Zonal shift in the cold airmass stream of the East Asian winter monsoon

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Abstract
The East Asian winter monsoon (EAWM) exhibits long-term variations in intensity and spatial pattern, though the latter one is less understood. To investigate the long-term spatial variations of the EAWM and their possible causes, we propose a new position index of the EAWM by quantifying the low-level East Asian stream (EAS) of cold airmass in the Lagrangian sense. Based on the new-defined index, we find that the EAS undergoes an evident zonal shift between two channels over the land and coast. At interdecadal timescale, the peak location of the EAS is displaced eastward, with an increasing southward cold airmass flux at the coast since the mid-1960s. The interannual shift of the EAS presents not only the zonal oscillation of peak location between two channels but also the width changes of coastal channel over the northwestern Pacific. These shifts in the EAS are related to the strength changes of two source cold airmass streams from Siberia or Bering Sea, which are associated with the phase changes in the upper-tropospheric atmospheric teleconnections. At interdecadal timescale, the phase change in the North Atlantic Oscillation modulates the zonal shift in the EAS via the East Atlantic-West Russia teleconnection. At interannual timescale, the Pacific/North American teleconnection becomes the dominant factor altering the zonal shift and width change of the EAS.

1. Introduction
The East Asian winter monsoon (EAWM) is recognized as an important component of the East Asia climate system, connecting the polar region with middle and low latitudes (Wang and Lu 2017). The long-term variation in the EAWM is one of the strongest climate variabilities in boreal winter and has a great impact on the regional climate/weather. Interannual variations, with periods of 2–4 and 6–8 years, are a major feature of the EAWM (Jhun and Lee 2004). Such variations are closely connected with the El Niño–Southern Oscillation (ENSO) and Arctic Oscillation (Zhang et al 1997, Gong et al 2001, Chen et al 2004, Chen et al 2013). On the other hand, the EAWM experienced decadal weakening in the late 1980s (Wang et al 2009a, Lee et al 2013, Ding et al 2014) and re-intensified after the early 2000s (Wang and Chen 2014a). This interdecadal weakening and recent strengthening of the EAWM are related to the weakened quasi-stationary planetary waves (Wang et al 2009a) and diminished Arctic sea ice concentration (Wang and Chen 2014a), respectively.

Previous studies have extensively investigated the variabilities in the intensity of the EAWM at various timescales (e.g. Kim et al 2014, Wang and Chen 2014b), while some studies suggested that the diversity in the spatial patterns of the EAWM can be another key aspect of the regional climate. Cold surges over East Asia usually have two types of pathways (called northern or southern routes), inducing different patterns of temperature anomalies (Wang et al 2009b, Song and Wu 2017, Yang et al 2020). The different pathways may be associated with the tilt of the East Asian trough, suggesting the diverse spatial pattern has a close relation with the large-scale circulation anomalies (Wang et al 2009b). The equatorward flux of cold air also has several different modes regarding their longitude ranges over East Asia (Park et al 2011, Abdillah et al 2017, 2021). When
the cold air penetrates through the inland (coast) region of middle-latitude East Asia, it tends to induce low-temperature anomalies mostly in southern China (northeastern Asia) (Liu et al 2021). The spatial pattern of precipitation in the tropical region also varies as the cold air pathway is changed. Therefore, an integrated measure of both intensity and spatial patterns of the EAWM are important for understanding the variabilities of regional/global climate.

To reveal the spatial variations in the EAWM, it calls for a quantitative measurement. Previous studies describe the EAWM in various perspectives including Siberian High, Aleutian Low, strong northerly wind, East Asian trough, and the upper-tropospheric jet (e.g. Sun and Li 1997, Jhun and Lee 2004, Kim et al 2014, Wang and Chen 2014b). In this study, we propose to use the East Asian cold airmass stream (EAS, Iwasaki et al 2014, Shoji et al 2014) to represent the EAWM. This is because the EAWM is mainly featured by frequently occurred cold air outbreaks, which is essentially the strong southward movement of cold airmass in middle and lower troposphere. As the low-level equatorward branch of monsoon meridional circulation, the EAS also can be seen as a member of EAWM. On the other hand, the EAS indicates the compositcd path and spatial range of cold air outbreaks (the most essential weather process of winter monsoon), which undertake the mass and heat exchanges between high and low latitudes in East Asia. Thus, we focus on the EAS rather than its driven systems such as Siberian High, Aleutian Low and East Asian trough.

Existing indices of the EAWM are usually defined by the atmospheric variables on a single pressure level within a fixed region, as summarized in Wang and Chen (2010). The definitions designed in the Eulerian sense are not convenient to describe the spatial changes of the EAS. To describe the changes of EAS more comprehensively, we need a new index that takes both the vertical structures and thermodynamic/dynamic features of cold airmass stream into account. Unlike most of the existing EAWM indices, the isentropic analysis of the EAS adopted in this paper provides an explicit estimation on both thermodynamic and dynamic features of cold airmass in the Lagrangian sense. Through quantifying the spatial changes of the EAS, this study aims to provide new insights into the variabilities of the EAWM. Recent studies have already shown the climatology of EAS intensity and its impacts on the climate and weather over downstream regions (Yamaguchi et al 2019, Abdillah et al 2021, Liu et al 2021). In this study, we mainly focus on the spatial pattern of the EAS and its long-term changes. By capturing the peak location and structure of the EAS, the spatial variation in the EAWM at different timescales can be estimated. The possible mechanisms modulating the spatial variation in the EAWM are also discussed.

2. Data and methods

The atmospheric variables used in this study are derived from the Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al 2015) during a period covering 59 winters (December, January and February) from 1958 to 2017. This dataset has a horizontal resolution of 1.25°, 37 vertical pressure levels and a time interval of 6 h. The JRA-55 has been shown to have good performance in analyzing the EAWM and cold airmass over East Asia (Kanno et al 2016, Liu and Zhu 2019, Liu et al 2021). The time series of atmospheric teleconnection indices and sea surface temperature (SST) indices are provided by the National Oceanic and Atmospheric Administration.

To quantitatively describe the EAS, we adopt an isentropic analysis method proposed by Iwasaki et al (2014). This method defines the cold airmass as an airmass layer under the threshold potential temperature ($\theta_T = 280$ K). The selection of $\theta_T = 280$ K is based on the analysis of mass stream function with mass-weighted isentropic zonal mean, so that most of the equatorward flow from polar regions are confined in the layer of cold airmass. Many previous studies have chosen 280 K as the threshold potential temperature (e.g. Kanno et al 2016, Abdillah et al 2017). The horizontal flux of cold airmass ($F$) can be calculated by the vertical integrals of the horizontal wind ($v$) and pressure ($p$) from $\theta_T$ surface ($p(\theta_T)$) to ground surface ($p_0$):

$$F = \int_{p(\theta_T)}^{p_0} v dp.$$  \hspace{1cm} (1)

In addition, the framework of cold airmass isentropic analysis used in this study provide many other parameters estimating the coldness, generation/loss and vertical structures of cold airmass stream. This method has been used to identify the EAS and to analyze its association with cold air outbreaks (Shoji et al 2014, Abdillah et al 2017).

3. Results

3.1. Spatial changes in the EAS

Figure 1(a) shows the climate-mean distribution of the cold airmass flux in East Asia. The horizontal flux of cold airmass is mainly characterized by a strong eastward flow from Siberia to northeastern Asia. In addition, a relatively weak westward cold airmass flow from the Bering Sea merges into the main eastward flow in northeastern Asia, where the cold airmass flux turns southeastward. The climatic mean southward component of cold airmass flux over northeastern Asia exceeds 1000 hPa m s$^{-1}$, which is much larger than zonal mean southward cold airmass flux (344 hPa m s$^{-1}$) between 40° N and 60° N (Shoji et al 2014, Liu et al 2021). Such a strong southward
stream of cold airmass (red vectors in figure 1(a)) basically represents the climatology feature of the EAWM in the middle and lower troposphere. Thus, the threshold for defining the EAS in this study is set to 1000 hPa m s\(^{-1}\).

Based on the recognition and quantification of the EAS, we could define its intensity index \(I_{\text{EAS}}\) as the average value of winter-mean southward cold airmass flux \(F_{-v}\) larger than 1000 hPa m s\(^{-1}\) over East Asia (70° E–180° E, 40° N–60° N):

\[
I_{\text{EAS}} = \frac{1}{n} \sum F_{-v}(\text{lon}, \text{lat}) |F_{-v}| > 1000, \tag{2}
\]

where \(n\) denotes the number of grids with winter-mean southward cold airmass flux larger than 1000 hPa m s\(^{-1}\). A previous study showed that the EAS may have three main modes with peaks at different longitudes (Abdillah et al. 2017). Therefore, the position index of the EAS \(P_{\text{EAS}}\) is defined as the longitude of cold airmass flux-weighted center of the EAS:

\[
P_{\text{EAS}} = \frac{\sum \text{lon} \cdot F_{-v}(\text{lon}, \text{lat}) |F_{-v}| > 1000}{\sum F_{-v}(\text{lon}, \text{lat}) |F_{-v}| > 1000}. \tag{3}
\]

The latitude weighting has been considered in the areal average of both two indices. With this newly
defined index, we could quantitatively describe the spatial change in the EAS in the Lagrangian sense.

Figures 1(b) and (c) illustrate the long-term variations in the intensity and position of the EAS, respectively. The intensity of the EAS ($I_{EAS}$) experienced a decrease since the mid-1960s and a slight increase from the mid-1990s to the mid-2000s (figure 1(b)). Such a long-term variation in $I_{EAS}$ basically matches the well-known interdecadal changes in the EAWM detected by various studies (Ding et al 2014, Chen et al 2019). For the position of the EAS ($P_{EAS}$), an interdecadal eastward shift from 126°E to 132°E was observed during the 1960s–2000s, after which it began to move westward in the early 2000s (figure 1(c)). Our recent study shows that the pathways of cold air outbreak events also experienced an interdecadal zonal shift, which is consistent with the spatial change of the EAS (Liu et al 2021). Based on the climatic mean $P_{EAS}$, the spatial pattern of the EAS can be divided into a western type and an eastern type. The EAS is dominated by the western type from 1958 to 1984 and then turns into the eastern type from 1985 to 2007. The $P_{EAS}$ also features clear interannual variations with a standard deviation of approximately 5.2°. Therefore, the EAS position exhibits obvious zonal shifts at both interdecadal and interannual timescales.

It should be emphasized that the above-mentioned climatological distribution of the EAS can be observed in other mainstream reanalysis datasets, including the ERA5 (fifth generation of European Centre for Medium-Range Weather Forecasts Reanalysis) and NCEP1 (National Centers for Environmental Prediction Reanalysis 1) datasets. The time series of the EAS position using different datasets have a very high correlation, with the highest coefficient of 0.96 between the ERA5 and JRA-55 (supplementary figures S1, S2(a) and table S1 available online at stacks.iop.org/ERL/16/124028/mmedia). A sensitivity test shows that the main results of this study have good agreement with the results obtained using other thresholds (800, 1000 and 1200 hPa m s$^{-1}$; supplementary figure S2(a) and table S2). Furthermore, we check the effect of linear trend on our result. The correlation coefficient between raw and detrended time series of intensity (position) index has a very high value of 0.97 (0.93), suggesting the results of this study will not change whether the dataset is detrended or not. These tests confirm the robustness of the long-term zonal shift in the EAS observed in this study.

The interdecadal zonal shift of the EAS position may also contribute to the well-known weakening and strengthening of the EAWM, in addition to the changes in $I_{EAS}$. Most of the mainstream definitions for EAWM detection are based on meteorological variables in a fixed region. Our study indicates that even if $I_{EAS}$ does not change, the retreating (returning) movement of the EAS from (to) a fixed region induces variation in the intensity of the EAWM. Figure 1(c) shows that the main body of EAS moves evidently from inland to coastal region in the 1980s. So, this eastward shift of EAS may contribute partly to the well-known weakening of EAWM in the 1980s. This result provides another perspective on the possible reason for interdecadal changes in the EAWM. Nevertheless, statistical analyses show that the correlation coefficient between $I_{EAS}$ and $P_{EAS}$ is $-0.16$, which does not pass the significance test. This result indicates that the zonal shift of the EAS position is somewhat independent of its intensity, highlighting the importance of clarifying the features and possible mechanisms of the zonal shift of the EAS.

3.2. Zonal shift of the EAS position at interannual and interdecadal timescales

To further reveal the zonal shift of the EAS, figure 2 shows the distributions of EAS at different timescales. The climatology of the EAS features an inland channel (112°E–129°E) and a coastal channel (129°E–147°E) with peaks at 123°E and 132°E, respectively (figure 2). The formation of these two channels may be due to the blocking effect of topography on the Korean Peninsula and the northern adjacent areas. Such two channels of cold airmass also have been reported in previous study (Park et al 2011). In terms of the magnitude of the southward cold airmass flux, the inland channel of the EAS is slightly larger than the coastal channel. Regarding the interdecadal changes, the variation in the EAS is divided into two periods (western type: 1958–1984, eastern type: 1985–2007) according to figure 1(c). During the decades in which the western (eastern) type prevailed, the peak of the inland channel was stronger (weaker) than the climatic mean, while the peak of the coastal channel was weaker (stronger) than the climatic mean (figure 2(a)). It should be noted that the total southward cold airmass flux of the EAS including the two channels has comparable values between the two periods. Therefore, the interdecadal shift of the EAS can be described as an evident seesaw between the strengths of the inland and coastal channels, while the total strength of the EAS changed to a lesser extent.

To analyze the interannual shift in the EAS position, the interdecadal component is removed by subtracting the 11-year running mean series from the raw series (figure 1(c)). Then, the years exceeding one standard deviation (marked by triangles and circles in figure 1(c)) are composited. Figure 2(b) shows that the strongest peak of the EAS still presents a zonal shift between the two types of years. During the years in which the western type prevailed (line in purple), the inland channel is slightly stronger than the climatic mean, while the coastal channel is greatly suppressed. Moreover, a large difference in the zonal expansion of the coastal channel is also observed. The longitudinal range of the coastal channel (129°E–139°E) has a reduction of nearly 50% compared with
Figure 2. Changes in the longitudinal distribution of the southward cold airmass flux on the (a) interdecadal and (b) interannual timescales. The blue shading denotes the climatic mean (1958–2017) distribution of the southward cold airmass flux. The purple and green lines in (a) denote the southward cold airmass flux averaged over the periods in which the western (1958–1984) and eastern (1985–2007) types prevailed. The purple and green lines in (b) denote the southward cold airmass flux averaged over the years in which the western (marked by triangles in figure 1(c)) and eastern (marked by circles in figure 1(c)) types prevailed. The zonal expansion of the EAS is represented by its eastern boundary, which is located at the intersection of the dotted line and gray dashed line. The climatic mean expansions of the inland and coastal channels are marked at the bottom axis.

the span of the climatic mean (129°E–147°E). For the years in which the eastern type (line in green) prevailed, the coastal channel is strengthened, with its eastern boundary extending to 157°E, while the inland channel is weaker than the climatic mean. Overall, the total southward cold airmass flux of the EAS has a large difference between the years in which the two types prevailed. The eastern type EAS is usually accompanied by a relatively large $I_{EAS}$ and vice versa. Therefore, we see that the interannual change in the EAS is represented by both the zonal shift of the peak and the extension/contraction of the EAS coastal channel over the northwestern Pacific. Such interannual changes are more complex than the interdecadal changes.

3.3. Large-scale cold airmass flux associated with the zonal shift of the EAS

The climatology of cold airmass flux in figure 1(a) shows that the inland channel is dominated by cold airmass streams from Siberia, while the coastal channel is supplied by both streams from Siberia and the Bering Sea. Therefore, the zonal shift of the EAS position may be closely related to the change in large-scale anomaly of the upstream cold airmass flow. Figure 3 shows the magnitude of cold airmass flux regressed onto the interdecadal and interannual time series of the EAS position. At interdecadal timescale, the zonal shift of the EAS is mainly associated with the variation in the strength of the high-latitude cold airmass stream from Siberia (figure 3(a)). During the western type EAS period, the southward cold airmass flux increases over the region from Siberia to northern China (inland channel), induced by the intensification of the main source stream of the EAS over Siberia (supplementary figure S3(a)). The secondary source stream from the Bering Sea is weakened, causing a slight decrease of southward airmass flux in the coastal channel. In contrast, the eastern type EAS period features a weakened stream from Siberia and a strengthened stream from the Bering Sea (supplementary figure S3(b)).

At interannual timescale, however, the zonal shift of the EAS is linked to both high-latitude cold airmass streams from Siberia and the Bering Sea, among which the stream from the Bering Sea becomes the dominant factor (figure 3(b)). The composition of western type EAS years shows that the strengthening of southward cold airmass flux mainly appears to the northwest of the inland channel (supplementary
Figure 3. Anomalies of cold airmass flux (colored shading) associated with the zonal shift of the EAS at (a) interdecadal and (b) interannual timescales. Stippling indicates the regions exceeding the 95% confidential level. Vectors denote the climatic mean of cold airmass flux. The red vectors represent the southward cold airmass fluxes larger than 1000 hPa m s$^{-1}$. The black boxes denote the inland and coastal channels of the EAS, as marked in figure 2.

3.4. Possible mechanisms modulating the zonal shift of the EAS position

To explore the mechanisms governing the zonal shift of the EAS position at different timescales, figures 4(a) and (b) show the meridional winds regressed onto the interdecadal and interannual time series of the EAS position. In East Asia at both interdecadal and interannual time scales, the magnitude of wind anomaly increases with height and reaches a maximum at approximately 300 hPa. These vertical distributions suggest that the zonal shift of the EAS position may be modulated by circulation anomalies in the upper troposphere. We also noticed that anomalies of meridional winds show a wave-train like spatial pattern, which indicates the circulation anomalies over East Asia may be a part of the upper tropospheric teleconnection. Such a wave-train like pattern can also be found in the cold airmass flux anomalies (supplementary figure S3). Although the zonal shift of the EAS position has similar large-scale anomalies on the two timescales, some differences are still observed. For the interdecadal changes (figure 4(a)), the zonal shift of the EAS is significantly related to the wind anomalies over Eurasia. The regressed wind anomaly reaches a maximum in western Eurasia ($0^\circ$ W–$60^\circ$ E). For the interannual changes (figure 4(b)), the strongest anomalies are located in the northern Pacific ($150^\circ$ E–$120^\circ$ W). These differences could effectively explain the dominant effect of cold airmass streams from Siberia and the Bering Sea at interdecadal and interannual timescales, respectively (figure 3).

Figures 4(c) and (d) further illustrate the 300 hPa geopotential anomaly and wave activity flux associated with the zonal shift of the EAS. The wave activity flux used here is defined by Takaya and Nakamura (2001). At interdecadal timescale (figure 4(c)), a wave-train propagates from the northern Atlantic to northern China, with a spatial pattern similar to the EAWR teleconnection (Barnston and Livezey 1987). Such a spatial pattern of the wave activity flux could influence the circulation anomaly over northern China at approximately 120° E, modifying the strength of cold airmass flux from Siberia (figure 3(a)). We also noticed that the geopotential anomaly over the Atlantic shows a north–south dipole pattern, which is one of the most prominent teleconnection patterns called the North Atlantic Oscillation (NAO in Wallace and Gutzler 1981, Barnston and Livezey 1987). The EAWR and NAO share an anomaly center at the northern part of North Atlantic. These results suggest that the interdecadal...
Figure 4. (a), (b) Anomalies of meridional winds (colored shading) associated with the zonal shift of the EAS at (a) interdecadal and (b) interannual timescales. (c), (d) Anomalies of geopotential height (colored shading) and wave activity flux (vectors) at 300 hPa associated with the zonal shift of the EAS at (c) interdecadal and (d) interannual timescales. The colored lines in (c) and (d) denote the teleconnection patterns of the North Atlantic Oscillation (NAO) (red line), East Atlantic–West Russia (EAWR) (blue line) and Pacific/North American (PNA) (yellow line). The stippling in (a)–(d) indicates the regions exceeding the 95% confidential level.

Table 1. Correlation coefficients between the interdecadal/interannual filtered position index of the EAS and indices of atmospheric teleconnections. The effective sample size has been considered in the significance test of filtered timeseries. Significant values 99%, 95% and 80% are marked by ***, ** and *, respectively.

| Interdecadal | Interdecadal | Interannual | Interannual |
|--------------|--------------|-------------|-------------|
| $P_{EAS}$ vs NAO | 0.81*** | 0.54** | 0.46*** | 0.30*** |
| $P_{EAS}$ vs EAWR | 0.81*** | 0.54** | 0.46*** | 0.30*** |

phase change of the NAO could modulate the interdecadal zonal shift of the EAS via the EAWR teleconnection. In addition, the correlation tests further verify the strong connection between the interdecadal zonal shift of the EAS and phase changes in NAO (0.81) and EAWR (0.54) (table 1).

At the interannual timescale (figure 4(d)), the geopotential height over the northern Pacific shows the largest anomaly. The pattern of the wave-train with alternating positive and negative centers over the vicinity of Hawaii, south of the Aleutian Islands, and the North America is similar to that of the PNA teleconnection pattern (PNA in Wallace and Gutzler 1981). The anomaly center at the south of the Aleutian Islands, as a part of PNA, could influence the circulation anomaly over northeastern Asia. Thus, the interannual phase change in the PNA is thought to modify the strength of cold airmass stream from the Bering Sea (figure 3(b)). The correlation coefficient between the interannual filtered position index of the EAS and the PNA index is 0.46 (table 1). Moreover, the EAWR teleconnection is still observed and plays a minor role by modifying the cold airmass flux from Siberia. The EAWR index has a correlation coefficient with the interannual filtered position index of the EAS of 0.30, which exceeds the 95% confidential level. As a result, the interannual phase changes in the PNA and EAWR teleconnections jointly modulate the interannual zonal shift in the EAS. Overall, the possible mechanisms of the zonal shift in the EAS position may be described as follows: the phase change of high tropospheric atmospheric teleconnections alters the strength of the two cold airmass streams at Siberia and the Bering Sea that form the EAS. Therefore, the interdecadal and interannual shifts in the EAS position may be mainly attributed to the phase changes in the NAO and PNA, respectively.

We have noticed that many studies have shown a strong connection between the intensity of EAWM and the Pacific SST anomaly, including ENSO (interannual) and IPO (interdecadal). However, there is barely no significant correlation between the EAS zonal shift and Pacific SST anomaly (supplementary figure S4). The SST anomalies in the coastal waters of East Asia is thought to be a result of the EAS zonal shift rather than a cause. The correlation coefficient between EAS position and Nino3.4 (IPO) index is 0.18 (0.19), which does not pass the significant test.
Moreover, we check the potential impact of recent global warming on the interannual and interdecadal variations of the EAWM spatial pattern. The global warming does have effects on decreasing the cold air mass depth and reducing the southerly winds, but the magnitudes of these effects are negligible comparing to the climatological mean values. Thus, the main results of this study may not change obviously in response to the surface warming trend. Based on the analyses in this section, we think the upper tropospheric teleconnections may be the dominant factors for spatial changes in the EAS.

4. Conclusions

In this study, the EAWM was found to show obvious spatial variations, featured by the zonal shift of the southward cold air mass stream. By defining a position index of the EAS, the long-term variation in the spatial pattern of the EAWM can be described quantitatively. At the interdecadal timescale, the two main channels of the EAS, namely, the inland channel and coastal channel, show seesaw variations in their strengths, causing a zonal shift in the peak of the EAS. The interannual changes in the EAS show not only a zonal shift in the EAS peak but also expansion/contraction along the eastern boundary of the coastal channel. Further analyses show that the zonal shift of the EAS position is directly or remotely modulated by atmospheric teleconnections at approximately 300 hPa. At interdecadal timescale, the phase shift of the NAO could influence the phase of the EAWR teleconnection, inducing the strengthening or weakening of the main source stream from Siberia to the EAS. At interannual timescale, the PNA governs the anomalous geopotential height over the northern Pacific, leading to a large variability in the strength of the secondary source stream from the Bering Sea to the EAS.

In addition to the opposite variations observed in the strength of the inland channel and coastal channel, these two channels also show differences in their flow directions and downstream paths (figure 1(a)). The cold airflow within the inland channel gradually turns from southeastward to southwest, forming a cold air mass path along eastern China to middle and even low latitudes. The cold airflow in the coastal channel, however, has a relatively larger eastward component and extends across Japan to the Kuroshio region. Previous studies have discussed the intrusion of cold air masses through inland channels and their distinct weather/climate effects (e.g. Wang et al 2009b, Abdillah et al 2021, Liu et al 2021). This is because most of the mainstream EAWM indices are proposed based on the historical period before the 2000s, when the EAS shows the western type (i.e. the inland channel is stronger than the coastal channel in most years). As the EAS shift eastward, the inland channel will have less occurrence frequency of cold air outbreak (or cold surge), which cools down the maritime continent and eastern China and depresses the precipitation in central China (supplementary figure S5). Our study also highlights that the coastal channel of the EAS is important and has even more complex variations than the inland channel. The coastal channel of the EAS may impact the storm track and air-sea heat budget over the northern Pacific. In this aspect, the investigation of the structure of the EAS and its spatial variation could be key for further understanding the EAWM and its impacts on regional weather and climate.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: The JRA-55 is provided by the Japan Meteorological Agency (https://jra.kishou.go.jp/JRA-55); The atmospheric teleconnection indices data is provided by National Oceanic and Atmospheric Administration (https://psl.noaa.gov/data/climateindices/list/).

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