Analysis of the variations in the strength and position of stratospheric sudden warming in the past three decades

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ABSTRACT
The authors investigate the statistical features of variations in the strength and position of stratospheric sudden warming (SSW) in the Northern Hemisphere based on ERA-Interim data from 1979 to 2016. It is found that there are 55 SSW events in the past 38 years (average: 1.4 times per year), including 33 major SSW events and 22 minor SSW events. The events mainly occur in February. The variations of the maximum meridional gradient of the zonal mean temperature of the SSW events show increasing trends from 1979 to 1983 and from 1998 to 2011, and decreasing trends from 1984 to 1997 and from 2012 to 2016. However, the linear trend of the variations in the past three decades shows a negative trend. Meanwhile, the strength and duration of major SSW events show similar features. Some SSW events occur at nearly the same time at different levels from 100 hPa to 10 hPa, while others first occur at 10 hPa and then the signal propagates downwards to lower levels. A very interesting phenomenon is that the maximum temperature centers of these 55 SSW events are mainly located over the Eurasian continent between 30°E and 120°E. This may be related to a polar vortex shifting to the Eurasian continent in the past three decades.

1. Introduction
Stratospheric sudden warming (SSW) is a special phenomenon in the stratosphere caused by atmospheric waves, which mainly occurs in winter and spring. This phenomenon was first discovered by Sherhag (1952). Later, Matsuno (1971) proposed that planetary waves propagate from the troposphere to the stratosphere and then break up. The energy released would drive the occurrence of the SSW. Except for one event—a major SSW event that appeared in the Southern Hemisphere in September 2002 (Allen et al. 2003)—SSW events mainly occur in the polar stratosphere in the Northern Hemisphere. In the case of an SSW event, the stratospheric temperature rises sharply in a short period of time and, correspondingly, the stratospheric circulation is affected; specifically, the circumpolar zonal westerly circulation obviously weakens, and even reverses. The polar vortex deforms and collapses because of this disturbance.

Stratospheric temperature and wind anomalies associated with SSW can propagate downwards for a period of weeks to influence the troposphere, which has a significant impact on surface temperatures in the Northern Hemisphere winter (Baldwin and Dunkerton 2001). These SSW-related, seasonal-scale, top-down circulation anomalies have a significant influence on the East Asian winter climate—especially the East Asian winter monsoon (Chen, Xu, and Cai 2015; Chen and Wei 2009). Significant changes in the amplitude and phase of tropospheric planetary waves can be observed during SSW events (Deng, Chen, and Yi 2015; Lu and Ding 2013). SSW events are always accompanied by enhanced zonal mean gravity wave amplitudes, and different types of SSW events have different effects on gravity waves (Jia et al. 2015). Lu and Ding (2015) studied the relationship between SSW events and cold waves in China by using isentropic potential vorticity, finding that SSWs cause an...
anomalous Atlantic–East Asian mode that forces the polar 
vortex towards the northeast of Eurasia. As a result, high 
potential vorticity will propagate westwards and down-
wards, which is conducive to cold weather in China. The 
weakened circulation anomalies in the polar stratosphere 
during SSW events propagate downwards to cause nega-
tive Arctic Oscillation anomalies, resulting in an enhanced 
East Asian winter monsoon (Li, Li, and Song 2011; Li et al.  
2010). In addition, SSW events influence the distribu-
tion of atmospheric chemistry components in the Northern 
Hemisphere (Wang, Liu, and Cai 2008).

In terms of prior work on analyzing the characteristics of 
SSW events, Schimanke et al. (2011) and Charlton et al. 
(2007) did so using a coupled ocean–atmosphere model 
and six general circulation models. Deng and Chen (2006) 
analyzed the temporal and spatial distribution character-
istics of SSW during 1950–2003 with NCEP data. Xu 
and Chen (2016) classified SSW events according to the 
polar vortex shape and studied the effects of planetary 
wave activity on different types of SSW events. Charlton-
Perez et al. (2008) and Taguchi (2017) investigated the 
frequency and dynamics of SSSWs in the past and future. 
Xie et al. (2012, 2014, 2018), found that El Niño Modoki 
events make the northern polar vortex stronger and 
colder, and suppress the upward propagation of planetary 
wave activity. This also leads to a significant reduction in 
ozone in the tropical mid–lower stratosphere, which is 
different from the influence of canonical El Niño. 
However, the statistical features of the variations in the 
strength and position of SSW events have received 
relatively less attention. Here, we investigate these features of 
SSW events over the past three decades.

2. Data and methods

The temperature, geopotential field and winds are 
based on ERA-Interim data from 1979 to 2016. The 
dataset has a horizontal resolution of 1° × 1°.

The definition of an SSW event follows that of the 
World Meteorological Organization, i.e. when the meridio-
nal gradient of zonal mean temperature from 60°N to 90° 
N turns to positive for at least five days at 10 hPa (Hu et al. 
2015). SSW events can be divided into major and minor 
events based on their warming intensity, according to 
whether an event causes the polar circulation to reverse. 
The meridional gradient of zonal mean temperature and 
circulation anomalies can be written as follows:

\[
\Delta [T] = [T]_{60^\circ N} - [T]_{90^\circ N};
\]

\[
\Delta [H] = [H]_{60^\circ N} - [H]_{90^\circ N}.
\]

Here, \( T \) is temperature and \( H \) is the geopotential field. 
A major SSW event is defined as \( (\Delta [T] > 0, \Delta [H] > 0) \). This 
means that the meridional gradient of zonal mean 
temperature from 60°N to the pole becomes negative, 
and at the same time the meridional gradient of the 
zonal mean geopotential height is reversed. A minor 
SSW event can be defined as \( (\Delta [T] > 0, \Delta [H] < 0) \). This 
means that the meridional gradient of zonal mean 
temperature from 60°N to the pole becomes negative, 
but the meridional gradient of the zonal mean geopotential 
height is not reversed. When \( \Delta [T] \) turns to be 
positive, it is the start of an SSW event; when \( \Delta [T] \) turns 
to be negative, that is the end.

The notation \( T_{t,k} \) is used to represent the tempera-
ture at moment \( t \) and space \( k \) during an SSW event. The 
expression \( \Delta T_{t,k}^{6h} = T_{t+1,k} - T_{t,k} \) represents the tem-
perature anomalies at moment \( t \) and space \( k \), and 
\( \Delta T_{t,k} = (T_{t,k})_{\text{max}} - (T_{t,k})_{\text{min}} \) is used to search for the max-
imum temperature change during an SSW event, where 
the interval of \( t \) is 6 h and the interval of \( k \) is 1°. Thus, 
when \( t = 1 \), the location where the \( k \) of the largest 
\( (T_{t,k})_{6h} \) is the initial warming center; and when 
\( \Delta T_{t,k} \) reaches its maximum, \( k \) is the max warming center. 
SSW events occur mainly in the high latitudes between 
60°N and 90°N, so we only consider this range when 
defining the warming center.

3. Results

It can be seen from Table 1 that there are 33 major SSW 
events and 22 minor SSW events from 1979 to 2016, 
which is basically consistent with the results of Li et al. 
(2010) and Sheng, Wang, and Min (2005). The average 
duration of all SSW events is 14.5 days. The longest one 
is No. 8001, which lasted 40 days. As for major SSWs, 
their average length is 18.1 days.

In order to investigate the SSW strength, Figure 1(a) 
shows the variations of maximum \( \Delta [T] \) and maximum 
\( \Delta [H] \) from 1979 to 2016. The red dots indicate major SSW 
events and the black dots indicate minor SSW events. It is 
found that the average maximum \( \Delta [T] \) is 22.4 K. The 
maximum value of 45.5 K relates to No. 9201, a minor 
SSW event, which could not make the polar circulation 
revert; and the minimum value of 3.6 K relates to No. 
9601, major SSW event. The changes in maximum \( \Delta [T] \) 
show an increasing trend from 1979 to 1983, a 
decreasing trend from 1984 to 1997, an increasing 
trend from 1998 to 2011, and then a decreasing trend 
from 2012 to 2016. The linear trend and the 10-year 
running mean of the changes in the past three decades 
show a negative trend.
Table 1. SSW events from 1979 to 2016 defined in this study. Number 7901 (for example) means the first SSW event in 1979. Duration refers to the duration of the SSW in days. Note that the winter circulation is destroyed by the warming, without recovery, turning into summer circulation in the stratosphere during the late winter and early spring. This warming is generally called ‘final SSW’. There is no final SSW in Table 1.

| Number | Start date | Duration | Event intensity |
|--------|------------|----------|-----------------|
| 7901   | 23 Jan.    | 11       | minor           |
| 7902   | 20 Feb.    | 19       | major           |
| 7903   | 25 Nov.    | 5        | minor           |
| 8001   | 17 Feb.    | 40       | major           |
| 8101   | 30 Jan.    | 26       | major           |
| 8102   | 1 Dec.     | 7        | major           |
| 8201   | 24 Jan.    | 6        | minor           |
| 8301   | 27 Jan.    | 15       | minor           |
| 8302   | 23 Feb.    | 22       | major           |
| 8401   | 19 Feb.    | 36       | major           |
| 8402   | 30 Dec.    | 14       | major           |
| 8601   | 15 Feb.    | 5        | minor           |
| 8701   | 16 Jan.    | 26       | major           |
| 8702   | 7 Dec.     | 13       | major           |
| 8901   | 15 Feb.    | 30       | major           |
| 9001   | 8 Feb.     | 20       | minor           |
| 9101   | 26 Jan.    | 12       | major           |
| 9201   | 11 Jan.    | 13       | minor           |
| 9202   | 1 Feb.     | 17       | minor           |
| 9301   | 24 Feb.    | 5        | minor           |
| 9302   | 30 Dec.    | 6        | major           |
| 9401   | 7 Mar.     | 13       | minor           |
| 9501   | 27 Jan.    | 18       | major           |
| 9502   | 22 Mar.    | 5        | minor           |
| 9601   | 27 Feb.    | 7        | minor           |
| 9602   | 2 Dec.     | 6        | major           |
| 9701   | 19 Dec.    | 19       | major           |
| 9801   | 1 Feb.     | 16       | minor           |
| 9802   | 9 Mar.     | 12       | minor           |
| 9803   | 14 Dec.    | 13       | major           |
| 9901   | 23 Feb.    | 10       | major           |
| 0001   | 29 Feb.    | 6        | minor           |
| 0101   | 30 Jan.    | 14       | major           |
| 0102   | 23 Dec.    | 18       | major           |
| 0201   | 22 Jan.    | 5        | minor           |
| 0202   | 13 Feb.    | 24       | major           |
| 0203   | 29 Dec.    | 17       | major           |
| 0301   | 1 Feb.     | 24       | major           |
| 0302   | 6 Mar.     | 11       | major           |
| 0303   | 19 Dec.    | 19       | major           |
| 0501   | 22 Feb.    | 25       | major           |
| 0601   | 9 Jan.     | 27       | major           |
| 0701   | 4 Feb.     | 12       | major           |
| 0702   | 3 Mar.     | 5        | minor           |
| 0801   | 23 Jan.    | 11       | minor           |
| 0802   | 13 Jan.    | 22       | major           |
| 0901   | 21 Jan.    | 12       | major           |
| 1001   | 21 Jan.    | 9        | major           |
| 1201   | 12 Jan.    | 22       | major           |
| 1301   | 5 Jan.     | 19       | major           |
| 1401   | 28 Feb.    | 14       | minor           |
| 1402   | 31 Dec.    | 5        | major           |
| 1501   | 23 Jan.    | 14       | minor           |
| 1502   | 16 Mar.    | 5        | minor           |
| 1601   | 8 Feb.     | 6        | minor           |

The westerly circulation in the polar stratosphere turns to easterly during major SSW events. It corresponds to $\Delta[H] > 0$ and the zonal mean zonal wind at 60°N being smaller than zero – namely, $|u|_{60°N}$, where $u$ means zonal wind. Thus, $|u|_{60°N}$ is used to represent the intensity changes in major SSW events during 1979 to 2016. It is found that the zonal mean zonal wind at 60°N is still westerly in nine major SSW events. Figure 1(b) shows the variations in the maximum $\Delta[H]$ and minimum $|u|_{60°N}$ of major SSW events from 1979 to 2016. There is good correlation between the variations of minimum $|u|_{60°N}$ and maximum $\Delta[H]$, with their correlation coefficient reaching $-0.83$, except for these nine major SSW events. We find that there is no linear trend of maximum $\Delta[H]$ from 1979 to 2016. The average value is 57.6 dagpm, with the maximum value of 122.1 dagpm corresponding to No. 0601, a major SSW event, and the minimum value of only 12.2 dagpm corresponding to No. 1201, also a major SSW event. For $|u|_{60°N}$ excluding the nine major SSW events, the linear trend of minimum $|u|_{60°N}$ variations is also not significant. The average minimum $|u|_{60°N}$ is about $-11.6$ m s$^{-1}$, with the minimum value of $-26.5$ m s$^{-1}$ also corresponding to No. 0601 and the maximum value of $-0.08$ m s$^{-1}$ to No. 1001.

Figure 2(a) shows the interannual variations of the frequency of SSW events. There is no SSW event in 1985, 1988, 2004, or 2011. In 1981, 1983, 1984, 1897, 1992, 1993, 1995, 1996, 2001, 2007, 2008, 2014, and 2015, there are two SSW events. Especially, in the years 1979, 1998, 2002 and 2003, three SSW events occurred. It is found that SSW events occurred on average 1.4 times per year, with an average of 1.6 times per year in the 1990s and 2000s. The fewest number of SSWs occurred at the beginning of the 21st century, with an average of 1.14 times per year. Figure 2(b) shows the total number of SSW events in each month during winter and spring over the past 38 years. It can be seen that the most frequent month for SSW events is February, with 20 SSW occurrences. January is the second most frequent month of SSW occurrence, with a total of 17 times. December yields 11 occurrences, and November only one.

Figure 3 shows the occurrence time of each major or minor SSW event at different height levels in the past 38 years. A line represents an SSW event and a point represents the occurrence time when an SSW event appears at this level. In total, 36 SSW events first appeared at 10–100 hPa, in which 30 were major and 6 were minor SSW events. For major SSW events, 30 first occurred at 10–100 hPa, 1 at 10–70 hPa, and 2 at 10–50 hPa. For the 22 minor SSW events, 6 occurred below 50 hPa. This perhaps implies that major SSW events have a much more significant influence on the stratosphere between 10 and 100 hPa than minor events.
It is also found that the signals of 46 SSW events could propagate downwards to the lower levels and cause warmings there, indicating a downward influence of SSW. However, the signals of three SSW events show an anomalous upward propagation. Some SSW events occurred nearly at the same time at different levels from 100 hPa to 10 hPa, while others first occurred at 10 hPa and then the signal propagated downwards to lower levels.

Zhang et al. (2016, 2018) found that the winter polar vortex has been shifting to the Eurasian continent. A question arises here as to whether a portion of SSW events has also shifted in the past few decades. In order to explore the spatial distribution of SSW events, we define two warming centers (see section 2), i.e. the initial warming center and the maximum warming center.

Figure 4(a–c) show the initial warming centers of all SSW events at 10 hPa, 50 hPa and 100 hPa from 1979 to 2016. It can be seen that the initial warming centers have obvious regional characteristics at 10 hPa (Figure 4(a)). The initial warming centers are mainly located in the eastern and northern sea of Novaya Zemly, the Kara Sea, the Tajmyr Peninsula, North Land, and the west of the New Siberian Islands in the Eastern Hemisphere, as well as the area near Ellesmere Island and Queen Elizabeth Islands in the Western Hemisphere. The initial warming centers of major SSW are mainly distributed in the Arctic Ocean. However, the minor SSW events are relatively fragmented in the middle and high latitudes. At 50 hPa (Figure 4(b)), it can be seen that the initial warming centers located in the Eastern Hemisphere significantly decrease. These centers are mainly concentrated in the north of Greenland, the islands of northern Canada, and its northern region in the Northern Hemisphere. The major SSW events are mainly located in these regions, but the number of minor ones is reduced obviously and their centers move to lower latitudes compared with those at 10 hPa. At 100 hPa (Figure 4(c)), the initial warming centers diffuse to the south. In the Eastern Hemisphere, these centers are located in Eurasia, the oceans of North Land, and the northern part of the Kacha Islands. In the Western Hemisphere, they are scattered over Iceland, the south of Greenland, Ellesmere Island, and Queen Elizabeth Islands. Therefore, the distribution of the initial warming centers of SSW events located in the high latitudes at high levels can diffuse to near the polar region at lower levels. From the high levels to low levels, major SSW events show a transition from the high latitudes of the Eastern Hemisphere to the middle and high latitudes of the Western Hemisphere. Minor SSW events show an evident reduction.

The positions of the maximum warming centers for the SSW events at 10 hPa are shown in Figure 4(d). Note that the size of the dots indicates the value of the maximum warming center. It is found that the positions of the maximum warming centers show a significant
Figure 2. (a) The interannual variations of the frequency of SSW events. (b) The total number of SSW events in each month during winter and spring over the past 38 years.

Figure 3. The occurrence time of each major or minor SSW event occurring at different height levels in the past 38 years: (a) major SSW events; (b) minor SSW events. A line represents an SSW event and a point represents the occurrence time when an SSW event appears at this level. The time interval is 6 h.
regional feature. They are mainly distributed in the Eastern Hemisphere, especially in the Eurasian continent between 30°E and 120°E. A few are scattered in the polar region, central and eastern Russia of the Eastern Hemisphere, and Iceland, Greenland, and Hudson Bay in the Western Hemisphere. The maximum warming centers of the minor SSW events are mainly concentrated in the Eastern Hemisphere. The average temperature of the maximum warming centers is 50.9 K, with the maximum value of 88.4 K located in western Russia in association with a major SSW event (No. 0802), and the minimum value in Hudson Bay on the west Coast of Canada being only 17.1 K, corresponding to the No. 9602 SSW event. The very interesting phenomenon of the maximum temperature centers of these 55 SSW events being mainly located in the

Figure 4. The location of initial warming centers of all SSW events at (a) 10 hPa, (b) 50 hPa, and (c) 100 hPa. Red dots mean major SSW events and black ones mean minor SSW events. (d) The maximum warming centers, wherein the size of the dots indicates the maximum warming value, with a larger size meaning a larger value; red dots indicate major SSW events and black ones minor events.
Eurasian continent between 30°E and 120°E might be related to the polar vortex shifting to the Eurasian continent in the past three decades.

4. Conclusions and discussion

The statistical features of the variations in the strength and position of SSW events in the Northern Hemisphere from 1979 to 2016 are investigated in this study using ERA-Interim data. We identify 55 SSW events as having occurred in the past 38 years (average: 1.4 times per year), including 33 major SSW events and 22 minor SSW events. The variations in the maximum meridional gradient of the zonal mean temperature of the SSW events show increasing trends from 1979 to 1983 and from 1998 to 2011, and decreasing trends from 1984 to 1997 and from 2012 to 2016. The linear trend of the variations in the past three decades shows a negative trend. Meanwhile, the strength and duration of the major SSW events show similar features. Some SSW events occurred nearly at the same time at different levels from 100 hPa to 10 hPa, while others first occurred at 10 hPa and then the signal propagated downwards to lower levels.

In order to explore the spatial distribution of SSW events, we define two warming centers: the initial warming center and the maximum warming center. The distribution of initial warming centers for the SSW events located in the high latitudes at high levels can diffuse to near the polar region at lower levels. A very interesting phenomenon is that the maximum temperature centers of these 55 SSW events are mainly located in the Eurasian continent between 30°E and 120°E. This might be related to the polar vortex shifting to the Eurasian continent in the past three decades. It is worth noting that the factors causing the variations in the maximum meridional gradient of the zonal mean temperature and positions of warming centers are not analyzed in this study, but are interesting points deserving of further investigation in future work.

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