Two Types of the Scandinavian Pattern: Their Formation Mechanisms and Climate Impacts

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ABSTRACT

On the basis of daily data from the Japanese 55-year Reanalysis (JRA-55) for extended winters (December–March) from 1958/59 to 2014/15, this study examines the formation mechanisms and climate impacts of the subseasonal Scandinavian (SCA) pattern. Results indicate that the SCA pattern manifests itself as Rossby wave trains, arising from the initial height disturbances over the North Atlantic and propagating into the Scandinavian peninsula and central Siberia. One type of SCA may arise from a Rossby wave train over the North Atlantic that is closely coupled to an anomalous convective heating dipole and persists for about 2 weeks (convection-preceded SCAs). Another type of SCA arises from the weak height disturbances over the North Atlantic; the height disturbance over the Arctic also contributes to the SCA formation, with no significant convective heating anomalies being observed in the North Atlantic (convection-free SCAs). The results also indicate that both SCA types may cause strong climate anomalies in the Arctic and Eurasia that persist for about 2 weeks. The surface air temperature (SAT) anomalies assume a dipolar structure with one extremum located over the Greenland Sea through Barents Sea and the other extremum over the Eurasian continent. Associated with the SAT anomalies is a significant increase or decrease of sea ice cover over the Greenland Sea and Barents Sea, while over the Eurasian continent snow depth anomalies are found to occur over eastern Europe, western Asia, and the Russian Far East. Furthermore, as convection-free SCAs propagate vertically into the stratosphere, significant changes of intensity and air temperature of the stratospheric polar vortex are observed.

1. Introduction

The Scandinavian (SCA) pattern, which was originally named the EU1 (Eurasian type 1) pattern by Barnston and Livezey (1987), is a low-frequency teleconnection pattern over the North Atlantic–Eurasian sector. As one of the active atmospheric teleconnections over the region, the SCA pattern may induce significant climate anomalies over Eurasia and the surroundings. In winter seasons for the positive phase of the SCA pattern, most of Eurasia north of 40°N is colder than normal with significant cooling over central Siberia while significant warming is observed over the Greenland–Norwegian Sea and Barents–Kara Sea (Bueh and Nakamura 2007; Liu et al. 2014). It is also found that the interaction of the

SCA pattern with the surface thermal anomalies may lead to a rapid buildup of the surface cold high, which is often followed by a cold-air outbreak toward mid-latitude East Asia (Takaya and Nakamura 2005a,b). Particularly, a farther eastward movement of the positive-phase SCA pattern enhances the low-level Siberian high and dramatic surface air temperature (SAT) drops are found to occur over China about one week later (Bueh et al. 2011). Sohn et al. (2011) and Wei et al. (2014) further found that the SCA pattern is responsible for the leading mode of interannual East Asian winter monsoon variability.

Bueh and Nakamura (2007) examined the maintenance mechanism of the SCA pattern and found that the upstream portion of the SCA pattern is forced and maintained by the feedback forcing from high-frequency eddies along the Atlantic storm track, while the downstream portion of the SCA pattern over the Eurasian continent manifests itself as a Rossby wave train propagating from the North Atlantic across the Scandinavian peninsula into central Siberia, which is

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also subject to the feedback forcing from local high-frequency eddies. More recently, Liu et al. (2014) found that the Scandinavian center of the SCA pattern may also be forced by the wind divergence over the region across western Europe into the eastern Mediterranean Sea.

Due to the use of monthly mean data, Bueh and Nakamura (2007) were unable to describe the day-to-day evolution process of the SCA pattern and underlying dynamics, which are important for both the understanding of the formation mechanism of the SCA pattern and the prediction of the climate anomalies and thus become the subject of the present study. Very recently, Dai et al. (2017) and Dai and Tan (2019) found that atmospheric teleconnection patterns such as the Pacific–North American (PNA) and the eastern Pacific (EP) patterns may be driven by the anomalous convection over the tropical western Pacific. These findings motivate us to examine in this study whether a similar situation occurs for the SCA pattern. It turns out that part (more than half) of the SCA events in our study period are preceded by anomalous convection events over the North Atlantic. The formation mechanisms and climate impacts of both the convection-preceded and convection-free SCA patterns are the subject of this study.

2. Data and methods

This study uses daily data from the Japanese 55-year Reanalysis (JRA-55) (Ebata et al. 2011; Kobayashi et al. 2015) for extended winters [December–March (DJFM)] from 1958/59 to 2014/15, with a horizontal resolution of $1.25^\circ \times 1.25^\circ$. Variables used include daily geopotential height, air temperature, horizontal winds, and convective heating rate at standard pressure levels, as well as air temperature at 2-m height, sea ice concentration, and snow depth. Anomalies for daily variables at each grid point are obtained by removing the seasonal cycle, which is defined as a 31-day running mean of the 57-winter mean value for each calendar day. The interannual variability of the anomalies is also eliminated by removing the winter mean.

The SCA pattern is obtained from the rotated empirical orthogonal functions (REOFs) of DJF-mean 300-hPa geopotential height (Z300) anomalies over the Eurasian sector (20° – 87.5° N, 60° W– 150° E) for 1958/59–2014/15 winters in a way similar to Liu et al. (2014). First, the 10 leading EOFs are obtained, and then a varimax rotation is performed. The seventh REOF is identified as the SCA pattern and the positive phase corresponds to an anticyclonic anomaly to

FIG. 1. The SCA pattern defined as the seventh REOF mode of the DJF-mean Z300 anomalies over the Eurasian sector (20° – 87.5° N, 60° W– 150° E) for 1958/59–2014/15 winters. Contour interval is 10 m with zero contours omitted.

the east of Scandinavia (Fig. 1). The daily SCA index is then obtained by projecting daily Z300 anomalies onto the SCA pattern and then standardized. The projection area is 20° – 87.5° N, 0° – 150° E in order to better describe the structure of the SCA pattern over the Eurasian continent.

Both lagged composites and lagged regression are performed to show the formation process of the SCA pattern and its associated climate impacts. As the two phases of the SCA pattern present nonlinearities, lagged composites are performed separately for positive and negative SCA events. The statistical significance of most lagged composites is assessed with a Student's t test, while a Monte Carlo simulation with 1000 randomly generated composites is used to estimate the statistical significance of lagged composites of polar vortex index, area-mean temperature anomalies, and area-mean vertical wave activity fluxes. We evaluate the statistical significance for lagged regressions following Kosaka et al. (2012). The number of effective degrees of freedom N_{eff} corresponds to

$$N_{\text{eff}} = \frac{N}{1 + 2 \sum_{\tau=1}^{\tau=\tau_{\text{max}}} \left(1 - \frac{\tau}{N}\right) [r_x(\tau)r_y(\tau)]}.$$

Here N is the length of time series x and y , and r_x and r_y are the autocorrelation functions for x and y , respectively, with a lag of τ days. The maximum lag τ_{max} is set to be the maximum number that does not exceed $N/2$.

In addition to SAT, snow depth, and sea ice cover, the impact of the SCA pattern on the stratospheric polar vortex is also examined in the present study. To measure the intensity of the polar vortex, a polar vortex index is defined following Kolstad et al. (2010) and Woo et al. (2015) as Z_p , where

$$Z_p = -\sum(Z' \cos\phi) / \sum(\cos\phi).$$

FIG. 2. Lagged regressions of Z300 anomalies upon the daily SCA index. Contour interval is 10 m with zero contours omitted. Shading indicates the 95% confidence level based on a Student's t test.

Here, Z' is the geopotential height anomaly at 10 hPa, φ is the latitude, and the sum is performed over the region north of 65°N . According to the above definition, a positive polar vortex index represents a strong polar vortex and negative geopotential height anomalies over the polar region.

3. Results

a. Structure and evolutionary features of the SCA pattern

Shown in Fig. 1 and the panel of day 0 in Fig. 2 are the two SCA patterns based on seasonal-mean and daily Z300 anomalies, which describe the interannual and subseasonal variability of Z300 anomalies, respectively. We see that the subseasonal SCA pattern (Fig. 2, day 0) highly resembles the interannual SCA pattern (Fig. 1) for the Scandinavian and Siberian centers. An apparent difference occurs in the North Atlantic center. The Atlantic center for the interannual case is located in the northeastern Atlantic, whereas for the subseasonal case the North

Atlantic center extends widely from the North Atlantic into the Arctic with two subcenters over Baffin Bay and the western Mediterranean Sea, respectively. Actually, we will show that these two subcenters are the imprints left by different types of SCA.

The autocorrelation of the daily SCA index indicates that the SCA has an e -folding time scale of about 1 week. This implies that the lifespan of the SCA pattern is about 2 weeks. To see the formation and development features of the subseasonal SCAs, we now examine lagged regressions of Z300 anomalies against the daily SCA index (Fig. 2). As can be seen, the SCA pattern manifests itself as a Rossby wave train propagating from the North Atlantic across the Scandinavian peninsula into central Siberia. Clearly, the height disturbance over the North Atlantic, Alaska, and the Arctic near the Eurasian continent contribute to the initial formation of the SCA pattern (days -15 to -12 ; Fig. 2). As we will see, these weak height disturbances are actually the imprints of initial disturbances of different SCA types. The full SCA pattern forms around day -3 with the three main centers located over

the northern North Atlantic, Scandinavian peninsula, and central Siberia, respectively. The SCA pattern matures at day 0 and decays afterward. The most attractive feature revealed in the evolutionary process of the SCA pattern is the downstream development: the two anomalous height anomalies over the North Atlantic remains stationary with the Scandinavian center and Siberian center forming in turn as new height anomalies in the downstream region of the two height anomalies over the North Atlantic.

b. Features of convective heating

We now look at the lagged regressions of convective heating rate anomalies against the daily SCA index (Fig. 3). From Fig. 3 we do see an active convective heating dipole over the extratropical North Atlantic with one extremum over the Gulf Stream extension and the other over the northeastern North Atlantic, which is in contrast to the PNA and EP teleconnection case where the anomalous convective heating dipole is located over the tropical western Pacific (Dai et al. 2017; Dai and Tan 2019). This convective heating dipole occurs as early as around day -18 . Afterward, it intensifies rapidly and peaks at around day -6 . Then, it begins to decay. The vertical cross section along the two extrema of the convective heating dipole at day -6 [see Fig. S1 (upper left) in the online supplemental material] indicates that the convective heating anomalies are confined mainly within the lower troposphere with the maximum convective heating at around 850 hPa. This type of convective heating is termed the “shallow convective heating mode,” in contrast to the “deep convective heating mode” with the peak value at around the 500-hPa level (Minobe et al. 2010). This shallow convective heating mode is frequently observed over the region from the Gulf Stream extension northeastward into the northeastern North Atlantic and the Barents Sea (Fig. S1, bottom; Minobe et al. 2008; Minobe et al. 2010; Ling and Zhang 2013). It is believed that the boundary convergence associated with the sea surface temperature (SST) front and the extratropical frontal cyclones may play some roles in the formation of the shallow convective heating mode over the Gulf Stream extension, but the exact mechanisms still remain unclear (Minobe et al. 2010; Madonna et al. 2014; Parfitt and Seo 2018).

To describe the convective heating dipole and its relation to the SCA quantitatively, we define the convection index (CI) by projecting the daily 850-hPa convective heating rate anomalies onto the 2-week mean [from day -14 to day -1 ; see Fig. S1 (upper right) in the online supplemental material] of the daily

convective heating anomalies over the North Atlantic sector (20° – 70° N, 70° W– 0°) shown in Fig. 3. We choose a 2-week average because the regressed convective heating anomalies remain stationary and vary in magnitude slowly with time lag. A normalized CI is used as a measure of intensity of the convection pattern, with positive (negative) CI indicating reduced (enhanced) convection over the Gulf Stream extension and enhanced (reduced) convection over the northeastern North Atlantic. The autocorrelation and histograms of the convection index indicate that the convection events have an e -folding time scale of 4 days and satisfy approximately the normal distribution (not shown). How the convective heating dipole contributes to the SCA formation will be examined just below.

c. Formation features of convection-preceded and convection-free SCA events

The above result indicates that the SCA is closely linked to the convective heating dipole over the North Atlantic. To show more clearly the formation features of the SCA patterns, we divide the SCAs into two categories: convection-free and convection-preceded events, and examine their formation processes separately. To show possible asymmetry of the SCA of different phases, positive and negative SCA patterns are also examined separately. To this end, we define a SCA event if the standardized SCA index exceeds one standard deviation for 4 consecutive days, and the day of the peak SCA index is denoted as day 0. Two events must be more than 15 days apart; otherwise, only the stronger one is retained to ensure independency. A SCA event is considered as a convection-preceded event if the absolute value of the mean convection index over day -10 to day -1 exceeds 0.5; otherwise, a SCA event is considered as convection-free if the absolute value of the mean CI over day -10 to day -1 is no more than 0.4. The choice of this threshold is to ensure that the sample size for each group is sufficiently large for composite analysis. The results thus obtained are not very sensitive to the threshold used.

Based on the above criteria, we identify 220 SCA events in total for the study period. Among them, 115 events are convection-preceded, and 89 events are convection-free (Table 1), implying that more than half SCA events are convection-preceded. For most of these convection-preceded SCA events (90 events), the SCA and convection are of the same signs [i.e., positive (negative) SCA events are preceded by positive (negative) convection pattern], whereas for the rest of them (25 events) the SCA and convection are of opposite signs [i.e., positive (negative) SCA events

FIG. 3. Lagged regressions of anomalous 850-hPa convective heating rate upon the daily SCA index. Contour interval is 0.2 K day^{-1} with zero contours omitted. Hatching indicates the 95% confidence level based on a Student's t test.

are preceded by negative (positive) convection pattern]. For SCA events with their signs opposite to the convection patterns, we do not take them into further consideration for the reason of small sample size. (The reader is referred to Fig. S2 for details of the evolution

process of Z300 anomalies for positive SCA events preceded by a negative convection pattern.)

Figures 4 and 5 show the formation processes of SCA events represented by lagged composites of Z300 anomalies (contours) based on convection-free

TABLE 1. Numbers of SCA events with or without convection preceded. Here SCA^+ (SCA^-) stands for positive- (negative-) phase SCA events and Conv^+ (Conv^-) stands for positive (negative) convection pattern. Conv-free stands for convection-free SCA events. Boldface values are used in this study.

	All	Conv^+ -preceded	Conv-free	Conv^- -preceded
SCA^+	115	38	47	20
	All	Conv^- -preceded	Conv-free	Conv^+ -preceded
SCA^-	105	52	42	5

and convection-preceded events. The wave activity fluxes associated with the Z300 anomalies (Plumb 1985; Karoly et al. 1989) are indicated by arrows while the convective heating rate anomalies at 850 hPa are indicated by color shading. As can be seen, both types of SCA manifest themselves as Rossby wave trains propagating from the North Atlantic into the Eurasian continent and they distinguish themselves very clearly in the early stages of development.

For positive convection-free SCA events, the height anomalies and the wave activity fluxes indicate that the SCA manifests itself as a Rossby wave train originating from a positive height anomaly over the midlatitude Atlantic (Fig. 4, left). The North Atlantic center of the SCA pattern forms around day -8 , located over the southern North Atlantic for this case rather than the northeastern North Atlantic as in other types of the SCA pattern (Fig. 4, right; Fig. 5). The Scandinavian center appears at day -2 ; apparently, the negative height anomaly over Greenland also contributes to the development of the Scandinavian center through direct downstream energy propagation (day -6 to day -2 ; Fig. 4, left). The Siberian center of the SCA is found to occur at day -2 , which is a sign of the formation of full SCA pattern. The SCA pattern matures at day 0 and decays afterward.

Differently for negative convection-free SCA events, it develops from two local circulation anomalies over the northeastern Atlantic and the Arctic region near the northern Asian continent, which appear at around day -10 (Fig. 4, right). As we noted previously, the Arctic signal also appears as a precursor in the regression map (Fig. 2). Afterward, the two anomalies continue to amplify, with the North Atlantic anomaly remaining stationary and the Arctic anomaly moving westward. These two anomalies evolve finally into the North Atlantic and Scandinavian centers of the SCA, respectively (day -4 ; Fig. 4, right), and the Siberian center appears around day -4 . The SCA pattern matures at day 0 and begins to decay afterward. An apparent westward moving to the northern North Atlantic of the Scandinavian center is observed during the decaying

process of the SCA pattern, which is absent for positive convection-free SCA pattern (Fig. 4, left) and positive and negative convection-preceded SCA patterns (Fig. 5).

In contrast, for convection-preceded SCA events, their early development assumes quite different features from convection-free SCA events (Fig. 5). The most attractive formation feature of the SCA for this case is the appearance of the wave train over the North Atlantic (NA), with the two anomalous centers located over the northern and southern North Atlantic. Interestingly, the two centers of the NA wave train are closely coupled with two convective heating anomalies (shading). For positive convection-preceded SCA events (Fig. 5, left), the positive height anomaly over the Gulf Stream extension of the NA wave train is coupled to a reduced convective heating anomaly, while the negative height anomaly over the northern North Atlantic of the NA wave train is coupled to an enhanced convective heating anomaly. The NA wave train and the two associated convective heating anomalies persist for as long as 2 weeks from day -15 to day 0. Further inspection of the height anomalies and the associated wave activity fluxes indicates that the NA wave train actually develops from a wave train over the Pacific–North American region (day -15 to day -9 ; Fig. 5, left). Actually, the North American wave train and the NA wave train are also seen in the regression map (Fig. 2).

Obviously, the positive convection-preceded SCA pattern manifests itself as a Rossby wave train emanating from the NA wave train and exhibits apparent downstream development feature (Fig. 5, left). The northern North Atlantic center of the NA wave train becomes the North Atlantic center of the SCA pattern, the future Scandinavian center appears at day -9 over the Urals, and the Siberian center appears at day -3 . The SCA pattern matures at day 0 and begins to decay afterward.

Similar formation and development features are observed for the negative phase of convection-preceded SCA events except for the reverse of the sign (Fig. 5, right).

d. Role of high-frequency eddy feedback forcing in the development and maintenance of the NA wave train and the SCA pattern

In this subsection, we further examine the physical meaning of the anomalous convective heating dipole and the role of high-frequency eddy feedback forcing in the development and maintenance of the NA wave train and the SCA pattern. As we saw previously, the convective heating dipole is a shallow heating mode, the two extrema of which occur in the core and exit region of the Atlantic storm tracks, respectively (cf. Fig. 3 to the gray

FIG. 4. Lagged composites of Z300 anomalies (contours), the associated horizontal wave fluxes (arrows), and 850-hPa convective heating rate anomalies (shading) for (left) positive and (right) negative convection-free SCA events. Contour interval is 30 m for Z300 and 1 K day⁻¹ for convective heating rate, with zero contours omitted. Stippling and hatching indicate the 95% confidence level for Z300 and convective heating rate, respectively, based on a Student's *t* test. Only vectors larger than 1 m²s⁻² are shown for brevity.

FIG. 5. As in Fig. 4, but for (left) positive and (right) negative convection-precipitated SCA events.

FIG. 6. Differences of lagged composites of (left) 300-hPa storm-track anomalies (contours) superimposed on the climatology of 300-hPa storm track (shading) and (right) 850-hPa convective heating-rate anomalies, between positive and negative convection-preceded SCA events. The storm track is defined as the square of high-frequency (2–8 day) meridional wind anomalies. Contour interval is $50 \text{ m}^2 \text{ s}^{-2}$ for both the climatology and anomalies of the storm track and is 2 K day^{-1} for convective heating rate, with zero contours omitted. Stippling indicates the 95% confidence level based on a Student's t test.

shading of Fig. 6). Therefore, we believe that the convective heating dipole may be a reflection of the modulations of the NA wave train on the extratropical cyclone–anticyclone (storm tracks) activity over the regions.

To confirm the above argument, we now turn to examine how the storm tracks vary with phases of the NA wave train. Here we define the phases of the NA wave train as the same signs of the corresponding convection-preceded SCA patterns and define the storm tracks as the square of the high-frequency (2–8 days) meridional wind anomalies. Shown in Fig. 6 is the composite difference of the storm tracks between positive and negative NA wave trains. Obviously, for the positive NA wave train, both the storm tracks and convective heating are enhanced over the region of the negative height anomaly of the NA wave train, which is located just at the exit of the climatological Atlantic storm track (gray shading in Fig. 6), and reduced over the region of the positive height anomaly of the NA wave train, which is located at the southern flank of the climatological Atlantic storm track. The reverse is true for negative NA wave train.

Actually, not only the extratropical cyclone–anticyclone activity and the associated convective heating may be modulated by the NA wave train, but also the feedback forcing of the cyclones and anticyclones may in turn contribute to the development and maintenance of low-frequency NA wave trains, as in other types of low-frequency wave trains (Lau and Holopainen 1984; Takaya and Nakamura 2005b; Dai and Tan 2019). To estimate the barotropic component of high-frequency eddy feedback forcing due to solely the vorticity flux convergence, which can be regarded as the net eddy forcing at upper level, a similar procedure as in Takaya and Nakamura (2005b) is adopted. Shown in Fig. 7 are the lagged composites of Z300 anomalies (contours) and the barotropic forcing by the high-frequency (2–8 day) eddies represented as the height tendency (shading) from day –15 to day +6. We see that the height anomalies overlap almost completely the height tendency over the northern center of the NA wave train for both phases of the NA wave train from day –12 to day 0. This suggests that the high-frequency eddies contribute significantly to the development of the northern center of the NA wave train (i.e., the North Atlantic center of the SCA pattern). In the southern center of the NA wave train, no significant height tendency signal is observed for both phases of the NA wave train except for the period from day –6 to day –3 for the negative-phase NA wave train. This implies that the contribution of high-frequency eddies to the development of the southern center of the NA wave train is extremely weak.

Further inspection of Fig. 7 indicates that the high-frequency eddy feedback forcing also has an important contribution to the development and maintenance of the Scandinavian center during day –9 through day +3 for positive convection-preceded SCA pattern, and during day –3 through day +3 for negative convection-preceded SCA pattern. But for the central Siberian center, no obvious contribution from high-frequency eddies is observed. Similarly, for convection-free SCA patterns, the high-frequency eddies also have important contribution to the development and maintenance of the North Atlantic and Scandinavian centers, and no obvious contribution to the development and maintenance of the Siberian center (Fig. S3).

It should be noted that for the SCA pattern as an interannual variability, Bueh and Nakamura (2007) also concluded that the high-frequency eddy feedback forcing makes important contribution to the development and maintenance of the North Atlantic and Scandinavian centers of the SCA pattern for January, which is in agreement with our conclusion.

e. Weather and climate impacts

1) SURFACE AIR TEMPERATURE ANOMALIES

Through strong thermal advection associated with the huge and intense Scandinavian and Siberian centers, the SCA brings about strong SAT anomalies to the Arctic and Eurasia. Since no apparent difference is found for the SAT anomalies between the two types of SCA, we here just take positive convection-preceded SCA events as an example.

As shown in Fig. 8, the SAT anomalies take the form of dipolar structure with one extremum located over an area from the Greenland Sea to the Kara Sea and the other located over a vast area covering almost the whole area of northern Asia north of 45°N. The SAT anomalies persist for about 2 weeks with the peak values observed at day 0 (Fig. 8). The maximum of the SAT anomaly over the Barents Sea can reach as high as +9°C while in central Siberia the maximum SAT anomaly can reach as low as –6°C, which are considerably larger compared to the case of the SCA pattern as an interannual variability (Bueh and Nakamura 2007). The reverse is true for negative convection-preceded SCA events (not shown). For convection-free SCA events, the SAT anomalies also take the form of dipolar structure similar to the above, but with smaller amplitude (not shown).

It should be noted that the SAT anomaly pattern for the subseasonal SCA pattern highly resembles the SAT anomaly pattern for the SCA pattern as a climate variability at interannual time scale (Bueh and Nakamura 2007; Liu et al. 2014) except that the former has a larger

FIG. 7. Lagged composites of low-frequency Z300 anomalies (contours) and geopotential height tendency induced by high-frequency eddies (shading) for (left) positive and (right) negative convection-preceded SCA events. Contour interval is 30 m for height anomalies and 10 m day^{-1} for geopotential height tendency, with zero contours omitted. Stippling (hatching) indicates the 95% confidence level for height anomaly (geopotential height tendency) based on a Student's t test.

FIG. 8. Lagged composites of 2-m air temperature anomalies (shading) and 850-hPa horizontal wind anomalies (arrows) for positive convection-preceded SCA events. Contour interval is 1 K with zero contours omitted. Thick contours indicate ± 3 K and numbers indicate local extrema at day 0. Stippling indicates the 95% confidence level for temperature anomalies based on a Student's t test. Only vectors larger than 2 m s^{-1} are shown for brevity.

magnitude (-6°C) than the latter (-2.7°C). This suggests that the SCA pattern at interannual time scale may be a result of the winter-season mean of the subseasonal SCA.

2) SEA ICE AND SNOW DEPTH ANOMALIES

Because of its profound impacts on SAT, the SCA can also exert significant influence on sea ice over the Arctic and snow depth over Eurasia.

For sea ice anomalies, Fig. 9 indicates that as positive convection-preceded SCA events occur, significant reduction of sea ice cover is observed in the Greenland Sea and Barents Sea, which also persists for about 2 weeks (Fig. 9). The reverse is true for negative convection-preceded SCA events (Fig. S4). For convection-free SCAs, the Greenland Sea and Barents Sea also experience similar sea ice cover anomalies but with a much weaker magnitude, compared to the convection-preceded SCA case (Figs. S5 and S6).

As indicated in Fig. 10, the SCAs, either convection-preceded or convection-free, can bring about significant snow depth anomalies in Europe and western Asia. As positive SCAs occur, the 2-week mean of snow depth is significantly reduced in Europe and enhanced in western

Asia (Fig. 10, top). The reverse is true for negative SCAs (Fig. 10, bottom).

3) POLAR STRATOSPHERIC ANOMALIES

Kolstad et al. (2010) once examined the tropospheric precursors of the stratospheric sudden warming (SSW) and found that the anomalous height anomalies in the troposphere at the early stage of weak stratospheric polar vortex, from day 45 to day 31 before the central day of SSW, resemble the SCA pattern. Actually, the time period for planetary waves to propagate from troposphere to stratosphere is several days to 1 week. In view of this fact, we pay attention to a shorter time period of roughly 20 days before the central date and examine how and to what degree the two SCA types influence the polar stratosphere. Lagged composites of the stratospheric polar vortex index based on convection-free and convection-preceded SCA events indicate that the polar vortex significantly weakens for positive convection-free SCA events from day +3 on, which persists for more than 2 weeks (red curve, Fig. 11, top left), with a rise of an area-mean air temperature north of 65°N of 2K (red curve, Fig. 11, bottom left).

FIG. 9. Lagged composites of anomalous sea ice concentration for positive convection-preceded SCA events. Contour interval is 2% with zero contours omitted. Stippling indicates the 95% confidence level based on a Student's t test.

For negative convection-free SCA events the situation is reversed. A strengthened polar vortex with a cooler condition is observed (blue curve, Fig. 11, left panels), which is statistically significant only for several days after day 0. In sharp contrast, for convection-preceded SCAs, no significant changes are observed in both the polar vortex intensity and air temperature in the stratospheric polar region (Fig. 11, right panels).

The sharp difference in the impacts on the polar vortex may come from the difference in the structure of the two SCA types (convection-free or convection-preceded) and the associated wave activity fluxes entering into the stratosphere. For convection-free SCAs, they are weak disturbances in height field before day -6 (Fig. 4), and correspondingly, the associated wave activity fluxes reaching 100 hPa are also weak before day 0 (Fig. 12, left). However, after day -6, the height anomalies become strong, and the Scandinavian and Siberian centers of the positive (negative) phase SCAs interfere constructively (destructively) with the anomalous centers of climatological waves of wavenumbers 1 and 2 (Fig. S7). [The reason we consider the planetary waves of wavenumbers 1 and 2 is that

for wintertime atmospheric conditions, only planetary waves of wavenumbers 1 and 2 can propagate vertically into the stratosphere (Charney and Drazin 1961).] Consequently, the vertical wave activity fluxes (Plumb 1985) in the stratosphere are significantly enhanced for positive-phase SCAs, and reduced for negative-phase SCAs after day 0 (Fig. 12, left). The persistently enhanced (reduced) vertical wave activity fluxes are favorable for the weakening (strengthening) and warming (cooling) of the polar vortex (Garfinkel et al. 2010; Sjöberg and Birner 2012). For convection-preceded SCAs, Fig. 12 (right) shows that the wave activity fluxes at 100 hPa after day 0 are weaker and persist for a shorter period of time, compared to the convection-free SCAs, because the North Atlantic center of the SCA pattern interferes destructively (constructively) with the climatological waves of wavenumber 1 for positive (negative) convection-preceded SCA pattern (Fig. S7), which offsets partially the corresponding constructive (destructive) interfering effects of the Scandinavian and Siberian centers. Consequently, the weakening (strengthening) and warming (cooling) of the polar vortex with a

FIG. 10. Lagged composites of anomalous snow depth for two types of SCA events, averaged over day -3 to day $+10$. (top left) Positive and (bottom right) negative convection-preceded SCA events. (top right) Positive and (bottom right) negative convection-free SCA events. Contour interval is 0.01 m with zero contours omitted. Stippling indicates the 95% confidence level based on a Student's t test.

weaker degree than the convection-free SCA case would be expected. However, before day -6 , the North Atlantic center of the positive (negative) NA wave train (Fig. 5; also Fig. S8) interferes strongly and destructively (constructively) with the anticyclonic (cyclonic) center of the climatological waves of wave-number 1. As a result, the corresponding vertical wave activity fluxes before day 0 are heavily reduced (enhanced) far below (above) the climatology (Fig. 12, right), which is highly favorable for the strengthening (weakening) and cooling (warming) of the polar vortex and strongly offsets the later weakening (strengthening) and warming (cooling) effects caused by the positive (negative) SCAs. Consequently, no significant changes are observed after day 0 in the intensity and air temperature of the polar vortex for convection-preceded SCAs, as we saw in Fig. 11 (right).

4. Summary and discussion

Based on JRA-55 this study examines the formation features and climate impacts of the SCA pattern as a subseasonal climate variability over wintertime Eurasia. Results definitely show that the SCA patterns distinguish

themselves into two types: convection-free and convection-preceded SCAs.

The positive convection-free SCA pattern manifests itself as a Rossby wave train originating from a positive height anomaly over the midlatitude North Atlantic, while the negative convection-free SCA pattern arises from both a positive height anomaly over the northeastern North Atlantic and a negative height anomaly in the Arctic near the Asian continent. Positive and negative phases of the convection-preceded SCA patterns arise from the NA wave train of two anomalous centers located over the northern and southern North Atlantic, respectively. The NA wave train has its wave source over North America and is closely coupled to an anomalous convective heating dipole, and both the NA wave train and the convective heating dipole may persist for as long as about 2 weeks. This implies that the NA wave train or the convective heating dipole may serve as a good precursor of the SCAs, 2 weeks in advance relative to the mature day of the SCAs.

As the SCA pattern occurs, either convection-free or convection-preceded, Eurasia and nearby Arctic regions experience dramatic weather/climate events for about 2 weeks. The SAT anomalies take the form of a dipolar structure with one extremum over the Arctic and the other extremum over Eurasia, associated with significant anomalies of sea ice cover across the Greenland Sea into the Barents Sea. The spatial patterns of the SAT and sea ice anomalies bear large resemblance to the warm Arctic–cold Eurasian pattern (WACE) (Mori et al. 2014; Kug et al. 2015; Luo et al. 2016; Sung et al. 2018). If we define the WACE index as the difference of area-mean temperature anomalies between the Arctic (70° – 80° N, 30° – 70° E) and Eurasia (40° – 60° N, 60° – 130° E), following Kug et al. (2015) and Luo et al. (2016), the correlation between the SCA index and the WACE index on interannual time scale reaches as high as 0.72, indicating that the SCA contributes to roughly 50% of variance of SAT anomalies caused by the WACE. The result suggests that it is the atmospheric process associated with the SCA that causes the sea ice anomalies over the Greenland Sea and Barents Sea, not the reverse, as Mori et al. (2014) suggested. Particularly, this study suggests that the North Atlantic may influence the Arctic and Eurasia through the convection-preceded SCA pattern on subseasonal time scale.

It should be noted that on interannual time scales, Sato et al. (2014) and Jung et al. (2017) similarly concluded that the SST anomalies over the western North Atlantic may cause the SST and sea ice anomalies over the Barents Sea through triggering a SCA-like wave train propagating from the North Atlantic into eastern

FIG. 11. Lagged composites of (top) the polar vortex index at 10hPa and (bottom) area-mean temperature anomalies over the area north of 65°N at 50hPa for (left) convection-free SCA events and (right) convection-preceded SCA events. Red curves represent positive SCA and blue curves represent negative SCA. Vertical solid lines indicate day 0 of SCA events, and horizontal dashed lines indicate the winter climatology. Thick segments indicate the 95% confidence level based on a Monte Carlo test.

Europe and central Siberia. This SCA-like wave train arises from a height anomaly somewhat west of the southern center of the NA wave train.

This study examines further the impacts of the SCAs on the polar stratosphere. The results show that the impact of convection-preceded SCAs on the polar stratosphere is weak and insignificant. In contrast, for convection-free

SCAs they can cause significant changes of the intensity and air temperature of the polar vortex when they propagate vertically from the troposphere to the stratosphere. Further statistics on SSW–SCA relationships indicates that among 34 SSW events for 55 winters from 1958 to 2013, there are 8 SSW events that are preceded by positive convection-free SCA event

FIG. 12. Lagged composites of the vertical wave activity fluxes at 100hPa associated with planetary waves for (left) convection-free SCA events and (right) convection-preceded SCA events. Red curves represent positive SCA and blue curves represent negative SCA. The vertical wave activity flux is an area-weighted average between 45° and 55° and is multiplied by a factor of 100 for a better graphical display. Vertical solid lines indicate day 0 of SCA events and horizontal dashed lines indicate the winter climatology. Thick segments indicate the 95% confidence level based on a Monte Carlo test.

within 20 days before the central dates of the SSW events (24 February 1966; 20 March 1971; 29 February 1980; 24 February 1984; 11 February 2001; 21 January 2006; 22 February 2008; 9 February 2010), but no positive convection-preceded SCA event is found to occur within 20 days before the central dates of SSWs. A composite of Z300 anomalies based on these 8 SSW events (Fig. S9) shows clearly the appearance of SCA pattern with its Siberian anomaly extending farther to the Russian Far East, which is also favorable for the onset of the SSW events (Garfinkel et al. 2010, 2012). This suggests that a successful prediction of the occurrence of different types of SCA benefits both the surface weather prediction in the Arctic and Eurasia, and the prediction of atmospheric circulation conditions in the polar stratosphere. This is also an interesting question deserving future study.

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