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Do Extratropical Cyclones Impact Synoptic-Scale Variability of the Arctic Oscillation During Cold Season?

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Key Points:

- The correlation between the AO synoptic variability and the exchange of cyclones between the Arctic and subpolar regions is investigated
- A novel concept of Joint Net Cyclone Flux is derived, which is significantly correlated with the AO synoptic variability
- The quantitative piecewise forcing of the extra-tropical cyclones on the synoptic AO-like geopotential height anomalies is revealed

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The Arctic Oscillation (AO) is the most significant mode of sea level pressure (SLP) anomalies in the Northern Hemisphere, exhibiting significant multiple-timescale variability from synoptic to decadal. Using NCEP Climate Forecast System Reanalysis data from 1979 to 2022 during the cold season (November–April), this study identifies the relationship between the number of extra-tropical cyclones entering and exiting the Arctic and the AO synoptic variability. The Joint Net Cyclone Flux (JNCF) is significantly correlated with the spatio-temporal evolution of the synoptic AO and the composites of SLP associated with the JNCF produce AO-like patterns. Subsequent piecewise potential vorticity inversion reveals the impacts of extratropical cyclones on the synoptic-scale AO-like geopotential height anomalies at different altitudes. The effects of extratropical cyclones are more important than Arctic stratospheric PV intrusions. Furthermore, the upper-level dynamic processes among all extratropical cyclone effects dominate the evolution of synoptic-scale AO-like geopotential height anomalies.

Plain Language Summary The Arctic Oscillation (AO) plays an important role in the variability of weather and climate across the entire Northern Hemisphere. This study investigates the correlation between the numbers of extratropical cyclones entering and leaving the Arctic and the AO synoptic variability. The value of the NCF in the North Atlantic region minus that in the North America region is defined as the Joint Net Cyclone Flux (JNCF) which is significantly correlated with the AO synoptic variability with a correlation coefficient of 0.32. The composites of SLP relative to the JNCF index manifest as AO-like anomalies. Piecewise potential vorticity (PV) inversion results further reveal the quantitative forcing of extra-tropical cyclones on the synoptic-scale AO-like geopotential height anomalies at different altitudes. The effects of extratropical cyclones are more important than Arctic stratospheric PV intrusions. Furthermore, the upper-level dynamic processes among all extratropical cyclone effects dominate the evolution of synoptic-scale AO-like geopotential height anomalies, whereas the mid-troposphere latent heat release contributes little. Interestingly, the effects of the lower-troposphere static stability and baroclinicity on the AO-like synoptic anomalies are completely opposite between the western and eastern parts of the North Atlantic-Arctic sector.

1. Introduction

The Arctic Oscillation (AO) is defined as the first mode of the Empirical Orthogonal Function of extratropical sea level pressure (SLP) (20°–90°N). Its geopotential height anomaly shows a quasi-barotropic vertical structure spatially extending from the near-surface to the stratosphere (Thompson & Wallace, 1998, 2000; Thompson et al., 2000). Many studies have emphasized that the AO plays a significant role in regulating the weather and climate across the entire Northern Hemisphere, such as the East Asian monsoon (Cheung et al., 2012; Chen et al., 2005, 2019; D. Y. Gong & Ho, 2003; D. Y. Gong et al., 2001, 2011; Huang et al., 2013; Wu & Wang, 2002a, 2002b; L. Wang et al., 2009; L. Wang & Chen, 2010; L. Wang & Lu, 2016), the Indian winter monsoon (Midhuna & Dimri, 2019), Arctic sea ice (Jevrejeva et al., 2003; Rigor et al., 2002; Stroeve, Maslanik, et al., 2011), Eurasian snow cover (Bamzai, 2003), and winter surface air temperatures in the Northern Hemisphere (He & Wang, 2013; Kryjov, 2002; H. J. Park & Ahn, 2016; D. X. Wang et al., 2005). The spatial pattern of the AO is characterized by regional heterogeneity, with a primary maximum value center over the Arctic and opposing maximum value centers over the North Pacific and the North Atlantic. Therefore, it is necessary to take into account the regional heterogeneity of the AO in studies. Some previous studies have questioned the relevance of the AO relative to the North Atlantic Oscillation (NAO) (Ambaum et al., 2001; Deser, 2000; Thompson et al., 2003). Whereas others have suggested that the NAO appears to be part of the AO (Thompson & Wallace, 1998; Wallace, 2000). The temporal correlation between the AO and the NAO is 0.95 for monthly data and they are nearly indistinguishable in structure (Deser, 2000).

Due to the multiple timescales of the AO, its variability is highly complex. Baldwin and Dunkerton (2001) suggested that the AO originates in the Arctic stratosphere. Wallace (2000) proposed that the interaction between the zonally symmetric flow and mid-to-high latitude eddies affects the interannual variability of the AO, while other mechanisms, including air-sea interaction, control the decadal variability of the AO. Additionally, the AO maybe influenced by various external forcings such as solar activity (Chen & Zhou, 2012; da Silva & Avissar, 2005; Huth et al., 2007), volcanic activity (Qu et al., 2021; Stenchikov et al., 2006), tropical forcing (Jia et al., 2009; Lin et al., 2002; Lu & Pandolfo, 2011; Zhou & Miller, 2005), and Eurasian snow cover (Allen & Zender, 2011; G. Gong et al., 2002, 2003a, 2003b). On interannual timescales, Simmonds et al. (2008) have found that the AO correlates with the frequency of Arctic cyclones. Beyond the low-frequency timescale variations of the AO driven by external forcing, high-frequency timescale events, such as East Asian cold surges (Jeong & Ho, 2005; T. W. Park et al., 2011; Woo et al., 2012), extreme heat events in the U.S. (Higgins et al., 2002; Lim & Schubert, 2011; Wettstein & Mearns, 2002), and extreme precipitation in China (Mao et al., 2011), have also been shown to be closely related to the AO. However, the specific spatiotemporal evolution and mechanisms of the AO on high-frequency timescales remains unclear.

X. D. Zhang et al. (2004) defined all cyclones north of 60°N as Arctic cyclones and divided the Arctic into four regions: the North Pacific, North America, North Atlantic, and Eurasia, to study the climatic characteristics of Arctic cyclones. In winter, Arctic cyclones are less frequent but more intense, while in summer, they occur more frequently but are weaker compared to winter and have a longer life cycle (Sorteberg & Walsh, 2008; Vessey et al., 2020; Zahn et al., 2018; X. D. Zhang et al., 2004). High-latitude cyclones can also undergo explosive development similar to mid-latitude cyclones (Rinke et al., 2017). Numerous studies have highlighted that extratropical cyclone have significant impacts on Arctic sea ice (Aue & Rinke, 2023; Aue et al., 2022; Basu et al., 2019; Boisvert et al., 2016; Finocchio et al., 2020, 2022; Kriegsmann & Brümmer, 2014; Liu & He, 2023; Lukovich et al., 2021; Tian et al., 2022; Webster et al., 2019; Wernli & Papritz, 2018; J. L. Zhang et al., 2013). Additionally, extratropical cyclones have been linked to extreme Arctic wave events (Waseda et al., 2021), increased Arctic precipitation (Oh et al., 2020; Stroeve, Serreze, et al., 2011), Arctic temperature warming (Murto et al., 2022; Rogers & Mosleythompson, 1995), and the Beaufort High (Kenigson & Timmermans, 2021). Extratropical cyclones can have different meridional displacement directions. Cyclones that originate in the mid-latitudes and then enter the Arctic transport moisture and heat poleward (Fearon et al., 2021; Sorteberg & Walsh, 2008; Tsopouridis et al., 2021; Tsopouridis et al., 2021a, 2021b; Villamil-Otero et al., 2018; Weijenborg & Spengler, 2020), while cyclones that originate in the Arctic and then move toward the mid-latitudes remove polar moisture and heat. The effects of cyclones with different meridional displacement directions on the Arctic are different. Therefore, when investigating the relationship between extratropical cyclones and the AO, cyclones should be categorized into at least two types: those originating outside the Arctic and entering it, and those generated within the Arctic and leaving it. Furthermore, given the zonal heterogeneity of the AO, it is also important to consider the different paths of cyclones entering and leaving the Arctic (X. D. Zhang et al., 2004).

Inspired by the above discussion, the main scientific questions of this study are as follows: Considering the meridional movement directions of extratropical cyclones and the zonal heterogeneity of the AO, do cyclones entering the Arctic and those leaving the Arctic exert a synergistic influence on the synoptic-scale AO variability during the cold season (November–April)? If the extratropical cyclones do impact the AO synoptic variability, what are the phenomena and mechanisms driving this influence? The structure of the paper is as follows: Section 2 outlines the data and methods used in this study. Section 3 presents the relationship between extratropical cyclones in different regions and the AO synoptic variability, as well as the mechanisms that extratropical cyclones influence on the AO synoptic variability. And Section 4 offers the conclusion and discussion.

2. Data and Methods

The data used in this study are the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) and its extended version, the Climate Forecast System Version 2 (Saha et al., 2010, 2011). CFSR takes into account the coupling of the atmosphere, ocean, land, and sea ice, and provides high temporal and spatial resolution. The CFSR data utilized in this study cover the cold season (November–April) from 1979 to 2022, with a spatial resolution of 0.5° × 0.5°, a temporal resolution of 6 hr, and 37 vertical levels.

The CFSR data is widely used in the studies of jet streams (Hu et al., 2023), mid-latitude cyclones (Qian et al., 2024), subsurface ocean (Hu et al., 2022), oceanic eddies (Hu et al., 2021) etc. The daily AO index (AOI) is obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center. For the daily AOI, the long-term trend is removed and we calculate the 3-day mean to match the cyclone number index. The AO synoptic variability is defined as the 3-day mean of AOI in this study (the results of 3- to 7-day mean are similar). Meanwhile, the long-term trend in each variable used in composite analysis is also removed.

Cyclones are identified and tracked using TRACK (Hodges, 1994, 1995, 1996, 1999) applied to the 6 hourly 850 hPa relative vorticity computed from the NCEP CFSR winds. This method has been widely applied in observational and modeling studies for extratropical cyclone identification (Catto et al., 2010; Hoskins & Hodges, 2002, 2005; Seiler & Zwiers, 2016). Before cyclone identification, the data are preprocessed by spectrally filtering the data to reduce noise and the large-scale background circulation represented by the 0–5 waves is removed. The spectral filtering uses a triangular truncation at 42 waves (T42) and a spectral tapering is used to mitigate the Gibbs phenomenon. A threshold of $1 \times 10^{-5}\ s^{-1}$ is used for initially identifying cyclone feature points as maxima on a polar stereographic projection, these are refined using B-spline interpolation and steepest ascent to find the off-grid locations of the maxima and finally transformed back to the sphere for the tracking. The tracking is performed by first initializing a set of tracks using a nearest neighbor method and then refining these by minimizing a cost function for track smoothness subject to adaptive constraints on displacement distance and track smoothness (Hodges, 1995, 1999) suitable for extra-tropical cyclone motion. Cyclone tracks with lifetimes shorter than 2 days (8 timesteps for 6-hourly data sets) and movement distances less than 10° geodesic (about 1,000 km) are excluded. Additionally, the entire cyclone track including leap days is also excluded to facilitate composite analysis.

In the PV framework, the extratropical cyclone activities can be linked with PV anomalies at different levels from troposphere to stratosphere (Davis & Emanuel, 1991; Reader & Moore, 1995). From PV anomalies in the free atmosphere and potential temperature anomalies at the surface, the three-dimensional geopotential height fields can be retrieved. Piecewise potential vorticity inversion (PPVI) is based on the Ertel potential vorticity (PV) and uses numerical methods to obtain the geopotential height anomaly field from each piecewise PV anomaly field. This method quantitatively estimates the contribution of different forcings represented by each piecewise PV to the changes in the geopotential height (Davis, 1992). Kang and Son (2021) derived a compact linearized PPVI equation, which is simple to calculate and requires fewer computational resources compared to that derived by Davis (1992), with very small errors compared to the reanalysis. This study employs the method proposed by Kang and Son (2021), with the following formula which can be solved by a successive overrelaxation method:

$$q_n' \approx -g\frac{\partial\overline{\theta}}{\partial p}\left[\frac{1}{f}\nabla_p^2\Phi_n' + \frac{f}{\sigma}\frac{\partial^2\Phi_n'}{\partial p^2}\right] \tag{1}$$

Where q is the Ertel PV, θ is the potential temperature, Φ is the geopotential, g is the constant of gravity, f is the planetary vorticity, and $\sigma = -\left(\frac{R_d\pi}{p}\right)\left(\frac{\partial\overline{\theta}}{\partial p}\right)$ where R_d is the gas constant of dry air, $\pi = \left(\frac{p}{p_s}\right)^{R_d/C_p}$ is the Exner function, and c_p is the specific heat of dry air under constant pressure. The overbar and prime represent the time mean and climatological anomaly respectively. The subscript n denotes the relevant piece of PV. The Dirichlet boundary conditions are used for the horizontal direction and Neumann boundary conditions are used for the vertical direction.

3. Results

According to the dipole pattern of the AO (Thompson & Wallace, 1998), the area north of the 65°N boundary is considered as the Arctic region (Sepp & Jaagus, 2011). A total of 3,156 cyclone tracks originating in the mid-latitudes and entering the Arctic are identified, as well as 1,793 cyclone tracks generated in the Arctic and moving toward the mid-latitudes during the cold season from 1979 to 2022 (Figure 1). Similar to the four regions defined by X. D. Zhang et al. (2004), the parallel circle of 65°N is divided into four sectors: the North Pacific (135°E − 135°W), North America (135°W − 55°W), North Atlantic (55°W − 30°E), and Eurasia (30°E − 135°E). The selection of four sectors is sufficient to distinguish the pathway of extratropical cyclones entering and leaving the Arctic, though Sepp and Jaagus (2011) selected more sectors. Moreover, The four sectors

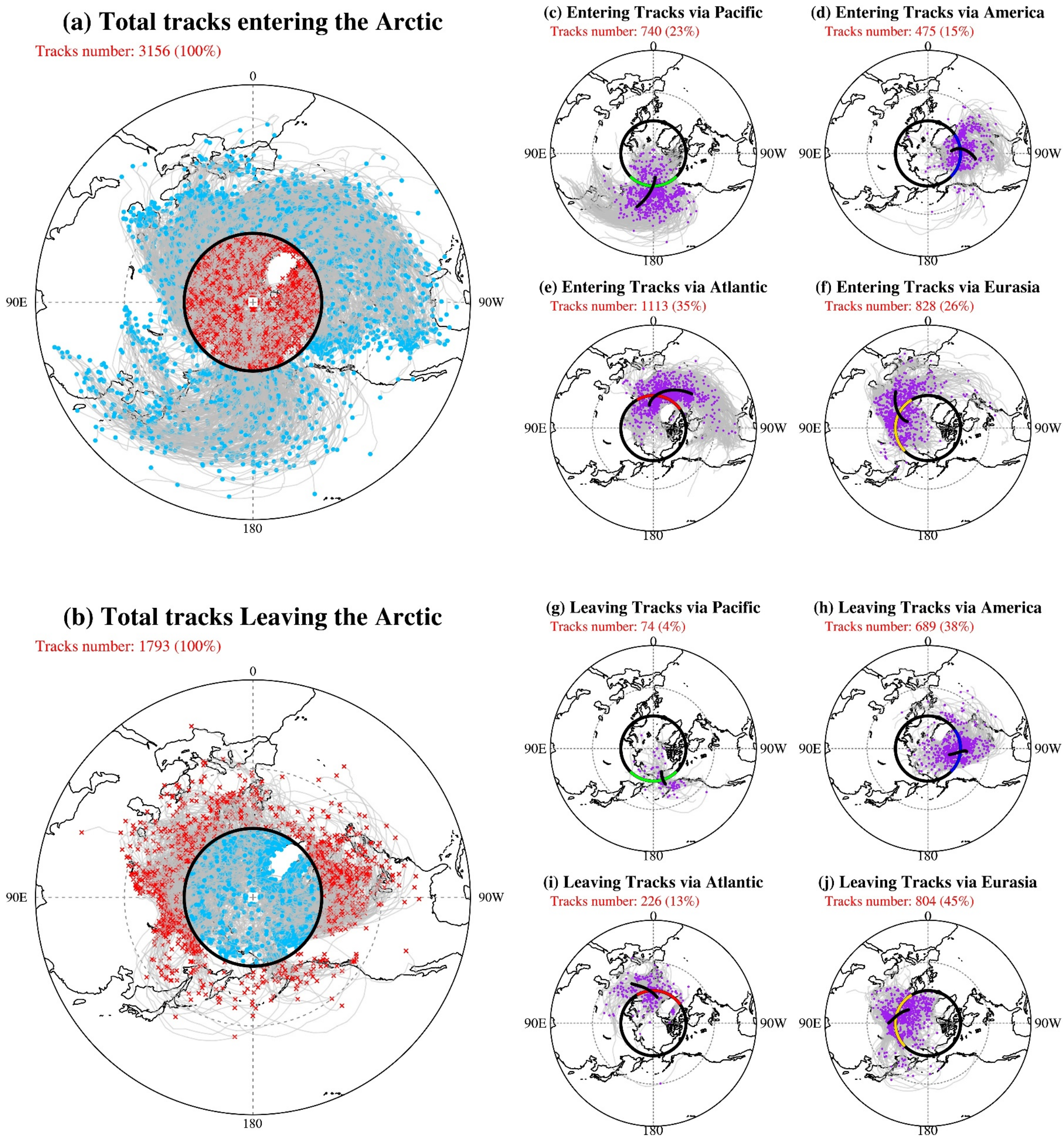

Figure 1. The tracks of the (a) total cyclones originating in the mid-latitude and entering the Arctic, and (b) total cyclones originating in the Arctic and moving to the mid-latitude. The blue dots denote the cyclogenesis and the red "×" marks represent the cyclolysis. The black circles are the latitude of 65°N. (c)–(f) The tracks of cyclones entering the Arctic through the four regions respectively. (g)–(j) The tracks of cyclone leaving the Arctic through the four regions respectively. The purple dots denote the position when a cyclone is the most intense. The green, blue, red, and yellow arcs respectively indicate the zonal range of the North Pacific (135°E − 135°W), North America (135°W − 55°W), North Atlantic (55°W − 30°E), and Eurasia (30°E − 135°E) regions. The bold black curves represent the mean track. The number and corresponding percentage of tracks are labeled in the top left of each panel.

are zonally shifted eastward and westward 10° to compare with our result. The results of shifted sectors are similar to the results in this paper indicating that the results are insensitive to the choice of sector boundaries (Figures not shown).

The two oceanic regions of the North Pacific (23%) and North Atlantic (35%) are the main paths for cyclones originating in the mid-latitudes to enter the Arctic. Another set of cyclones enters the Arctic through Eurasia (26%). Cyclones generated in the Arctic primarily leave the Arctic through land regions. The cyclones leaving the Arctic through the North America and Eurasia regions respectively accounts for 38% and 45% of the total number of cyclones leaving the Arctic (Figure 1). In terms of the average intensity represented by maximum vorticity or minimum SLP anomalies, cyclones in the North Atlantic region are strongest when crossing 65°N, while those in the North Pacific region are the weakest (Figure S1 in Supporting Information S1). Cyclones entering the Arctic through the North Atlantic region are closest to the polar circle when they reach their peak intensity compared to those through other regions. For cyclones leaving the Arctic, a significant portion reach their peak intensity before leaving the Arctic (Figure 1).

To further investigate the impact of extratropical cyclones following different pathways on the AO synoptic variability, we first analyzed the time series of the number of cyclones entering and leaving the Arctic. Since there are many zero values in the daily time series of cyclone number (181 days per cold season), we applied the 3-day accumulation to the daily time series (60 timesteps per cold season). Overall, the correlation between the total number of cyclones entering or leaving the Arctic and the synoptic-scale AOI is very weak. However, interesting results emerge when considering different cyclone pathways. The number of cyclones in the North Pacific and the Eurasia regions are nearly uncorrelated with the synoptic-scale AOI, whereas the number of cyclones in the North America and the North Atlantic regions is significantly correlated with the synoptic-scale AOI (Table S1 in Supporting Information S1).

Since cyclones both entering and leaving the Arctic influence the moisture and heat transport of the Arctic, it is necessary to consider the effects of cyclones entering and leaving the Arctic simultaneously. We define the difference between the number of cyclones entering the Arctic and that leaving the Arctic as the Net Cyclone Flux (NCF). There remains very weak correlation between the total NCF and the synoptic-scale AOI, and the SLP composite results based on the total NCF index further indicating that using the total NCF to discuss the relationship between extratropical cyclones and the AO synoptic variability is not appropriate (Figures 2a and 2d). Notably, the NCF in the North America and North Atlantic regions shows higher significant correlation coefficients of −0.22 and 0.26 with the synoptic-scale AOI, respectively (Table S1 in Supporting Information S1).

We also produced the SLP anomaly composites based on the NCF index in different regions (Figure S2 in Supporting Information S1). The NCF in the North America and North Atlantic regions is significantly correlated with the SLP anomalies over the Arctic. Although the composites of NCF in the Eurasia and the North Pacific regions show significant SLP anomalies, these anomalies are mainly located outside the polar region, and the very low and insignificant correlation coefficient (0.05) with the synoptic-scale AOI suggests that they are unlikely to impact the AO synoptic variability (Table S1 in Supporting Information S1).

From the above analysis, we know that the NCF in the North America and the North Atlantic regions is the key factor correlating with the AO synoptic variability, and they exhibit opposite spatiotemporal correlations with the synoptic-scale AO. Therefore, we define the value of NCF in the North Atlantic region minus that in the North America region as the Joint Net Cyclone Flux (JNCF). The correlation coefficient between the JNCF and the synoptic-scale AOI (0.32) is higher than that between the synoptic-scale AOI and the NCF in either the North America or the North Atlantic region individually (Table S1 in Supporting Information S1).

The composite results associated with the JNCF index show that the JNCF significantly influences the SLP anomalies over the Arctic and North Atlantic, manifesting as synoptic-scale AO-like SLP or geopotential height anomalies (Figures 2b and 2e). The SLP composite associated with the JNCF index is approximately 50% of the intensity of the SLP composite based on the synoptic-scale AOI (Figure 2). Moreover, the AO pattern is commonly accompanied by significant temperature and wind anomalies in the Arctic region, especially in the North Atlantic (Figure S3 in Supporting Information S1). The performances of composite temperature and wind anomaly based on the JNCF index are similar to the SLP anomaly, which show AO-like patterns and reach about 50% intensity of the patterns based on the synoptic AO index. A key question arises: what are the physical processes whereby the JNCF influences the synoptic-scale AO-like geopotential height anomalies? The method of PPVI is applied to answer this question.

The activities of extratropical cyclones are commonly accompanied by positive PV anomalies in free atmosphere over the cyclone (Reader & Moore, 1995). The PV anomalies in the upper, middle, and lower troposphere are considered to be associated with the stratospheric intrusion caused by dynamical processes, the latent heat release, and the surface baroclinicity respectively (Davis, 1992; Kang & Son, 2021; Seiler, 2019). However, positive PV anomalies also exist to the north of jet stream accompanied by the cyclone activity. It is inaccurate to assume all the PV anomalies in the upper-level atmosphere are caused by stratospheric intrusions, which act as a precursor signal and have significantly influence on the variability of AO (Baldwin & Dunkerton, 2001). The PV anomalies

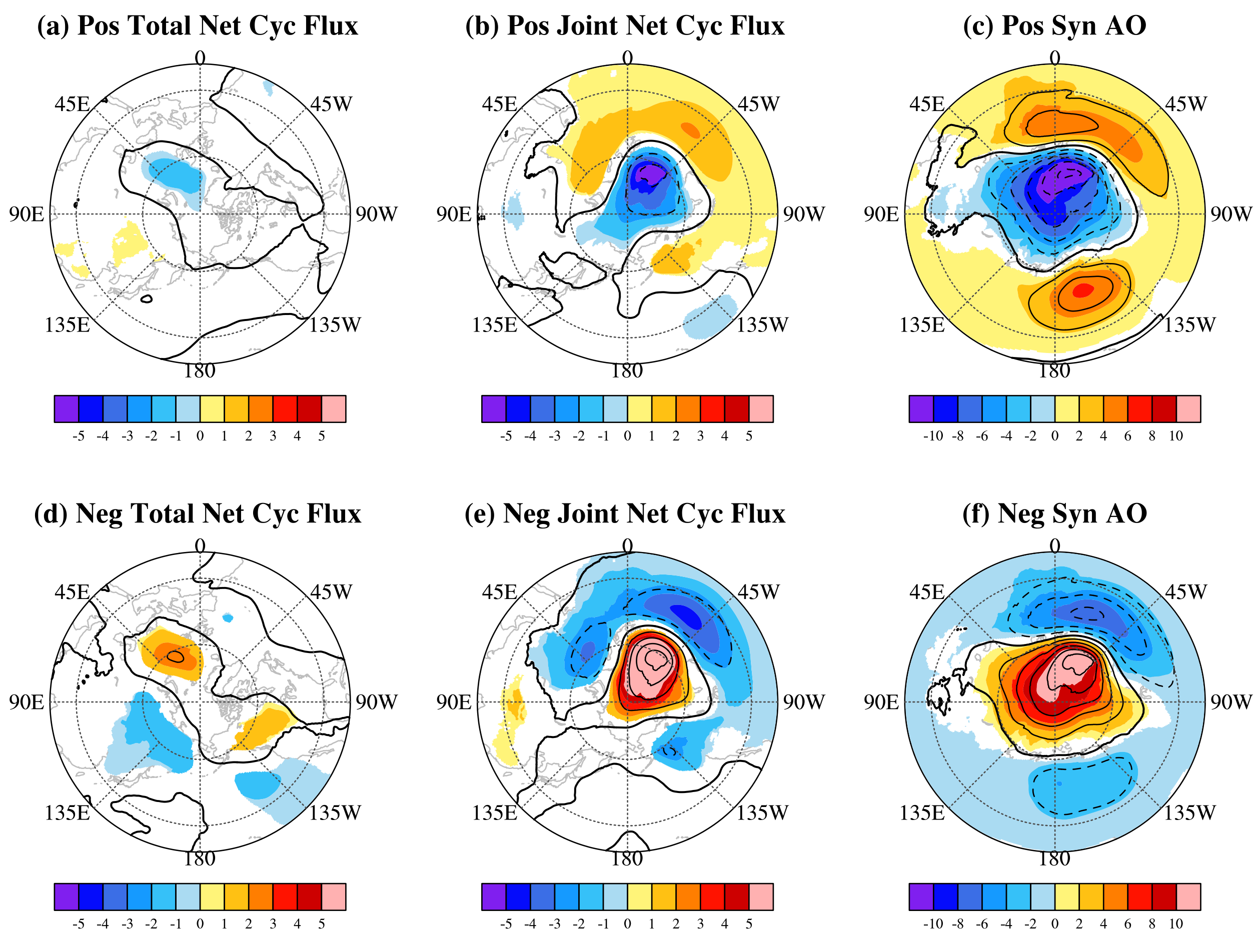

Figure 2. Composites of SLP anomalies (shadings, unit: hPa) and 850-hPa geopotential height anomalies (contours, unit: gpm). (a) The composites during the positive period of total Net Cyclone Flux index (greater than 1.0). (b) The composites during the positive period of Joint Net Cyclone Flux index (greater than 1.0). (d)–(e) are the same as (a)–(b) but for the negative period (less than −1.0). (g) and (h) are the composites of positive and negative AO phases respectively. Only the SLP anomalies with significance of 95% confidence level are drawn.

in the upper-level atmosphere should be separated into at least those associated with the jet stream and those caused by stratospheric intrusion (Qian et al., 2024). Following Qian et al. (2024), we divide the PV into four pieces according to different pressure levels. These are the lower tropospheric PV (1,000, 950, 900, 850 hPa) which represents the static stability and baroclinicity, the middle tropospheric PV (800, 700, 600, 500 hPa) which represents latent heat release, the upper tropospheric PV (400, 300, 250, 200 hPa) which represents upper-level dynamical processes, and the stratospheric PV (150, 100, 50, 20, 10 hPa) which represents stratospheric intrusion. Based on these PV selections, we perform PPVI for the positive and negative phases of the synoptic-scale AO-like geopotential height anomalies. The inversion results are shown in Figure 3.

The anomaly patterns derived from the full PV inversion are mostly consistent with the reanalysis (Figures 3a, 3b, 3g, and 3h). Given the uneven distribution of the maximum value centers of the synoptic-scale AO-like geopotential height anomalies, we focus primarily on the center located in the North Atlantic-Arctic sector (the black sectorial region in Figure 3). The most significant geopotential height anomaly changes from −6 to 6 days are driven by the effects of extratropical cyclones (red bars in Figures 4a and 4d), whereas the changes driven by the effects of Polar Vortex hardly vary (sky-blue bars in Figures 4a and 4d). The contribution associated with extratropical cyclone exchanges between the Arctic and subpolar regions, including surface baroclinicity, latent heat release, and upper-level dynamical process, is as important or even more important than the arctic stratospheric PV intrusion to the AO synoptic variability. Among all the impacts associated with extratropical cyclones, the upper-level dynamic processes associated with extratropical cyclones dominate the evolution of the synoptic-

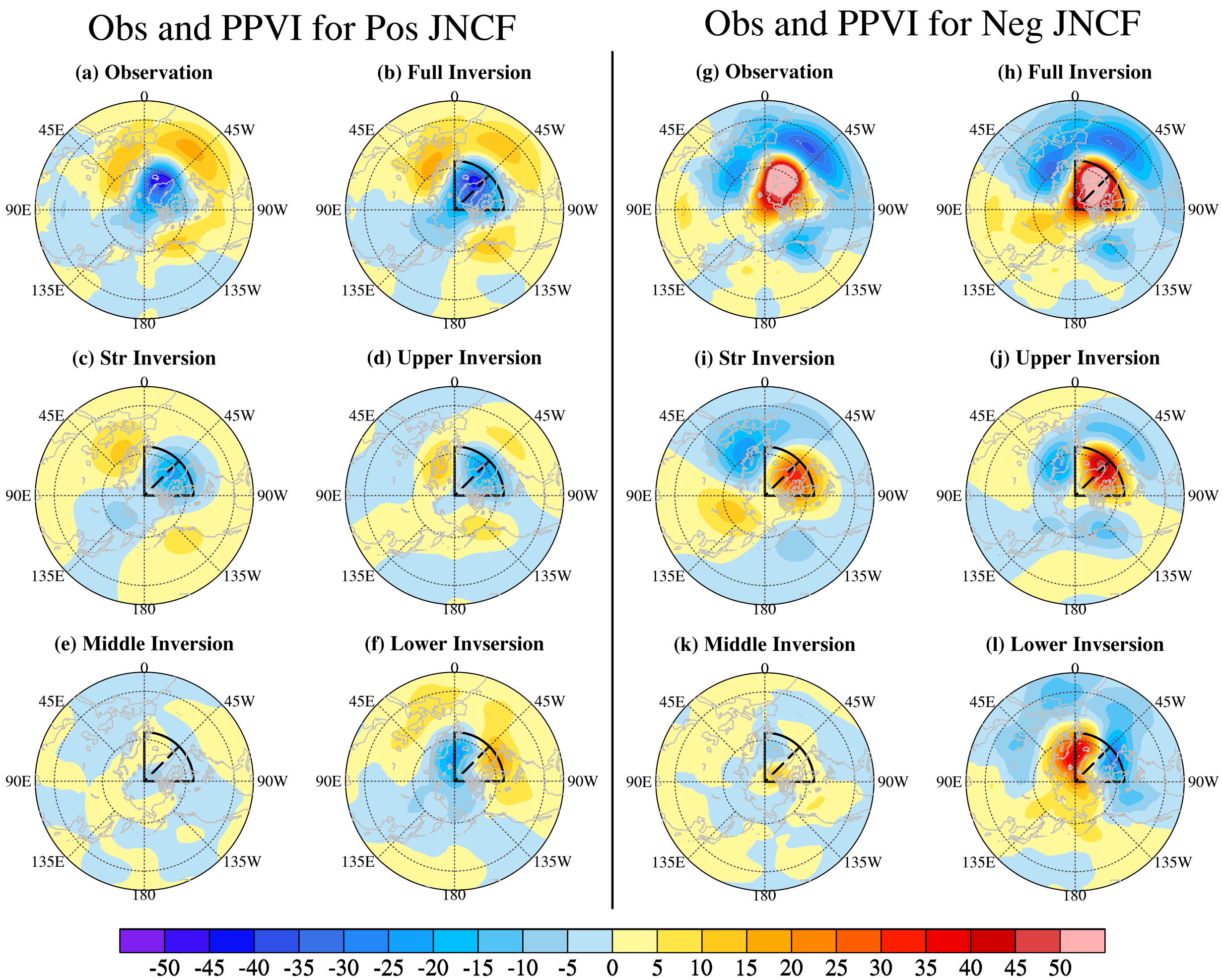

Figure 3. The 1,000-hPa geopotential height anomalies obtained from the reanalysis and PPVI (unit: gpm). (a) The composite of 1,000-hPa geopotential height anomalies by CFSR for positive period of JNCF index. (b)–(f) are the 1,000-hPa geopotential height anomalies obtained from the full PV, stratospheric PV, upper tropospheric PV, middle tropospheric PV, and lower tropospheric PV for positive period of JNCF index respectively. (g)–(l) are the same as (a)–(f) but for negative period of JNCF index. The black sector (90°W − 0°, 55° − 90°N) indicates the North Atlantic-Arctic sector and the dashed line is the boundary of western (90°W − 45°W, 55° − 90°N) and eastern (45°W − 0°, 55° − 90°N) parts of the sector.

scale AO-like geopotential height anomalies. Whereas the contribution from latent heat release in the mid-troposphere is negligible (Figures 4b, 4c, 4e, and 4f).

However, the geopotential height anomalies derived from the lower-tropospheric PV inversion exhibit an eastward displacement of the center of the maximum value compared to the reanalysis (Figures 3f and 3l). The eastern anomaly in the North Atlantic-Arctic sector is the same as the reanalysis, while the western anomaly is the opposite of the reanalysis. In the western part, lower-tropospheric stability and baroclinicity suppress the development of synoptic-scale AO-like geopotential height anomalies, while in the eastern part, they promote it. Most of extratropical cyclones enter the Arctic through the North Atlantic region during the positive period of JNCF index but through the North America region during the negative period of JNCF index. The Arctic seesaw effect further causes these opposing impacts (Figure S4 in Supporting Information S1).

4. Conclusion and Discussion

Using high-resolution CFSR data, this study identifies 3,156 cyclone tracks originating in the mid-latitude and entering the Arctic, as well as 1,793 cyclone tracks originating in the Arctic and moving to the mid-latitude during the cold season (November–April) from 1979 to 2022. We first examine the correlation between the number of cyclones and the synoptic-scale AO index (AOI). Results indicate that the total number of cyclones entering and

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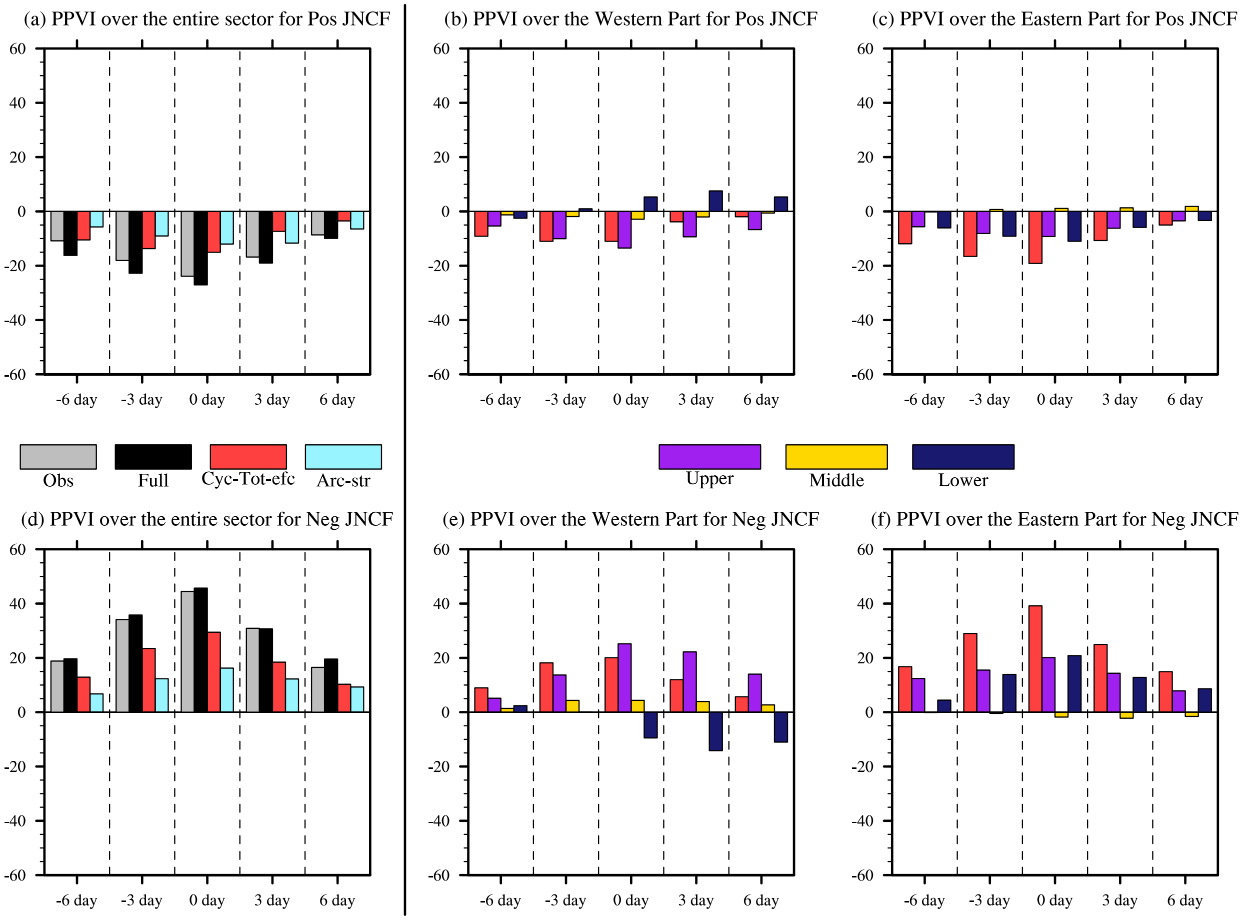

Figure 4. The regional average geopotential height anomalies (units: gpm) of the reanalysis and PPVI. (a) The average geopotential height anomalies of Arctic-Atlantic sector (black sector in Figure 3), (b) The average geopotential height anomalies of western sector, and (c) The average geopotential height anomalies of eastern sector for positive period of JNCF index. (d)–(f) are the same as (a)–(c) but for negative period of JNCF index. The negative value of *x*-axis denotes the days before composites. The gray bars represent the mean of the reanalysis. The black, sky-blue, blue, yellow and red bars indicate the geopotential height anomalies mean retrieved from full PV, stratospheric PV, upper-troposphere PV, mid-troposphere PV, and lower-troposphere PV respectively.

leaving the Arctic is uncorrelated with the synoptic-scale AOI. We then explored the relationship between cyclone numbers in four regions (the North Pacific, North America, North Atlantic, and Eurasian) and the synoptic-scale AOI, yielding interesting results.

The relationship between cyclone number in different pathways and the AO synoptic variability shows significant difference. Cyclone numbers in the North Pacific and Eurasian regions are hardly correlated with the synoptic-scale AOI, whereas those in the North America and North Atlantic regions are significantly correlated with the synoptic-scale AOI. Considering that both cyclones entering and leaving the Arctic influence the moisture and heat transport. We define the net cyclone flux (NCF) as the number of cyclones entering the Arctic minus that leaving the Arctic. The NCF index in the North America region presents a significant negative correlation with the synoptic-scale AOI (−0.22), while the NCF index in the North Atlantic regions shows a significant positive correlation (0.26). Composite sea level pressure (SLP) anomalies based on the NCF indices suggest that NCF in the North America and North Atlantic regions, exhibiting opposing spatiotemporal correlations with the AO synoptic variability, significantly influences the SLP anomalies over the Arctic and North Atlantic.

Building on this, we define the Joint Net Cyclone Flux (JNCF) as the NCF in the North Atlantic region minus that in the North America region. The JNCF shows a higher correlation with the synoptic-scale AOI (0.32). Composite SLP and geopotential height anomaly patterns associated with the JNCF index manifest as synoptic-scale AO-like patterns. To reveal the mechanism that JNCF influences the AO synoptic variability, the method of piecewise potential vorticity inversion (PPVI) is applied. The PPVI results indicate that the contribution associated with extratropical cyclone exchanges between the Arctic and subpolar regions, including surface baroclinicity, latent heat release, and upper-level dynamical process, is as important or even more important than the arctic stratospheric PV intrusion to the AO synoptic variability. Among all the impacts associated with extratropical cyclones, the upper-level dynamic processes associated with extratropical cyclones dominate the evolution of the synoptic-scale AO-like geopotential height anomalies, whereas the latent heat release in the mid-troposphere contributes little. The geopotential height anomaly centers derived from lower tropospheric PV inversion shift eastward compared to the reanalysis. In the western part of the North Atlantic-Arctic sector, lower-tropospheric instability and baroclinicity suppress the development of synoptic-scale AO-like geopotential height anomalies, while in the eastern part, they promote it. This opposite effect in the lower troposphere is determined by different pathways of extratropical cyclone entering the Arctic during the positive and negative periods of JNCF index.

In this study, the poleward motion of extratropical cyclones is very important for the synoptic AO variability. Tamarin and Kaspi (2016) revealed the importance of the upper-level PV anomaly as well as the crucial role played by latent heat release in the poleward motion of the cyclone. Furthermore, the poleward motion of individual cyclones increases with increasing global mean temperature which intensified the horizontal PV advection and latent heat release (Tamarin & Kaspi, 2017). Yao et al. (2023) found that the diabatic heating at 850 hPa and the horizontal advection by the stationary flow at 500 hPa are the main contributors to the poleward movement of extratropical cyclones. To some extent the exchanges of extratropical cyclones between the Arctic and subpolar regions also influences the interannual variability of the AO. The correlation coefficient between JNCF and the AO index on the interannual timescale is 0.73 (with p-value < 0.01), with the annual index of JNCF-related AO accounting for about 50% of the annual AO index variance (Figure S5 in Supporting Information S1). As mentioned in the introduction, the AO is significantly related to the NAO (H. N. Gong et al., 2018, 2024), we also compute the correlation coefficients between the extratropical cyclone numbers and the NAO index (Table S2 in Supporting Information S1). The relationship between the extratropical cyclone numbers and the NAO is similar to that between the AO, however the NAO shows a higher correlation coefficients with the cyclone numbers than the AO. Since different extratropical cyclones vary in intensity and how much moisture and heat they transport, the JNCF defined in this study only considers frequency, which ignores these cyclone properties. Future research needs to combine the factors such as cyclone intensity and their moisture and heat transports with the cyclones entering and leaving the Arctic.

Data Availability Statement

The reanalysis data of the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) and its extended version, the Climate Forecast System Version 2 (Saha et al., 2010, 2011) are able to download from https://rda.ucar.edu/. The daily AO index (AOI) is obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (https://www.cpc.ncep.noaa.gov/).

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