Modulation of a long-lasting extreme cold event in Siberia by a minor sudden stratospheric warming and the dynamical mechanism involved

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Abstract
Previous studies have paid much attention to the impact of major sudden stratospheric warming (SSW) events on the tropospheric circulation. However, the attention to the modulation of minor SSW events on the extreme cold events is limited. In this study, the extreme cold event in Siberia in the winter of 2000/2001, the longest-lasting one from 1980/1981 to 2019/2020, and its linkages to the minor SSW event have been examined. Our results show that the largest cooling occurred in Siberia during 30 December 2000 − 10 January 2001, and then the cooling weakened and migrated to Northeast China from 11 to 18 January 2001. During the recovery stage of this minor SSW event, the stratospheric polar vortex gradually strengthened, along with strengthening of the zonal winds over the Ural region. The vertical distribution of positive zonal wind anomalies in the Ural region favored the reflection of stratospheric planetary wave in the Atlantic-Euro and Siberia region. The changes of planetary wave propagation were beneficial to the strengthening of the trough in the Atlantic-Euro and Siberia region during 26 December − 10 January, which facilitated the growth and maintenance of the Ural ridge in the same period by strengthening the meridional flow. The strengthened Ural ridge resulted in the extreme cold event breaking out and lasting from 30 December to 10 January. Because the stratospheric polar vortex did not continue to strengthen and a new ridge generated in the Atlantic region during 11 − 18 January, the Ural ridge decayed and the cold air moved to Northeast China.

1 Introduction

Sudden stratospheric warming (SSW) events are one of the most important phenomena in the middle atmosphere. According to the World Meteorological Organization (WMO) (Butler et al. 2015), SSW events can be classified into major and minor events. If the temperatures at 10 hPa poleward of 65° N increase by more than 25 K within a week and the zonal mean zonal winds at 10 hPa and 60° N reverse during the same period, this is defined as a major SSW event; otherwise, it is called a minor SSW event. There are many common characteristics between minor and major SSW events (Andrews et al. 1987; Manney et al. 2015). Some studies have revealed that the surface air temperature in the mid-latitude region decreases if the weak stratospheric polar vortex related to major SSW events propagates into the troposphere over the Arctic (e.g., Huang and Tian 2019; Huang et al. 2021; Yu et al. 2018), while some other studies suggested that the surface air temperature decreases in response to minor SSW events (Lan and Chen 2013; Shen et al. 2020a, b; Wang and Chen 2010).

The extreme cold event is one of the most devastating hazards, which could cause extensive damage to the social economy, agriculture, transportation, and so on (e.g., Habeeb et al. 2015; Xu et al. 2018). Some studies showed the positive linear trends of extreme cold event occurrence over most mid-latitude continental regions since the late 1990s (Ding et al. 2021; Johnson et al. 2018). In particular, Eurasia in recent years has suffered from a series of extreme cold events. For example, China experienced abnormal cold events in January–February 2008 that persisted for nearly one month (Hong and Li 2009). And the temperature anomalies associated with the extreme cold event in Eurasia during January–February 2012 exceeded the 2nd percentile in Belgrade and Siberia (Luo
et al. 2014). Due to the extensive damage of these extreme cold events, an increasing number of studies pay attention to their contributing factors and underlying mechanisms.

Many factors were suggested to affect extreme cold events in Siberia region, including the sea ice over the Arctic (e.g., Zhang et al. 2022; Mori et al. 2014), El Niño–Southern Oscillation (ENSO) (e.g., Song and Wu 2022), Arctic Oscillation (AO) (e.g., He et al. 2017) and Pacific Decadal Oscillation (PDO) (e.g., Li et al. 2020). Recently, the relationship between the circulation in the troposphere and stratosphere has been discussed (e.g., Hu et al. 2019, 2021; Lawrence et al. 2020; Ma and Xie 2020; Smith and Polvani 2014; Xie et al. 2017, 2018), especially SSW events (e.g., Domeisen and Butler 2020; Hendon et al. 2019; Kidston et al. 2015; Lü et al. 2020). Some studies suggested that cold extremes over northern Europe and Asia are more intense in the 60 days after a major SSW event (Domeisen and Butler 2020; King et al. 2019). And the extreme cold events that occurred in Eurasia in the winters of 2012/13, 2016/2017 and 2017/18 were all found to be related to major SSW events (Lü et al. 2020; Nath et al. 2016; Tyrifs et al. 2019). Not only the major SSW events, but also the minor SSW events play a role in the extreme cold events (Lan and Chen 2013; Shen et al. 2020a, b; Wang and Chen 2010). Lan and Chen (2013) showed that the anomalous signals related to a minor SSW event appeared half a month earlier than the outbreak of the extreme cold event in the troposphere over Eurasia in 2012. Wang and Chen (2010) suggested that the downward propagation of a minor SSW event contributed to the increasing frequency of extreme cold events over many areas of the mid-latitude Northern Hemisphere in December 2009. Therefore, the links between minor SSW events and extreme cold events are also important. In particular, the cold air that persists over a relatively longer duration could always cause more severe impacts, such as prolonged damage to transportation and heavier agricultural losses (Brummer et al. 2017; Peng and Bueh 2011). It is essential to investigate the durations of the long-lasting extreme cold events and the links to the minor SSWs.

The above studies imply certain impacts of SSW events on extreme cold events over Eurasia. However, the underlying mechanisms of the effects of SSW events on different extreme cold events over Eurasia are different. Some studies suggested that the planetary wave propagated from the troposphere can be continuously absorbed in the stratosphere during the recovery stage of major SSW events, which tended to result in the Northern Annular Mode (NAM) migrating downward from the stratosphere to the troposphere (Kodera et al. 2016; Kretschmer et al. 2018). The signals of the NAM or AO extending downward to the surface act to modulate the temperature and circulation at surface (e.g., Baldwin et al. 2003; Thompson and Wallace 2000). Kolstad et al. (2010) implied that the probability of cold air outbreaks over Eurasia during the negative phase of the AO at the surface increases. The major SSW in January 2010 resulted in cooling over the mid-latitude in the Northern Hemisphere through absorbing the planetary wave (Cohen et al. 2010; Kodera et al. 2016). Planetary waves from the troposphere can also be reflected in the stratosphere during the recovery stage of major SSW events, which further modulate the tropospheric circulation (Kodera et al. 2013; Matthias and Kretschmer 2020; Nath et al. 2014). For instance, planetary waves were reflected to central Eurasia from the stratosphere to the troposphere during the major SSW event in January 2013, which led to the cold air break out via strengthening the trough over central Eurasia (Nath et al. 2016). Therefore, the planetary waves play a key role in the relationship between major SSW events and tropospheric anomalies (Matthias and Kretschmer 2020; White et al. 2019). However, the underlying mechanism of the minor SSWs on the long-lasting extreme cold events is unclear.

In this study, we examined the characteristics of the longest-lasting extreme cold event in Siberia in early winter 2000/2001 during the period of 1980/1981 to 2019/2020, and investigated the linkage between a minor SSW event and this extreme cold event along with the underlying dynamical mechanisms. The rest of the paper is organized as follows: The datasets and method are introduced in Sect. 2. Section 3 describes the characteristics of the extreme cold event in Siberia in winter 2000/2001. The dynamic mechanism is analyzed in Sect. 4. The linkage between minor SSW events and extreme cold events during 1980/1981–2019/2020 are examined in Sect. 5. Section 6 provides conclusions and some further discussion.

2 Datasets and method

This study used the daily mean temperature, horizontal winds, vertical velocity, geopotential height, and surface air temperature from MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, version 2) during 1980–2020, which has 42 pressure levels from the 1000–0.1 hPa on a 0.5° × 0.625° latitude/longitude grid (Gelaro et al. 2017).

\[
\frac{\partial T}{\partial t} = -u \left( \frac{\partial T}{\partial x} \right) - v \left( \frac{\partial T}{\partial y} \right) + \sigma \omega + \frac{\tilde{Q}}{C_p} \quad (1)
\]

The thermodynamic equation was chosen to examined the changes of temperature following Lv et al. (2004): where \( \sigma \) is static stability parameter, \( c_p \) specific heat capacity of air, \( T \) and \( \theta \) present air temperature and potential temperature, respectively, \( u \), \( v \) and \( \omega \) are zonal, meridional and vertical velocity in pressure coordinates, respectively, \( \tilde{Q} \) is diabatic heating. The first and second terms on the right-hand side of Eq. (1) represent the contribution of horizontal advection to air temperature tendencies. The third and fourth terms represent tendency of air temperature induced by vertical motion and diabatic heating, respectively.

The vertical component of three-dimensional Plumb flux (Plumb 1985), which can be used to measure the vertical propagation of waves, is given as follows:
Cold air that persists over a relatively longer duration could always cause more severe impacts, such as prolonged damage to transportation and heavier agricultural losses (Brunner et al. 2017; Peng and Bueh 2011). Therefore, it is essential to investigate the durations of the long-lasting extreme cold events and the underlying mechanism. The criterion for an extreme cold day is the averaged daily minimum surface air temperature in Siberia region being lower than its 10th percentile threshold in the winter from 1980/1981 to 2019/2020, following Zhang et al. (2005). The duration of an extreme cold event is defined as the number of consecutive extreme cold days. Previous studies have defined the Siberia as the region of 40°–65° N, 80°–120° E (Song and Wu 2019) or 45°–70° N, 75°–115° E (Chyi et al. 2020). Following their definitions, the region of 40°–70° N, 75°–120° E is considered as the Siberia region in this work.

Figure 1 shows the longest duration of all extreme cold events in Siberia in each winter from 1980/1981 to 2019/2020. The missing values in Fig. 1 refer to the fact that Siberia did not experience any extreme cold events in those years. The duration of the extreme cold event in winter 2000/2001 (15 days) was the longest from 1980/1981 to 2019/2020. The surface air temperature reached the standard of an extreme cold event in Siberia from 30 December 2000 to 13 January 2001. Note that if the Siberia was considered as the region in Chyi et al. (2020) and Song and Wu (2019), the extreme cold event in 2000/2001 was still the longest-lasting one during 1980/1981–2019/2020, with a duration of 14 days. Therefore, the results in Fig. 1 are not sensitive to the selection of Siberia region.

Figure 2 further shows the spatial patterns of the anomalies in daily minimum surface air temperature during 26 December 2000 – 18 January 2001. The surface air temperature decreased and reached the criteria of an extreme event in Siberia, with the anomalous cooling exceeding −20 °C during 30 December – 10 January (Fig. 2b–d). The extreme temperature anomaly weakened and migrated to Mongolia and Northeast China during the period of 11–14 January.
4.2 Anomalies of tropospheric circulation

To further investigate the dynamic mechanism between the outbreak of the cold air and the minor SSW event, Fig. 4 shows geopotential height and its anomalies at 500 hPa during 26 December 2000–18 January 2001. There were negative anomalies of geopotential height across the Atlantic to East Asia at about 60° N during 26–29 December. Also, a weak ridge was exhibited in the Ural region during the same period, as shown in Fig. 4a. During 30 December–10 January, the strengthened negative geopotential height anomalies were observed over the Atlantic-Euro and Siberia, which suggests that the trough in corresponding region had strengthened. Meanwhile, the Ural ridge had developed and extended to the polar region (Fig. 4b–d), and the strengthening of the Ural ridge may favor the southward advection of cold air to further cause the strong cooling of the surface air temperature in Siberia during 30 December–10 January (Fig. 1b–d). In the period of 11–18 January, a new ridge generated in the Atlantic region (Fig. 4e–f). The ridge in the Ural region weakened and the trough in East Asia and Atlantic-Euro region shifted eastward, which was helpful to the surface cold air traveling from Siberia towards Mongolia and Northeast China during 11–18 January (Fig. 4e–f). These results indicate that the ridge in the Ural region played an important role in the outbreak of this extreme cold event in 2000/2001.

A question arises as to what process dominants the target outbreak of extreme cold event. To address this question, Fig. 5 shows the tendencies of air temperature and the contributions from horizontal advection, vertical motion and diabatic heating following Eq. (1) at 700 hPa on 30
December 2000. There were negative trends of air temperature over the region of 40°–60°N, 80°–100°E (Fig. 5a), consistent with Fig. 2b. Negative air temperature tendencies in the region of Siberia are mainly contributed from the horizontal advection (Fig. 5b) and adiabatic heating (Fig. 5c), with a much smaller contribution from diabatic heating (Fig. 5d). The magnitude of negative anomalies there from horizontal advection is larger than that from adiabatic heating. These results imply that the horizontal advection of cold air played the dominant role in the negative tendencies of air temperature on 30 December 2000, which is closely related to the strengthened ridge in the Ural region.

The evolution of averaged geopotential height anomalies in the Ural region (50°–70°E) at 500 hPa and the averaged daily minimum surface air temperature anomalies in Siberia (75°–120°E) during 26 December–18 January are shown in Fig. 6a, b. A Monte Carlo approach based on 10,000 random reshufflings of the geopotential height anomalies is used to test the statistical significances in Fig. 6a. Positive geopotential height anomalies were observed in the polar region (north of 70°N) and they gradually weakened at the end of December. But the positive geopotential height anomalies gradually increased and extended to high-latitude region from 28 December, which suggested that the Ural ridge gradually strengthened and extended northward (Fig. 6a). Then, the daily minimum surface air temperature decreased and reached the standard of an extreme cold event from 30 December to 13 January (Fig. 6b). And the maximum of positive geopotential height anomalies in the Ural region (3–5 January) occurs earlier than the minimum of daily minimum surface air temperature anomalies in Siberia (4–6 January). Lead-lag correlation coefficients between averaged daily minimum surface air temperature anomalies in Siberia region (40°–70°N; 75°–120°E) and averaged geopotential height anomalies at 500 hPa in Ural region (60°–70°N; 50°–70°E) are further shown in Fig. 6c. The correlation coefficient between them reached minimum (~ 0.90) on lag-1, which suggested that the changes of geopotential height in Ural region led the anomalies of daily minimum surface air temperature in Siberia region by about 1 days. Therefore, the Ural ridge played a key role in the decreasing of surface air temperature in Siberia region.
4.3 Planetary wave changes in the stratosphere

A question arises as to why the Ural ridge grew and decayed. Previous studies have suggested that the changes of circulation in the troposphere could be modulated by the planetary wave activity in the stratosphere (Kodera et al. 2016; White et al. 2019). The Plumb flux was used to measure the strength and propagation of planetary waves in the stratosphere (Plumb 1985). Figure 7 shows the anomalies of the vertical component of the Plumb flux ($F_z$) at 100 hPa during 26 December 2000–18 January 2001. As can be seen, there were negative anomalies of $F_z$ in the Atlantic-Euro and Siberia region during 26th December-10th January, accompanied with the negative $F_z$ there (Fig. 7a–d). And the pattern of $F_z$ anomalies during 11–18 January was different to that during 26 December–10 January. Positive $F_z$ anomalies were evident in the Atlantic-Euro region, and they gradually shifted eastward (Fig. 7e, f). Figure 8 further displays the anomalies of $F_z$ averaged over 60°–75°N during 26 December–18 January. The planetary wave propagated from stratosphere to troposphere in the Atlantic-Euro and Siberia region during 26 December–10 January (Fig. 8a–d), but the planetary wave propagating into the stratosphere increased in the Atlantic region during the period of 11–18 January (Fig. 8e, f). These results are consistent with those in Fig. 7.

To provide more information of roles of the stratospheric and tropospheric processes in the target cold event, Fig. 9 shows lead-lag correlation coefficients between geopotential height (500 hPa, 45°–60°N) and $F_z$ (100–200 hPa, 60°–75°N) averaged over Atlantic-Euro (0°–30°E) and Siberia region (75°–120°E). The averaged $F_z$ led averaged geopotential height by about 2 and 4 days in Atlantic-Euro and Siberia region, respectively, with the largest statistically significant positive correlation coefficients. This implies that the stratospheric planetary waves played a key role in the development of tropospheric trough in Atlantic-Euro and Siberia region. These two strengthened Atlantic-Euro and Siberia troughs would induce the development of Ural ridge via strengthening the meridional flow (Cheung et al. 2012; Jiang and Wang 2012), further led to the outbreak of extreme cold event. Thus, the tropospheric process also had important impacts on the outbreak of extreme cold event. Note that the maintenance of the troughs in Atlantic-Euro and Siberia and Ural ridge, which modulated by the continuous recovery process of the minor SSW event, is a critical reason why the target extreme cold event lasted up to 15 days.

During the decay of the minor SSW event, the trough in Atlantic-Euro and Siberia weakened and shifted eastward, accompanied with decayed Ural ridge. Then, the temperature anomaly weakened and removed eastward. Another feature in Fig. 9 is that the correlation coefficient also reached peak when the geopotential height at 500 hPa led the averaged $F_z$ in Atlantic-Euro region by about 4 days. This was consistent with that the strengthened Atlantic-Euro ridge is accompanied by more planetary wave propagating into the stratosphere during 11–18 January 2001 (Fig. 7e, f, 8e, f). And previous results showed that the strengthening of the ridge in the Atlantic-Euro region may cause more planetary waves to propagate into the stratosphere (Castanheira and Barriopedro 2010).

Because of the important impacts of the stratospheric planetary waves on the Ural ridge at 500 hPa, we further investigated the dynamic mechanism responsible for the changes in planetary waves in the stratosphere at mid and high latitudes. Anomalies in the vertical shear of zonal wind averaged over 60°–75° N during 26 December 2000–18 January 2001 are presented in Fig. 10. There were two distinct areas of positive vertical zonal wind shear anomalies in the
Atlantic-Euro and Siberia region during 26 December–10 January (Fig. 10a–d). However, the patterns of the zonal wind vertical shear anomalies differed during 11–18 January. The positive anomalies in the vertical shear of zonal wind were only observed in Siberia (Fig. 10e–f). Chen and Robinson (1992) showed that the positive zonal wind shear anomalies are difficult for the planetary wave propagation in the stratosphere. Also, the reflection of planetary waves in the stratosphere coincided with the increasing zonal wind shear in the Atlantic-Euro and Siberia region during 26 December–10 January (Fig. 10a–d). In other words, the positive zonal wind shear anomalies were the main reason for the reflection of planetary wave in the stratosphere during 26 December 2000–10 January 2001.

4.4 Role of the stratospheric polar vortex

To further understand the reason for the changes in the vertical shear of zonal winds, Fig. 11 shows the anomalies of zonal winds averaged over 60°–75° N during 26 December 2000–18 January 2001. There are positive anomalies of zonal winds over the Ural region during 26 December–10 January. And the distribution of positive anomalies in the zonal winds in the middle stratosphere was wider than that in the lower stratosphere, which coincided with the positive anomalies of vertical wind shear on the east and west sides of the Ural region—that is, the Atlantic-Euro and Siberia region (Fig. 11a–d). However, positive zonal wind anomalies were only observed over Siberia in the middle stratosphere from 11 to 18 January (Fig. 11e–f). The results in Fig. 11 suggest that the vertical distribution of zonal wind anomalies may have played a key role in modulating the propagation of planetary waves during 26 December 2000–10 January 2001.

Note that the area of 60°–75° N discussed in Fig. 11 may be near the polar vortex edge over the Arctic, and so we further examined the relationship between the positive zonal wind anomalies over the Ural region in Fig. 12 and the polar vortex in the stratosphere. The anomalies of zonal winds at 10 hPa during 26 December 2000–18 January 2001 are presented in Fig. 12. According to the method of Nash et al. (1996), the stratospheric polar vortex edge is defined as the position of the maximum Ertel’s potential vorticity gradient in the region of the maximum westerly wind over the
averaged isentropic layers from 430 to 600 K. The polar vortex was located in the polar region (north of 60° N) from 26 December to 10 January (Fig. 12a–d). Also, positive zonal wind anomalies were observed along with the polar vortex edge during this period (Fig. 12a–d), which suggests that the stratospheric polar vortex gradually strengthened at 10 hPa. The centers of positive zonal winds anomalies were located in northern North America and Eurasia, respectively (Fig. 12a–d). The positive anomalies of zonal winds in Eurasia in Fig. 12a–d were corresponded to the positive zonal wind anomalies observed over the Ural region in Fig. 11a–d. The polar vortex migrated to Eurasia during 11–18 January (Fig. 12e–f) and positive anomalies of zonal winds did not exist over the Ural region in the stratosphere, which was not beneficial to the increasing of the zonal wind vertical shear in the Atlantic-Euro and Siberia region. Thus, the increasing of the planetary wave propagation into the stratosphere was possibly caused by the combined effect of the stratospheric polar vortex movement and the generation of the Atlantic-Euro ridge during 11–18 January.

The results in Fig. 12 also imply that the positive anomalies of zonal winds over the Ural region were closely related
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To the strengthening of the stratospheric polar vortex during 26 December–10 January. The stratospheric polar vortex strengthened during the recovery phase of the minor SSW event in late December and early January. Although this SSW event was defined as a minor event, the temperature in the stratosphere over the Arctic increased by nearly 35 °C from 17 to 20 December 2000. The value of the increasing of temperature in the stratosphere over the Arctic during this minor SSW event was close to that during a major SSW event. After 25 December, the temperature changed back to a normal winter condition in the stratosphere over the Arctic. Then, the zonal winds over the polar region increased due to the thermal wind relationship. However, owing to the large difference between the zonal wind and its climatology in late December during the minor SSW event, the recovery of the stratospheric polar vortex lasted from late December to early January. In addition, during the recovery process of the minor SSW event, the planetary waves propagated.

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**Fig. 10** Anomalies of vertical shear of zonal winds (unit: $s^{-1}$) averaged over 60°–75° N during 26 December 2000–18 January 2001. The values over the stippled regions are statistically significant at the 90% confidence level, based on a Monte Carlo test.

**Fig. 11** Anomalies of zonal winds (units: $ms^{-1}$) averaged over 60°–75° N during 26 December 2000–18 January 2001. The values over the stippled regions are statistically significant at the 90% confidence level, based on a Monte Carlo test.
from the stratosphere to the troposphere, which favored the temperature in the stratosphere over the Arctic to continuously decrease and the stratospheric polar vortex to continuously strengthen. This may be another important reason for the enhancement of the stratospheric polar vortex. The continuous strengthening of the stratospheric polar vortex during the recovery process of the minor SSW event not only favored a modification of the outbreak of cold air, but it also played a role in the long duration of this extreme cold event for about two weeks. During the decay of the minor SSW event, the condition was not beneficial to the reflection of planetary wave, which resulted in the temperature anomaly weakening and shifting eastward. Therefore, the minor SSW event had important impacts on this extreme cold event in the early winter of 2000/2001.

Besides SSWs, many other factors could influence the surface air temperature in Siberia region, such as sea ice over the Arctic (e.g., Zhang et al. 2022; Mori et al. 2014), AO (e.g., He et al. 2017), ENSO (e.g., Song and Wu 2022) and PDO (e.g., Li et al. 2020). These studies suggested that the decreasing of sea ice over the Arctic, the negative phase of AO, the positive phase of PDO and La Niña event are in favor of the outbreak of extreme cold events in East Asia, especially in Siberia region. We further examined the evolution of sea ice concentration (SIC) (the average of sea ice concentration over the Arctic (60°–90° N)), AO (the first leading mode from the empirical orthogonal function analysis of monthly mean height anomalies at 1000-hPa), ONI (three month running mean of sea surface temperature anomalies in the 5° N–5° S, 120–170° W region) and PDO (the leading principal component of monthly sea surface temperature anomalies in the North Pacific Ocean) indices in January from 1980/1981 to 2019/2020 (figure not shown). Anomalies of SIC, AO, ONI and PDO indices in January 2001 are small and not special, suggesting that the influence of sea ice over the Arctic, AO, ENSO and PDO on the extreme cold event in 2000/2001 might be weak.

5 Linkages of major and minor SSWs with the extreme cold events

The detail of minor SSWs in December-February from 1980/1981 to 2019/2020 has been shown in Table 1. Here the minor SSW event is defined as Butler et al. (2015), the
average temperature over the Arctic (65°–90° N) at 10 hPa increased by more than 25 K within a week and zonal-mean zonal wind remained westerly at 10 hPa and 60° N. The interval between different minor SSW events shall be at least 20 days (Charlton and Polvani 2007) and the time of the largest temperature at 10 hPa over the Arctic during a minor SSW event is regarded as the central date of this event. Also, the detail of major SSWs during this period was shown in Table 2. Because the major SSWs accompany by the sharp increasing of temperatures at 10 hPa poleward of 60° N and reversion of the zonal mean zonal winds at 10 hPa and 60° N, the central date of major SSWs was defined as the first day when the zonal-mean zonal wind at 10 hPa reversed into easterly wind. Same as the minor SSWs, the interval between different major SSW events is also at least 20 days (Charlton and Polvani 2007).

Figure 13a, b shows the composite anomalies in the surface air temperature in Siberia after the central days of major and minor SSW events, respectively. The surface air temperature decreased significantly within 40 days after the major SSW events (Fig. 13a) and 27 days after the minor SSW events (Fig. 13b). Note that if the starting day of one extreme cold event is within 40 days after the central date of the major SSW event and within 27 days after the central date of the minor SSW event, it was considered as the extreme cold event caused by major or minor SSW event. The evolution of frequency of the extreme cold days under the condition of major SSW and minor SSW events is further shown in Fig. 13c, d. Frequency of extreme cold days related to major SSW events mainly occurs during lag5-30 accompanied with two peaks on about lag8 and lag20, respectively (Fig. 13c). But the extreme cold days related to minor SSW events mainly occur 10–25 days after central date of minor SSW events (lag10-25) (Fig. 13d). This implies that the evolution of frequency of extreme cold days after major and minor SSW events is different.

Figure 13e shows the cumulative frequencies of extreme cold days from all extreme cold events and the long-lasting extreme cold events (that could last for at least 5 days) under the condition of minor SSW, major SSW, and non-SSW cases. The frequency of extreme cold days related to minor SSW events is about 1/4 of that related to major SSW events but about 1/7 of that under the condition of non-SSW. Whereas the frequency of the long-lasting extreme cold days related to minor SSW events is about 1/3 of that related to major SSW events and about 1/4 of that under the condition of non-SSW. This implies that the contribution of minor SSWs to the frequency of extreme cold days is relatively smaller than that from major SSWs. Interesting, more than 80% of the extreme cold days related to minor SSW events is contributed by the long-lasting extreme cold events, which implies that the minor SSW events play a critical role in the long-lasting extreme cold events.

The differences in the intensity of extreme cold event under different conditions are also examined. Here the intensity of extreme cold event is defined as the minimum of averaged daily minimum surface air temperatures in Siberia region during this event. The average intensity of extreme cold events related to major and minor SSW events is −37.9 °C and −37.1 °C, respectively. The difference between them is statistically insignificant, which indicates that the contributions of major or minor SSW events to the
intensity of extreme cold events are similar. Thus, the frequency of extreme cold days contributed by minor SSW events is relatively small than that by major SSW events, but the intensity of extreme cold events contributed by minor SSW events seems to be similar as that by major SSW events.

6 Conclusions and discussion

This study analyzed the influence of a minor SSW event on the longest-lasting extreme cold event in Siberia in the winters from 1980/1981 to 2019/2020. The Siberia region experienced extremely severe cold conditions, with the anomalous cooling exceeding −20 °C during 30 December 2000–10 January 2001. The cold air then weakened and shifted to Northeast China in the period 11–18 January 2001.

This extreme cold event occurred during the recovery phase of a minor SSW event from late December to early January. The dynamic linkage between the minor SSW event and extreme cold event during 30 December–10 January is shown in Fig. 14. The temperature peaked on 20 December and changed back to normal winter condition on about 25 December at 90° N and 10 hPa. Then, the stratospheric polar vortex gradually strengthened from 26 December to 10 January, along with the increases in the zonal winds in the stratosphere in the Ural region. The center of the positive zonal wind anomalies located in the Ural region in the middle and upper stratosphere, which was conducive to the positive vertical shear of zonal winds in the Atlantic-Euro and Siberia region in the lower stratosphere during 26 December–10 January (process 1). Such positive zonal wind shears tended to result in the reflection of stratospheric planetary wave (process 2), which was beneficial to strengthen the trough in the Atlantic-Euro and Siberia region in the troposphere (process 3). The strengthening of the trough in the Atlantic-Euro and Siberia region enhanced the meridional flow during 26 December–10 January, facilitating the development and maintenance of the Ural ridge (process 4). The strengthened ridge in the Ural region resulted in the southward advection of cold air and further caused the outbreak of the extreme cold event in Siberia region during 30 December 2000–10 January 2001 (process 5). During the decay of the minor SSW event (11–18 January), the stratospheric polar vortex did not continue to strengthen and a new ridge generated in the Atlantic region, which led to the weakening and eastward shifting of the trough in the Atlantic-Euro and Siberia region. Finally, the Ural ridge decayed and the temperature anomaly weakening and moving to Northeast China.

Fig. 13 The composite anomalies in the surface air temperature in Siberia after the central days of a major and b minor SSW events, respectively. The red line presents the values are statistically significant at the 90% confidence level. c, d The evolution of frequency of the extreme cold days induced by c major SSW and d minor SSW events. e Cumulative frequency of extreme cold days of all extreme cold events and the long-lasting extreme cold events that could last for at least 5 days under the condition of minor SSW, major SSW, and non-SSW cases.
The relationship between the SSW events and extreme cold events during 1980/1981–2019/2020 is further examined. Our results show that the contribution of minor SSWs to the frequency of extreme cold days during the past four decades is relatively smaller than that from major SSWs, but the intensity of extreme cold events contributed by minor or major SSW events seems to be similar. Interesting, the minor SSW events play a critical role in the long-lasting extreme cold events, more than 80% of the extreme cold days related to minor SSW events is contributed by the long-lasting extreme cold events.

Previous studies have tended to pay more attention to the influence of major SSW events on surface air temperature (Domeisen and Butler 2020; King et al. 2019; Nakagawa and Yamazaki 2006). Although the links between the minor SSW events and extreme cold events are limitation, some previous studies still discussed the role of minor SSW event played on the extreme cold events (Lan and Chen 2013; Wang and Chen 2010). Wang and Chen (2010) investigated the contribution of a minor SSW event in 2009 to the frequency of extreme cold event in Northern Hemisphere. Lan and Chen (2013) discussed the linkage between a minor SSW event in 2012 and the outbreak of the extreme cold event over Eurasia in 2012. However, in our study, we focused on the longest-lasting extreme cold event in Siberia from 1980/1981 to 2019/2020 and its linkages to the minor SSW event in the winter of 2000/2001. Besides, Wang and Chen (2010) and Lan and Chen (2013) suggested that the downward propagation of NAM index during minor SSW events could influence the circulation in the troposphere. But our study implies that the modulation of minor SSW events on the tropospheric circulation could be also by planetary wave reflection, especially in our target case, persistent planetary wave reflection during the recovery stage of the minor SSW event resulted in this extreme cold event becoming the longest-lasting one from 1980/1981 to 2019/2020. The long duration of extreme cold event in 2000/2001 may be also related to the strong increase of temperature over the Arctic in the stratosphere during the minor SSW event. The warming over the Arctic in the stratosphere in Wang and Chen (2010) and Lan and Chen (2013) exceeded 20 K, but were less than 25 K with in a weak, which are weaker than that of the minor SSW event in our studies. Some previous studies have found that changes in planetary waves are asymmetric in the Northern Hemisphere during SSW events (Lehtonen and Karpechko 2016; Lü et al. 2020; Nath et al. 2016). We further propose a possible dynamic mechanism between the horizontal distribution of planetary wave anomalies and the changes in the stratospheric polar vortex during an SSW event. Due to the important role played by planetary waves in tropospheric circulation anomalies, better understanding the dynamic mechanisms between the stratospheric polar vortex and the horizontal changes in planetary waves might provide some additional information to help predict the response of surface air temperature to SSW events.

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