Asymmetric Impact of the Scandinavian Pattern on Stratospheric Circulation Anomalies

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ABSTRACT: This study investigates the stratosphere–troposphere coupling associated with the Scandinavian (SCA) pattern in boreal winter. The results indicate that the SCA impacts stratospheric circulation but that its positive and negative phases have different effects. The positive phase of the SCA (SCA⁺) pattern is restricted to the troposphere, but the negative phase (SCA[−]) extends to the upper stratosphere. The asymmetry between phases is also visible in the lead–lag evolution of the stratosphere and troposphere. Prominent stratospheric anomalies are found to be intensified following SCA⁺ events, but prior to SCA[−] events. Further analysis reveals that the responses are associated with upward propagation of planetary waves, especially wavenumber 1, which is asymmetric between SCA phases. The wave amplitudes in the stratosphere, originating from the troposphere, are enhanced after the SCA⁺ events and before the SCA[−] events. Furthermore, the anomalous planetary wave activity can be understood through its interference with climatological stationary waves. Constructive wave interference is accompanied by clear upward propagation in the SCA⁺ events, while destructive interference suppresses stratospheric waves in the SCA[−] events. Our results also reveal that the SCA⁺ events are more likely to be followed by sudden stratospheric warming (SSW) events, because of the deceleration of stratospheric westerlies following the SCA⁺ events.

KEYWORDS: Asymmetry; Planetary waves; Stratosphere–troposphere coupling; Teleconnections

1. Introduction

The Scandinavian (SCA) pattern is one of the leading atmospheric patterns of variability over the North Atlantic–Eurasian sector during the boreal winter (Barnston and Livezey 1987). It consists of a primary center over the Scandinavian Peninsula and two weaker ones with opposite sign over the northeastern Atlantic and central Siberia (Bueh and Nakamura 2007). Previous studies have addressed the prominent impact of the SCA pattern on winter climate over the surrounding areas. On the one hand, the positive SCA phase is conducive to an extensive cooling from western Russia to central Siberia (Bueh and Nakamura 2007; Sohn et al. 2011) and further cold air outbreaks over East Asia (Zhou et al. 2009; Bueh et al. 2011). On the other hand, it also contributes to decreased precipitation over western Eurasia (Wibig 1999; Liu et al. 2014; Łupikasza and Cielecka-Nowak 2020). In addition, the SCA pattern is reported to influence blocking frequency over Europe (Barriopedro et al. 2006; Tyrlis and Hoskins 2008).

Many studies have reported that the stratospheric circulation can be affected by the troposphere, especially via the atmospheric teleconnections, such as the Arctic Oscillation (e.g., Li et al. 2013; Lawrence et al. 2020), North Atlantic Oscillation (Ambaum and Hoskins 2002; Kolstad and Charlton-Perez 2011; Choi et al. 2020), western Pacific (Orsolini et al. 2009; Nishii et al. 2010; Dai and Tan 2016; Bao et al. 2017), and Pacific–North American (Li et al. 2018) patterns. However, recent studies have also documented an impact of the SCA pattern on the stratosphere (Lee et al. 2020; Wang and Tan 2020). They proposed that the SCA pattern can result in changes of the stratospheric polar vortex strength and temperature. Wang and Tan (2020) also pointed out that the influence on stratosphere varies with different types of the SCA pattern. In addition, some tropospheric precursors such as Ural blockings, which resemble the SCA pattern, are found to influence stratospheric variability (Martius et al. 2009; Kolstad et al. 2010; Nishii et al. 2011; Karpechko et al. 2018; Peings 2019; White et al. 2019).

The coupling between troposphere and stratosphere is established through the upward propagation of planetary wave activity (e.g., Scaife and James 2000; Chen et al. 2003; McDaniel and Black 2005; Plumb 2010; Bancelá et al. 2012; Attard et al. 2016; Huang et al. 2018). The planetary waves are mainly generated in the troposphere due to topography, land–sea contrast, regional diabatic heating, and internal variability of tropospheric weather systems, and they transport westward angular momentum upward to the stratosphere when the mean flow is westerly (Andrews and McIntyre 1976; Dunkerton et al. 1981;

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FIG. 1. The SCA pattern and variation in its amplitude. (a) The sixth REOF (REOF6) mode of winter-mean geopotential height (Z) anomalies (m; interval: 15 m) at 300 hPa. Solid (dashed) contours indicate positive (negative) anomalies, and zero contours are omitted. (b) The normalized principal component of REOF6 (bars) and winter-mean SCA index obtained from CPC/NOAA (black line).

Baldwin and Dunkerton 2001). Accompanied with the upward propagation into the stratosphere, the planetary waves are responsible for the deceleration of zonal winds and weakening of the polar vortex (e.g., Polvani and Waugh 2004; Limpasuvan et al. 2005; Garfinkel et al. 2010; Kolstad and Charlton-Perez 2011; Martineau and Son 2015), which further induce extreme stratospheric variability such as sudden stratospheric warmings (SSWs; Matsuno 1971).

Based on the above studies, it is suggested that the SCA pattern exerts influence on the stratosphere, but here we find that the stratospheric circulation exhibit quite different features between its positive and negative phases. Therefore, this work aims to analyze this asymmetric influence of SCA phases on stratosphere and the remainder of the paper is organized as follows. Section 2 describes the data, definitions, and methods. Section 3 investigates the asymmetric responses in the stratosphere associated with the two SCA phases. Section 4 further diagnoses the corresponding evolutions of planetary waves. Section 5 compares their different influence on SSWs and section 6 presents the discussion and conclusions.

2. Data, definitions, and methods

The data used in this study are obtained from the latest European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5; Hersbach et al. 2020) from 1979 to 2018. This dataset is obtained at a horizontal resolution of $2.5^\circ \times 2.5^\circ$ and 37 pressure levels from 1000 to 1 hPa.

The boreal winter is defined as the period from December to February (DJF) with the omission of 29 February in leap years. All the hourly data are converted to daily mean values and daily anomalies are calculated as deviations by removing the 40-yr mean of that particular day from the raw data. The daily index is normalized by removing the winter mean and then dividing by their standard deviation.

The SCA pattern is obtained from the rotated empirical orthogonal functions (REOFs) on winter-mean geopotential height (Z) anomalies at 300 hPa over Eurasian sector (20° – 87.5°N , 60°W – 150°E), following Wang and Tan (2020). The sixth REOF (REOF6), featured as an anticyclonic anomaly over the east of Scandinavia, is identified as the positive phase of the SCA pattern (SCA^+) with an explained variance of 8.6% (Fig. 1a), which is significantly separated from neighboring modes according North et al. (1982). The principal component (PC) time series is highly correlated with monthly SCA index provided by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (CPC/NOAA; $r = 0.71$, p value < 0.01), confirming the reproducibility of the definitions (Fig. 1b). Then, the daily SCA index is computed by projecting daily 300-hPa Z anomalies onto the REOF6 pattern. Finally, an SCA^+ event is denoted when the normalized daily SCA index is greater than 1 standard deviation for at least 4 days to eliminate the high-frequency variability, and the day with the maximum index is used as the reference (day 0), and vice versa. To ensure independence, two events should be spaced at least 15 days apart, as the e -folding time scale of the

FIG. 2. Asymmetry between SCA^+ and SCA^- events. Composites of Z anomalies (m; interval: 75 m) at (a),(b) 10, (c),(d) 100, and (e),(f) 300 hPa when (left) SCA^+ and (right) SCA^- events occur. Solid (dashed) contours indicate positive (negative) anomalies, and zero contours are omitted. Values significant at 95% confidence level are shaded. Rectangles refer to the definition areas of the Z10 index.

daily SCA index is about two weeks. Accordingly, 41 SCA^+ events and 43 SCA^- events are identified.

Time-lag composites are performed to analyze the large-scale circulation associated with these SCA events, where days $-N$ and $+N$ refer to the composite at N days before and after the reference day, respectively. The two-tailed Student's t test is used to assess statistical significance by comparing the composite days with the other days during the boreal winter (Wilks 2006). The effective degrees of freedom (N^*) are computed by lag-one autocorrelation (r_1) as $N^* = N_0 \times (1 - r_1) / (1 + r_1)$ for each variable at each grid, where N_0 is the original length of the time series (Zwiers and von Storch 1995). The zonal Fourier harmonic analysis is employed to extract zonal wavenumbers 1 (WN1) and 2 (WN2) components from eddy height, by removing zonal mean from raw Z (van Loon et al. 1973), and the wave amplitude is computed as $\text{amp}(n) = \sqrt{a(n)^2 + b(n)^2}$, where a and b refer to the real and imaginary coefficients of each component (n). Two-dimensional Eliassen–Palm (E–P) flux is used to measure the propagation of planetary waves following Edmon et al. (1980) and only the vertical component is shown in the present study.

3. Large-scale circulation anomalies associated with two SCA phases

a. Different vertical structure between two SCA phases

Figure 2 compares the day 0 composites of Z anomalies at three typical height levels, 300, 100, and 10 hPa, between two SCA phases. In general, the circulation exhibits analogous and symmetric patterns in the troposphere, but asymmetric patterns in the stratosphere. In the troposphere, both events are featured as a triple centered pattern with three major centers over the Mediterranean, Scandinavian Peninsula, and central Siberia, respectively (Figs. 2e,f), as mentioned in previous

studies (Bueh and Nakamura 2007; Liu et al. 2014). The daily composite pattern in the troposphere also agrees closely with the interannual result (Fig. 1a). However, an apparent asymmetry occurs in the stratosphere. There is no obvious anomaly at 10 hPa at the peak of the SCA^+ events (Fig. 2a), whereas a prominent triple centered pattern is found for the SCA^- events (Fig. 2b). The three centers for the SCA^- events correspond to the tropospheric anomalies, except for a westward displacement of the western center over North America. To measure the strength of stratospheric anomalies, a Z10 index is defined as the difference of area-averaged 10-hPa Z anomalies between North America ($50^\circ\text{--}80^\circ\text{N}$, $120^\circ\text{--}40^\circ\text{W}$) and the Scandinavian Peninsula ($40^\circ\text{--}70^\circ\text{N}$, $10^\circ\text{W--}45^\circ\text{E}$), shown as rectangles in Figs. 2a and 2b. Specifically, the intensity of SCA^+ and SCA^- indices defined at 300 hPa is comparable (2.1 vs -1.9), but the Z10 indices are quite distinct between SCA^+ (-8.4 m) and SCA^- (443.5 m) events and their difference is significant at the 95% confident level. Combined with the circulation at 100 hPa (Figs. 2c,d), the anomalies reduce with altitude for the SCA^+ events, but are maintained or intensified with height for the SCA^- events, implying different vertical structures between SCA phases.

Figure 3 displays the height–longitude cross section averaged over $45^\circ\text{--}75^\circ\text{N}$ at day 0. The results confirm the notable differences in vertical structures between SCA phases. For SCA^+ events, prominent circulation is confined mainly to the troposphere, with peak values around 300 hPa (Fig. 3a). Besides, there is no obvious anomaly in the stratosphere, consistent with the results in Fig. 2a. In contrast, for the SCA^- events, all three centers extend from the troposphere to stratosphere with a slight westward tilt (Fig. 3b), consistent with upward propagation. In particular, the major center over Scandinavia exhibits comparable and continuous anomalous amplitude from the surface to the midstratosphere, implying a coupling between troposphere and stratosphere. Additionally, the differences between SCA phases are statistically significant over North America and the Scandinavian Peninsula in the

FIG. 3. Contrasting vertical structure of SCA events. Height–longitude cross section of Z anomalies (m; interval: 50 m) averaged over 45° – 75° N at day 0 for (a) SCA^{+} and (b) SCA^{-} events. Solid (dashed) contours indicate positive (negative) anomalies, and zero contours are omitted. Values significant at 95% confidence level are shaded.

stratosphere (figure not shown), confirming the discrepancy in stratospheric circulation between SCA phases.

b. Evolutions of circulation anomalies associated with two SCA phases

Figure 4 demonstrates the evolutions of SCA^{+} events in the troposphere and stratosphere, represented by the composites of Z anomalies at 300 and 10 hPa, respectively. Prominent stratospheric anomalies are present during the decaying stage of SCA^{+} events, which means that the development of this stratospheric circulation lags behind that in the troposphere. In the troposphere, the SCA pattern manifests as a Rossby wave train, extending northeastward over the Atlantic a few days before the peak (Fig. 4b), and matures over Scandinavia at day 0 as expected (Fig. 4c). However, in the stratosphere, Z anomalies only occur following the peak, after day +4 (Figs. 4d–f). Specifically, the stratospheric circulation anomalies develop from negative height anomalies over western Siberia and positive anomalies over Canada at day +4 onward, which are linked to the SCA^{+} anomalies in the troposphere but shifted westward with height (Fig. 4d), as expected for upward propagating waves. Anomalies then migrate westward over North America and reach their maximum around day +8 (Fig. 4e). Note that the positive height anomaly occupies the majority of the polar region, with a large zonal mean component suggesting a weakening of the stratospheric polar vortex and westerlies. This reveals the lagged impact of SCA^{+} events on stratospheric circulation.

The result for the SCA^{-} events, shown in Fig. 5, indicates a different evolution of stratospheric circulation. Unlike the lagged response for the SCA^{+} events (Fig. 4), the stratospheric anomalies show synchronous development with the troposphere for the SCA^{-} events. The anomalies at both levels are featured as Rossby wave trains with three major centers. Along with the evolution in the troposphere, the height anomalies in the stratosphere are gradually formed from North America across Scandinavia and then into central Siberia (Figs. 5b–d). As a result, the anomalies at both levels reach their strongest intensity simultaneously around day 0 (Fig. 5c) and then weaken afterward (Figs. 5d–f). Therefore, the asymmetric vertical structures (Fig. 3) are linked to the lead–lag evolutions of stratospheric circulation between SCA phases.

Figure 6 compares the temporal evolutions of the SCA index and Z10 index between SCA phases. The SCA index, referring

to the variability of tropospheric circulation, shows a symmetric variation between two SCA phases (Fig. 6a). However, the associated change of Z10 index displays asymmetry (Fig. 6b), suggesting asymmetric evolution of stratospheric anomalies. For the SCA^{+} events, the Z10 index is only prominent during the decaying stage from day +5 to day +15. In contrast, the index for the SCA^{-} events is significant during the developing and peak stage from day –10 to day +2 before reversing. The two SCA phases evidently exhibit asymmetric impacts on the stratospheric circulation. A lagged influence on the stratosphere occurs for the SCA^{+} events, whereas a synchronous response is found for the SCA^{-} events.

4. Planetary waves associated with different SCA phases

Results in the preceding section explore the different impact of SCA phases on stratosphere, suggesting asymmetric features in stratosphere–troposphere coupling. It is well known that the variability of stratospheric circulation is modulated by planetary waves, especially for WN1 and WN2 (Charney and Drazin 1961; McIntyre and Palmer 1983). This section therefore investigates planetary waves associated with SCA phases.

Figure 7 shows the time–height cross section of planetary wave amplitude anomalies along 60° N to represent their variation in the strength. The results reveal that the different stratospheric responses shown in the previous section are related to changes of wave amplitude, especially for WN1. For the SCA^{+} events, a significant amplification of WN1 occurs to day 0 in the troposphere and then in the stratosphere from day +5 to day +15 (Fig. 7a), when the stratospheric anomalies are most prominent (Fig. 6b). For SCA^{-} events, WN1 amplitudes are strengthened from day –10 to day 0 and tend to be weakened afterward in the stratosphere (Fig. 7c). The asymmetric development of stratospheric WN1 amplitude is consistent with the asymmetric evolution of the Z10 index (Fig. 6b), both of which are increased after SCA^{+} but before SCA^{-} events. Additionally, tropospheric wave amplitude precedes the stratospheric amplitude in both SCA phases, consistent with the upward propagation of planetary waves and its interaction with evolving stratospheric winds. Changes of WN2 amplitude occur simultaneously with the SCA phases (Figs. 7b,d) with a strengthening of WN2 in SCA^{+} and a weakening during SCA^{-} (cf. Lee et al. 2020) that is confined to

FIG. 4. Evolution of SCA^+ events. Composite evolutions of 300-hPa (shading) and 10-hPa (contours; interval: 75 m) Z anomalies for SCA^+ events. Thick segments represent regions significant at 95% confidence level. Solid (dashed) contours indicate positive (negative) anomalies, and zero contours are omitted.

the lower stratosphere, as expected if propagation is limited by strong stratospheric westerlies (e.g., [Charney and Drazin 1961](#)).

Figure 8 compares the height–longitude cross section of planetary wave anomalies, overlapped with their corresponding climatological means. It reveals the interference between anomalous waves and mean waves. Here, the WN1 is averaged from day -10 to 0 and day $+5$ to $+15$, while WN2 is averaged from day -5 to $+5$, when the wave amplitudes are prominent (Fig. 7). Previous studies have shown that the vertical propagation

FIG. 5. Evolution of SCA^- events. Composite evolutions of 300-hPa (shading) and 10-hPa (contours; interval: 75 m) Z anomalies for SCA^- events. Thick segments represent regions significant at 95% confidence level. Solid (dashed) contours indicate positive (negative) anomalies, and zero contours are omitted.

between troposphere and stratosphere can create wave interference (e.g., [Nishii et al. 2009](#); [Smith et al. 2010](#); [Smith and Kushner 2012](#)). The results confirm that the difference of planetary wave activity between SCA phases results from their interference with climatological waves. For the SCA^+ events, the WN1 and WN2 anomalies are in phase with their winter mean patterns from day $+5$ to day $+15$ and from day -5 to day $+5$, respectively (Figs. 8b,c), so that both wave amplitudes are enhanced (Figs. 7a,b). However, for the SCA^- events, the

FIG. 6. Temporal evolutions of the normalized (a) SCA index and (b) Z10 index for SCA^+ (red) and SCA^- (blue) events. Thick segments represent values significant at 95% confidence level.

wave anomalies are out of phase after the peak (Figs. 8e,f), corresponding to the decreased wave amplitudes (Figs. 7c,d), except for some in-phase WN1 anomalies before day 0 (Fig. 8d). Thus, the above results reveal that the constructive interference occurs in SCA^+ and destructive in SCA^- events.

Figure 9 shows the temporal evolutions of vertical E-P flux (F_z) anomalies at 100 hPa along 60°N , which is widely used to represent the propagation of planetary waves from the troposphere into the stratosphere (e.g., Andrews and McIntyre 1976; Polvani and Waugh 2004; Chen et al. 2005; Nath et al. 2016; Hoshi et al. 2019). The evolutions of both waves are consistent with the results for wave amplitudes (Fig. 7). For WN1,

enhanced upward wave fluxes can be seen from day +5 to +15 for SCA^+ events, but from day -10 to day 0 for SCA^- events (Fig. 9a). Additionally, the WN1 fluxes decrease after day 0 for SCA^- events, indicating reduced vertical propagation. The evolutions of WN1 fluxes resemble the results for the Z10 index shown in Fig. 6b, with a significant peak after SCA^+ events and before SCA^- events, suggesting its dominant role in asymmetric stratospheric variations related to SCA events. As for the vertical fluxes of WN2, the upward and downward fluxes peak after SCA^+ and before SCA^- events (Fig. 9b). We note that for SCA^+ events, the WN1 and WN2 increases occur at the same time, further enhancing the wave flux into the stratosphere prior

FIG. 7. Planetary waves associated with the SCA pattern. Wave amplitude anomalies (m) of (left) wavenumber 1 (WN1) and (right) wavenumber 2 (WN2) at 60°N for (a), (b) SCA^+ and (c), (d) SCA^- events. Values significant at 95% confidence level are stippled. Amplitudes are scaled by $1/\sqrt{1000/p}$ to better show the connections between troposphere and stratosphere and a 5-point smoothing is applied at time to eliminate the noise (i.e., the value at day 0 is smoothed by the ones between day -2 and day +2).

FIG. 8. Height–longitude cross sections of (left), (center) WN1 and (right) WN2 anomalies (shaded; m) and their winter mean (contours; interval: 25 m) at 60°N averaged over periods in the right corner for (a)–(c) SCA^+ and (d)–(f) SCA^- events. Values are also scaled by $1/\sqrt{1000/p}$ as in Fig. 7. Anomalies significant at 95% confidence level are stippled. Solid (dashed) contours indicate positive (negative) values, and zero contours are omitted.

to the subsequent deceleration of the mean winds, whereas for SCA^- they occur in opposition, with the increase in WN1 accompanied by a decrease in WN2.

5. Asymmetric relationships between SSW and two SCA phases

The preceding section reports apparent differences in stratospheric planetary waves between two SCA phases. It has been noted that the enhanced planetary waves can cause the weakening of circumpolar westerlies in the stratosphere (e.g., Polvani and Waugh 2004; Li et al. 2013; Dunn-Sigouin and Shaw 2015; Waugh et al. 2017; Butler et al. 2020; Lim et al. 2021). Under certain circumstances, SSWs are defined when the zonal winds reverse from westerly to easterly (Andrews et al. 1987; Limpasuvan et al. 2004; Charlton and Polvani 2007). Therefore, this section aims to figure out the asymmetric relationships between SSWs and SCA patterns.

Figure 10 composites the zonal-mean zonal wind anomalies along 60°N. There is a dramatic reduction in zonal winds

following SCA^+ (Fig. 10a), but no equivalent strengthening for SCA^- events (Fig. 10b). Specifically, successive and prominent easterly anomalies are found above 50 hPa after SCA^+ events, whereas the anomalies seem to be weak relevant to SCA^- events. The asymmetric evolutions of stratospheric westerlies between SCA phases are resulted from the changes of planetary waves, as both WN1 and WN2 peak coincidently in SCA^+ but offset in SCA^- events (Fig. 9). Besides, the asymmetric variations of stratospheric winds are also in agreement with the results in section 3b, which indicate a prominent stratospheric circulation after SCA^+ events (Fig. 4) but insignificant one after SCA^- events (Fig. 5).

The above result suggests that the continuously decelerated westerlies following SCA^+ events tend to be linked to SSWs. Here, the occurrence of a major SSW event is explored using the reversal of the 10-hPa zonal-mean zonal wind at 60°N as its central date (Charlton and Polvani 2007). On this basis, 22 SSW events are identified in the winters of 1979–2018 with an average frequency of 0.54 per year and 0.18 per month, similar to that found in previous studies (e.g., Charlton and Polvani 2007;

FIG. 9. Evolution of planetary wave activity fluxes during SCA events. Vertical Eliassen–Palm (E-P) flux (F_z ; $10^4 \text{ m}^2 \text{ s}^{-2}$) anomalies along 60°N at 100 hPa of (a) WN1 and (b) WN2 for SCA^+ (red) and SCA^- (blue) events. Thick parts represent the values significant at 95% level.

FIG. 10. Time–height sections of zonal-mean zonal wind anomalies (m s^{-1}) along 60°N for (a) SCA^+ and (b) SCA^- events. Values significant at 95% confidence level are stippled.

Butler et al. 2017; Choi et al. 2019). The occurrences of SSW events preceded by SCA events are analyzed (Table 1). When the central date of an SSW event is within 30 days after an SCA event, it is considered to be related to the corresponding SCA phases; otherwise it is categorized as a neutral event. The results are not very sensitive to the threshold when using different intervals of 20 or 15 days. Statistical analysis confirms that the SSW events tend to be more frequent after SCA^+ events with 95% significance according to a binomial probability test. Additionally, the difference of SSW frequency between SCA phases (0.29 vs 0.12) is also significant at the 95% confident level. The central dates of SSW events and their corresponding type of SCA pattern are listed (Table S1 in the online supplemental material). The occurrence of SSW events is similar to that in previous work (e.g., Dai and Tan 2016; Choi et al. 2019; Lee et al. 2019), suggesting the consistence in different studies. Moreover, Lee et al. (2019) analyzed the SSW event of 12 February 2018 and found a tropospheric precursor resembles the SCA^+ pattern. The present results further demonstrate the important role of SCA^+ pattern that precedes the SSWs, which implies a role in SSW prediction.

6. Conclusions and discussion

We investigated the stratosphere–troposphere couplings associated with SCA phases during the boreal winters of 1979–2018 and found that positive and negative phases exhibit different impacts on stratospheric circulation. In the troposphere, the SCA^+ and SCA^- events feature wavelike anomaly patterns that develop across the Atlantic to the Mediterranean, across the Scandinavian Peninsula and then to central Siberia, which has been discussed in previous studies (Bueh and Nakamura 2007; Wang and Tan 2020) with similar amplitude and strong symmetry between opposite phases. However, the SCA phases show difference in vertical structure. Anomalies are limited to the troposphere during SCA^+ events, without obvious anomalies above 100 hPa, but they extend vertically into the upper stratosphere during the SCA^- events. This difference is related to the different temporal evolution of SCA effects on upper tropospheric wave amplitudes. These vary by interference with climatological waves but peak just before SCA^- and just after SCA^+ .

Comparisons of circulation evolution and planetary waves reveal further asymmetric processes in the stratosphere between SCA phases. The SCA^+ events show a lagged weakening of the stratospheric circulation, accompanied by intensification of planetary wave amplitudes, with WN1 showing a more persistent and higher propagation than that of WN2. In contrast SCA^- does not show a corresponding strengthening of the stratospheric circulation. The intensification (weakening) of planetary wave activity during SCA^+ (SCA^-) results from constructive (destructive) interference with climatological waves. In addition, peaks in wave amplitude for WN1 and WN2 occur simultaneously for SCA^+ and in opposition for SCA^- . The combined simultaneous effects of WN1 and WN2 during SCA^+ appear to explain the asymmetry in the lagged response with strong weakening of the stratospheric circulation following SCA^+ and only a weak response following SCA^- .

The relationship between SCA phases and SSW events was also explored. Statistical analysis reveals that SSW events are more likely to follow SCA^+ events than SCA^- events or neutral states. The frequency of SSW preceded by SCA^+ events is nearly 30%, which is significantly higher than its climatological frequency (18%). This phenomenon results from the constructive wave interference and growth of both WN1 and WN2 after the SCA^+ events. The averaged 10-hPa westerly anomalies along 60°N from day 0 to day +30 for the SCA^+ events are -8.2 m s^{-1} , which is significant at the 99% confidence level compared to climatological means. As a result, the decrease of circumpolar zonal winds, accompanied with a rapid increase in stratospheric polar temperature, leads to more frequent occurrence of SSW events after SCA^+ events. Motivated by Wang and Tan (2020), comparisons are conducted between SCA^+ events that followed by SSWs and not (figure not shown). The upper tropospheric anomalies tend to

TABLE 1. The occurrence of SSW events and relationships with SCA phases.

Types	SCA^+	SCA^-	Neutral
No. of SSW events	12	5	5
SSW frequency (events per month)	0.29	0.12	0.10
Binomial probability	97%	17%	10%

be different over the North Atlantic; the positive height anomalies are found in the composites of 12 SCA⁺ events accompanied with SSWs, but are absent in other events. The anomalous circulation might play a role in inducing SSWs by interfering with climatological WN1, resulting in further intensification of upward wave propagation. Apart from the SCA⁺ pattern, it is noticed that some SSW events are also preceded by the western Pacific pattern, as reported in Dai and Tan (2016). It is worthwhile to figure out their relative contributions to the occurrence of SSWs in future works.

This study investigates the asymmetric influence of SCA pattern on stratospheric circulation during the boreal winter from 1979 to 2018. It should be noticed that the SCA pattern itself experiences variability. For instance, the SCA pattern shown in Fig. 1a is farther eastward compared to the results in previous studies (e.g., Barnston and Livezey 1987; Bueh and Nakamura 2007). Considering the difference between study periods, it is found that zonal shift may be attributed to the interdecadal change in late 1970s, which has been mentioned in Liu and Wang (2014). It would be interesting to further explore the decadal link between SCA pattern and stratospheric circulation.

On the other hand, the vertical coupling between SCA pattern and stratospheric circulation might also be established in turn. Based on previous studies concerning the influence of stratosphere on tropospheric teleconnections (e.g., Baldwin and O'Sullivan 1995; Scaife et al. 2005; Kidston et al. 2015), it is reasonable to hypothesize that the SCA pattern might be modulated by stratospheric anomalies as well. The present results show that stratosphere anomalies feature wavelike patterns in the initial stage of SCA events, but the insignificant anomalies indicate a great diversity between SCA events (Figs. 4a and 5a). Therefore, further analysis needs to be done to figure out the specific condition when the stratospheric influence can propagate downward to the SCA pattern.

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