is defined as the following formula:

$$\sigma = 0.31\left(\frac{f}{N}\right)\mathrm{d}U/\mathrm{d}z, \qquad (1)$$

where f denotes the Coriolis parameter, N and U are respectively the Brunt–Väisälä frequency and the wind speed, N takes the form of $\rho^{1/2}g\left[\frac{1}{\theta}\frac{\partial\theta}{\partial p}\right]^{1/2}$.

Figure 5(a) shows the climatological mean of the Eady growth rate. The region of positive Eady growth rate ranges from the southern part of East Asia (25 °N, 80 °E) to the middle Pacific ocean (25 °N, 180 °E), which is also collocated with the jet stream core (Figure 4(a)). The maximum growth rate centres in south China (25 °N, 110 °E), corresponds to the eastern edge of the jet stream. Therefore, it is concluded that synoptic eddies seem originate from the jet stream over East Asia and spread toward the Pacific Ocean. During the northern mode (Figure 5(b)), the baroclinicity is enhanced in the northern part of the climatological mean. It implies that synoptic eddy activity over the jet stream shifts poleward and propagates eastward along the westerly jet stream to the storm track area. However, during the southern mode (Figure 5(c)), the baroclinicity is intensified at the southern part of its climatological mean, resulting in the associated synoptic eddy activity over the storm track downstream shifts southward. Therefore, it may be concluded that the seeds which contribute to the development of the downstream Pacific storm track originate from the upstream jet over East Asia, close to the location of the southern edge of the EAWM. Furthermore, model output from Orlanski (2005) mimicked a clear physical process of the synoptic eddy seeding, with large amplitude eddies arriving downstream a few days later and contributing to enhance the downstream synoptic eddy development. The results of the present study show good

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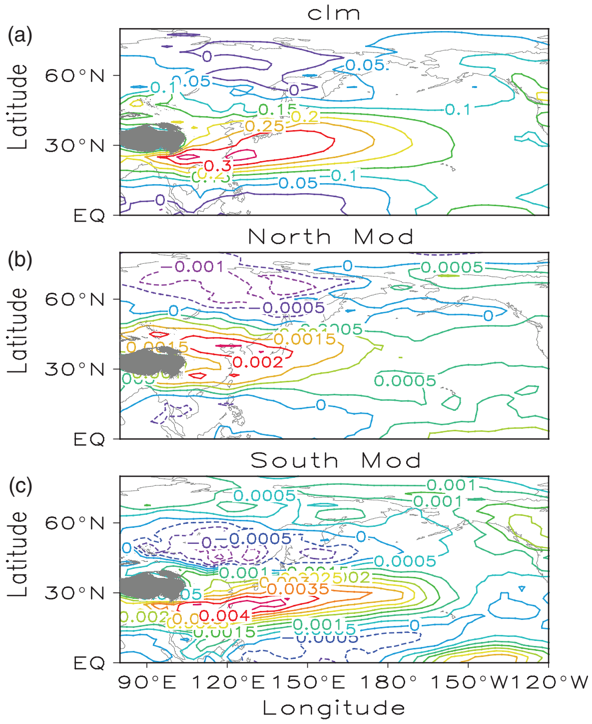

Figure 5. The Eady growth rate (unit: 1 day^{-1}) in (a) climatological winter mean; (b) regressed on the northern mode and (c) the southern mode of EAWM. The Tibetan plateau below 700 hPa is shaded. This figure is available in colour online at wileyonlinelibrary.com/journal/met

agreement with these simulations. In conclusion, the EWAM and associated jet stream anomalies play an important role as a 'seedbed' to generate synoptic waves. Moreover, these synoptic eddies may traverse East Asia through the upper level westerly jet and influence the downstream storm track activity. Therefore, the variation of the downstream Pacific storm track is very closely linked to the EAWM variability.

4. Discussion and conclusions

Based on EOF analysis of 2 m air temperature during winter season (DJF), Wang *et al.* (2010) identified two EAWM modes (i.e. the northern mode and the southern mode). The southern mode is characterized by zonal winds and a low level cold air mass which penetrate further south than during the northern mode. Comparing Wang's EAWM index with that defined by direct circulation variables (for instance, JL2004), it was found that the southern mode is in good agreement with the JL2004 EAWM index and the northern mode is nearly neglected by previous studies.

Although there is still no conclusive evidence for explaining what mechanism dominantly causes the different responses of the downstream storm track to the two EAWM modes, results suggest that the stronger temperature gradient associated with a southward movement of cold air concentrates on the front of the EAWM, which leads to enhanced baroclinicity instability closer to the entrance region of the jet stream. Therefore, the disturbances propagate along the 'waveguide' provided by the westerly jet and contribute to the downstream storm track variability. Analysis also shows that during the northern mode, the westerly (easterly) anomalous jet is located in the northern (southern) part of the climatological mean region. This leads to enhanced (suppressed) synoptic eddy activities in the westerly (easterly) anomalous jet. Furthermore, the propagation of the high (low) baroclinicity along the westerly (easterly) anomalies results in the northward shift of the Pacific storm track. In contrast, during the southern mode, the further southward penetration of the jet stream leads to a southward shift of the Pacific storm track. Therefore, the downstream Pacific storm track variability is highly correlated with the upstream EAWM and the associated jet stream. Additionally, these results are in good agreement with prior studies (Nakamura, 1992; Nakamura *et al.*, 2002; Robinson *et al.*, 2006) which showed that the primary mechanism for generating the Pacific storm track can be recognized as an upstream seeding effect over East Asia. The disturbances travel to the Pacific Ocean though the westerly jet stream waveguide associated with the EAWM.

In this study, it was found that the location and the intensity of the Pacific storm track vary with the different winter monsoon modes of variability. It has been well known that synoptic eddy activity varies with the basic jet location and that a weakening of synoptic eddy activity occurs when the jet stream is located at lower latitudes (Simmons and Hoskins, 1977; Rivière, 2009). It is conjectured that the jet stream reaches further south during the southern mode of the EAWM, and it seems that the synoptic waves embedded in the associated jet stream can be suppressed. Therefore, the intensity of the Pacific storm track associated with the southern mode is considerably weaker than that associated with the northern mode, but it is not clear what mechanism causes the prominent variation of the Pacific storm track locations. This issue needs to be addressed in more detail in future work.

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