Occurrence of Winter Stratospheric Sudden Warming Events and the Seasonal Timing of Spring Stratospheric Final Warming

JINGGAO HU AND RONGCAI REN

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, and Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters and KLME, Nanjing University of Information Science and Technology, Nanjing, China

HAIMING XU

Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters and KLME, Nanjing University of Information Science and Technology, Nanjing, China

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ABSTRACT

Based on the NCEP–NCAR reanalysis dataset covering 1958–2012, this paper demonstrates a statistically significant relationship between the occurrence of major stratospheric sudden warming events (SSWs) in midwinter and the seasonal timing of stratospheric final warming events (SFWs) in spring. Specifically, early spring SFWs that on average occur in early March tend to be preceded by non-SSW winters, while late spring SFWs that on average take place up until early May are mostly preceded by SSW events in midwinter. Though the occurrence (absence) of SSW events in midwinter may not always be followed by late (early) SFWs in spring, there is a much higher (lower) probability of late SFWs than early SFWs in spring after SSW (non-SSW) winters, particularly when the winter SSWs occur no earlier than early January or in the period from late January to early February. Diagnosis shows that, corresponding to an SSW (non-SSW) winter and the following late (early)-SFW spring, intensity of planetary wave activity in the stratosphere tends to evolve out of phase from midwinter to the following spring, being anomalously stronger (weaker) in winter and anomalously weaker (stronger) in spring. Furthermore, the strengthening of the western Eurasian high, which appears during early to mid-January in late-SFW years but does not appear until late February to mid-March in early-SFW years, always precedes the strengthening of planetary wave activity in the stratosphere and thus acts as a tropospheric precursor to the seasonal timing of SFWs.

1. Introduction

The large-scale circulation in the extratropical stratosphere cycles between circumpolar westerlies during winter and circumpolar easterlies during summer every year. The winter circumpolar westerlies characterize the life cycle of the stratospheric polar vortex. In winter, planetary waves from the troposphere can penetrate into the stratosphere and perturb the circumpolar westerlies, which are responsible for the recurrent stratospheric sudden warming events (SSWs) (Matsuno 1971; Andrews et al. 1987). SSWs are characterized by a dramatic increase in polar stratospheric temperature and a decrease in the circumpolar wind speed over a short time period. The occurrence of SSWs in winter largely dominates the intraseasonal variability of the extratropical stratospheric circulation (Andrews et al. 1987; Labitzke 1977; Limpasuvan et al. 2004; Charlton and Polvani 2007, hereafter CP07; Cai and Ren 2007; Ren and Cai 2008) and is strongly connected to leading changes in the troposphere such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and northern annular mode (NAM) (Baldwin and Dunkerton 2001; Baldwin et al. 2003; Limpasuvan et al. 2004).

In every spring when the stratospheric polar vortex breaks down, the transition from circumpolar westerlies to easterlies is usually accompanied by a similar rapid polar warming and weakening of the polar jet, which is known as the stratospheric final warming (SFW) (Andrews et al. 1987; Waugh et al. 1999; Black et al. 2006). SFWs,
as the termination of the winter season, take place every year and thus are considered to be more frequent than SSW events, which occur at a frequency of 0.6 yr\(^{-1}\) (e.g., CP07). Similar to SSW events, SFWs also have considerable influence on the large-scale circulation. For example, it has been argued that, relative to the climatological seasonal cycle, the onset of SFW events may act to accelerate the annual weakening of stratospheric circumpolar westerlies (Black et al. 2006; Black and McDaniel 2007a); early or late onset of SFWs may give rise to contrasting features of the tropospheric circulation in April, which exhibits more positive AO in late-SFW years but seems to not favor any AO polarities in early-SFW years (Ayarzagüena and Serrano 2009). In addition, SFW signals that first appear at upper or lower layers may also have different effects on the troposphere. Hardiman et al. (2011) identified more negative NAO patterns in April in those years when SFWs occurred first in the midstratosphere than in other years when SFW signals appeared first in the upper stratosphere. On the other hand, existing evidence also indicates notable differences in the spatial and temporal structures of the associated circulation between SFW and SSW events. In contrast to those during SSW events, the associated tropospheric anomalies in the high latitudes during SFW events have been found to be shifted much farther northward toward the pole (Black et al. 2006; Black and McDaniel 2007b).

Because of the important influence of SFWs on circulation and climate in the troposphere in spring transitional season, and the notable differences between SFWs and SSWs, investigations particularly toward SFWs have already become an important subject within the field of stratospheric dynamics, which will not only further advance our understanding of the stratosphere–troposphere dynamical coupling in spring, but also may provide us a new opportunity for improving our short-term prediction capabilities in terms of the tropospheric climate at this transitional time of the year.

The major variability of SFWs is found in the seasonal timing of SFW events or the onset date of SFW (SFWOD). During the period 1979–2010, the earliest SFWOD at 50 hPa was as early as mid-March while the latest was after 20 May (e.g., Ayarzagüena and Serrano 2009; Hu et al. 2014). At the decadal time scale, the stratospheric polar vortex during springtime in both hemispheres since the early 1980s has been found to be much stronger and colder than before and has been breaking down much later (Waugh et al. 1999; Pawson and Naujokat 1999; Labitzke and Naujokat 2000; Zhou et al. 2000; Haigh and Roscoe 2009). Hu et al. (2014) further indicated that this delaying trend of SFWOD in the Northern Hemisphere has persisted into the twenty-first century and remained significant in recent years. The significant interannual-to-decadal variability of the seasonal timing of SFWs has been attributed to the high sensitivity of SFWOD to the preexisting flow structure in the stratosphere and to the planetary wave activity from the troposphere (Waugh and Rong 2002; Black and McDaniel 2007b). It was argued that from winter to spring, weakening of the circumpolar westerly wind along with a warming of the polar vortex tends to occur only once in early-SFW years but may appear twice in late-SFW years (Wei et al. 2007). This seems to imply that timing of SFWs may be intimately associated with the occurrence of SSW events in the previous winter. However, there are also some studies indicating that no significant relationship exists between the persistence of the stratospheric polar vortex in spring and the condition of the polar vortex in midwinter (mainly in January) (Waugh et al. 1999; Manney et al. 2005; Kuttippurath and Nikulin 2012). The objective of this study is to reexamine the relationship between the onset of spring SFWs and the preexisting condition of the stratospheric polar vortex, which has not been clearly identified in previous literature, and to diagnose the basic dynamical processes responsible for the possible linkage between them. In this study, we first proved a significant relationship between the occurrence of winter SSW events and the timing of spring SFWs using the longer reanalysis time series. Then we diagnosed the dynamical processes including variations of planetary wave activity, which are responsible for the intimate linkage between the two warming phenomena. Since the occurrence of winter SSWs is known to be closely related to tropospheric precursors such as blockings (e.g., Martius et al. 2009; Nishii et al. 2011), the Siberian high and Eurasian snow cover (e.g., Cohen and Entekhabi 1999; Cohen and Jones 2011), and the El Niño–Southern Oscillation (ENSO) (e.g., Garfinkel and Hartmann 2008; Garfinkel et al. 2010; Ren et al. 2012; references therein), we also explored the possible tropospheric precursors to the seasonal timing of SFWs.

The structure of the paper is as follows. Section 2 describes the data and method. In section 3, we present the temporal relationship between SSWs and SFWs. In section 4, we focus on the dynamical linkage between the two kinds of stratospheric warming events, and section 5 provides our concluding remarks.

2. Data and method
a. Data

The daily data on 2.5° × 2.5° grids and at 17 standard pressure levels from 1000 to 10 hPa used in this study
were derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset covering the period from 1 January 1958 to 31 December 2012, including wind, geopotential height, and temperature fields (Kanay et al. 1996; http://www.esrl.noaa.gov/psd/data/). To obtain the anomaly field, the daily climatological annual cycle was obtained by first averaging the daily data on Julian days across all years from 1958 to 2012, and then a 31-day running-mean operator was applied to obtain a smoothly varying annual cycle. The daily anomalies were obtained simply by removing the annual cycle from the total fields.

b. Identifying SFW events in spring

One of the essential issues in defining SFWOD is how to avoid misinterpretation of midwinter vortex breakdown as a final spring warming event (Langematz and Kunze 2006). Different definitions of SFWOD may yield quite different results regarding SFW events. Based on the definitions in Black et al. (2006) and in Wei et al. (2007), they both found that atmospheric circulation in early-SFW years tends to proceed much more rapidly around the SFWOD than that in late-SFW years. Their results, however, seem in an opposite sense to the results of Waugh and Rong (2002). After checking their definitions, we found that several stratospheric warming events, such as that in January 1958 [late January in CP07, early February in Waugh and Rong (2002)], February 1963 [late January in CP07, early February in Waugh and Rong (2002)], and February 1973 [early February in CP07 (NCEP–NCAR dataset), mid-February in Waugh and Rong (2002)], which are commonly defined as SSW events (CP07; Bancalá et al. 2012), were categorized as final warming events in Waugh and Rong (2002). The criterion they used for SFW events in Northern Hemisphere was simply a weaker than 15.2 m s\(^{-1}\) westerly value along the vortex edge represented by the maximum potential vorticity gradient constrained by the location of the maximum wind speed along potential vorticity isolines (see also Nash et al. 1996).

In the current study, we generally followed Black et al. (2006) and Black and McDaniel (2007b) to define the SFWOD as the day when zonal-mean zonal wind at 65°N and at 10 hPa becomes easterly wind and never recovers until the subsequent autumn. Considering that the circumpolar westerlies may temporarily recover after the breakdown of the polar vortex in spring of some years, we further introduced a supplementary condition that the recovered zonal-mean westerlies must not persist beyond 5 days and not become stronger than 5 m s\(^{-1}\). This will further prevent misinterpretation of SSW events after which the vortex recovers in spring, as vortex-breakdown SFW events. Based on our definition, the SFWOD in 1971, 1978, 1984, 1989, 1999, 2008, and 2010 were adjusted. The climatological-mean SFWOD was found to be several days later than in previous studies (e.g., Black et al. 2006).

c. Identifying major SSW events in winter

Following the definition from the World Meteorological Organization (WMO), we identified an SSW event when the zonal-mean temperature difference between 90° and 60°N at 10 hPa becomes positive and persists for more than 5 days and, further, a major SSW event when the zonal-mean zonal wind at 65°N and at 10 hPa is reversed to easterly wind. The onset date of major SSW events is defined as the first day when the circumpolar easterly wind appears (this date is usually referred to as the “central date” in previous studies; e.g., Limpasuvan et al. 2004; CP07). As in CP07, an interval of at least 20 consecutive days of circumpolar westerlies must exist between two independent major SSW events. To be consistent with the definition of SFWs, we chose 65°N (e.g., Limpasuvan et al. 2004) instead of 60°N (e.g., Manney et al. 2005; CP07) as the basis latitude to define the reversal of zonal wind. However, it should be noted that the results presented below are insensitive to this choice. In this paper, we focus mainly on the relationship between SFWs and major SSWs, but the word major is omitted in the narrative for brevity.

3. Statistical relationship between the occurrence of winter SSWs and the timing of spring SFWs

a. Occurrence of SSWs

Listed in Table 1 are the onset dates of SSWs and SFWs defined in all of the 55 yr from 1958 to 2012 based on our definition. Following CP07 and Cohen and Jones (2011), we also indicate the type of each SSW event in Table 1, as vortex displacement (denoted as “D”) or vortex split (denoted as “S”). Comparing Table 1 with Table 1 in CP07, we find that the SSW events identified before 2002 are mostly consistent, with only a few exceptions. Specifically, the SSW events in February 1963 (late January 1963 in CP07), January 1977, March 1981, and February 2002 in Table 1 were only identified in CP07 from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) dataset; the SSW events identified by CP07 in March 1965 and March 2000 do not exist in our results (Table 1). Manney et al. (2005), based on the NCEP–Climate Prediction Center (CPC) analysis dataset, also identified...
the SSW events in March 1981 and February 2002, but as with us, not that in March 2000. However, our examination confirmed that the general conclusions of the current study changed little even when we excluded these several events (not shown).

We also notice from Table 1 that, during the 55-yr period from 1958 to 2012, 36 major SSWs occurred in 30 yr and with six double-SSW years (two major SSW events in one winter season), and there were 25 non-SSW years (no major SSW occurred). The frequency of major SSW events was found to be about 0.65, which is also comparable with that in previous studies (e.g., CP07; Bancalá et al. 2012).

b. Timing of spring SFWs and occurrence of winter SSWs

Figure 1 displays the interannual distribution of the onset dates of SFW (Fig. 1a) and major SSW events (Fig. 1b). It can be seen that interannual variability of SFWOD and the onset date of SSWs are both remarkable. SFWODs vary from mid-March to mid-May around the mean date 11 April, while the onset dates of SSWs vary from late November to mid-March around the mean date 25 January, which is consistent with the results in CP07 and Nishii et al. (2011).

Comparing Fig. 1a with Fig. 1b, we find that among the 18 yr with anomalously later SFW (red in Fig. 1a; SFWOD is more than 0.5 standard deviation (SD) later than average), there were 14 yr (red in Fig. 1b) where the SFW was preceded by midwinter major SSWs. In contrast, among the 15 yr with anomalously earlier SFW (blue in Fig. 1a; SFWOD is more than 0.5 SD earlier than average), there were only 3 yr (blue in Fig. 1b) where the SFW was preceded by midwinter major SSWs. This seems to suggest that later SFWs in spring are mostly preceded by occurrence of midwinter SSWs and earlier SFWs in spring are mostly preceded by non-SSW midwinters. Particularly, following the non-SSW winters during the period from 1990 to 1998, SFWs were mostly (seven of nine) earlier

### Table 1. The SSW and SFW event onset date, year, and type identified in the NCEP–NCAR dataset. The letters D and S respectively denote vortex displacement and vortex split. *

<table>
<thead>
<tr>
<th>Year</th>
<th>SSW date</th>
<th>SSW type</th>
<th>SFW date</th>
<th>Year</th>
<th>SSW date</th>
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<td>1986</td>
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<td>—</td>
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<td>9 Apr</td>
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*The types of SSW events were identified using the algorithm of CP07.
than average. This evident relationship between SFW and SSW can be seen more clearly from the data in Table 2.

Listed in Table 2 are the numbers of SSW years and non-SSW years and that were followed by early- and late-SFW events in the whole period 1958–2012, in the presatellite era 1958–79, and in the postsatellite era 1980–2012. As already seen in Fig. 1, most (least) early-SFW years are non-SSW (SSW) years (12 of 15) and most (least) late-SFW years are SSW (non-SSW) years (14 of 18). This is also evident for extremely early (late) SFWs when SFWODs are more than 1.0 SD earlier (later) than average. For extremely early-SFW years, the ratio of non-SSW to SSW years is 9:2. In contrast, for extremely late-SFW years, the ratio of non-SSW to SSW years is 1:8. In addition, we can easily confirm that this relationship between spring SFW timing and winter SSW occurrence is consistent in both the presatellite (1958–79) and postsatellite (1980–2012) subperiods. From the statistical analysis based on Fig. 1 and Table 2, we can interpret the relationship between SFW timing and SSW occurrence as that, for an SFW to be anomalously early (late), the preceding winter generally needs to be a non-SSW (SSW) winter.

However, we can also see from Table 2 that there were in total 30 SSW winters from 1958 to 2012, but only 14 (3) of these winters were followed by late (early) SFW [for SFWOD above 1.0 SD, the number of late- (early)]

<table>
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<td><strong>All</strong></td>
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<tr>
<td>SSW</td>
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<tr>
<td>Non-SSW</td>
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<td>10</td>
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<tr>
<td>Total</td>
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<td><strong>Early-SFW years</strong></td>
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<tr>
<td>&lt;−0.5 SD*</td>
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<td>2</td>
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<tr>
<td>&lt;−1 SD</td>
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<td>1</td>
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<tr>
<td><strong>Late-SFW years</strong></td>
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<td>&gt;+0.5 SD</td>
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<td>4</td>
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<tr>
<td>&gt;+1 SD</td>
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* SD represents the standard deviation of the time series of SFWOD during 1958–2012.

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SFW years was 8 (2)]. Furthermore, there were in total 25 non-SSW winters, but only 12 (4) of them were followed by early (late) spring SFW [for SFWOD above 1.0 SD, the number of early- (late-) SFW years was 9 (1)]. In other words, less than half of the SSW (non-SSW) winters were followed by anomalously late- (early-) SFW springs. This implies that the occurrence (absence) of a winter SSW event may not be sufficient enough to anticipate a late (early) SFW in the following spring. Nevertheless, comparing the number of late SFWs and the number of early SFWs (for both 0.5 SD and 1.0 SD of SFWOD), we still see that late SFWs (14 and 8) were much more frequent than early SFWs (3 and 2) after the occurrence of winter SSWs; and meanwhile, early SFWs (12 and 9) were much more frequent than late SFWs (4 and 1) after non-SSW winters. This relationship was also found to be true for the two subperiods: 1958–79 and 1980–2012.

c. Onset date of winter SSWs and the timing of spring SFWs

Figure 2a displays the subseasonal distribution of all of the 36 SSW events from 1958 to 2012, where SSW events are grouped into consecutive 10-calendar-day (three groups in each month) intervals starting from 21 November to 21 March of the following year. It can be seen that SSW events appear relatively more often in January and February than in other months (see also CP07); particularly, up to seven SSWs are in the interval of 21–28 February. As already seen from the data in Table 1 and Fig. 1, there were six double-SSW winters where the first event usually took place rather early on in winter (four in December, one in late November, and one in mid-January). To exclude the possible effects from double-onset dates in double-SSW years, we excluded the first of the SSW events in the six double-SSW winters and then examined the relationship between the onset date of winter SSWs and the seasonal timing of SFWs in the following spring.

It can be seen from Fig. 2b that, among the SFWs that occurred following winter SSW events, there were only three early SFWs (green; 0.5 SD; as seen in Table 2) and the SSW events that followed were all in early winter (before early January), while most of the SFWs were late SFWs (blue; 0.5 SD; as seen in Table 2) and preceded by SSWs that occurred in late winter (January–March). In particular, there were in total seven SSWs in the period from 21 January to 10 February, and six of them were followed by late SFWs.

In general, the above-reported statistical analysis indicates that late (early) SFWs tend to be preceded by SSW (non-SSW) winters. While the occurrence (absence) of winter SSWs may not necessarily be followed by late- (early-) SFW springs, late (early) SFWs are much more frequent than early (late) SFWs after SSW (non-SSW) winters. Further analysis indicated that when the onset date of SSS (with the first SSW in double-SSW years excluded) is rather early in winter, before January, the spring SFWs can still be anomalously early (albeit only a few), while the SSWs followed by late SFWs are all in late winter, after early January.

4. Dynamical linkage between winter SSWs and spring SFWs

To understand the statistical relationship between the occurrence of wintertime SSWs and the timing of springtime SFWs, in this section we diagnose the dynamical processes responsible for the linkage between these two warming phenomena. To capture the essential circulation features related to early and late SFWs, we defined the early- and late-SFW years based on the 1.0-SD criterion in Table 2 and identified 11 anomalously early-SFW years (1959, 1961, 1964, 1972, 1974, 1975, 1983, 1985, 1986, 1992, and 2005; mean date of 17 March).

Figure 3 shows the temporal evolutions of the composite zonal-mean zonal wind in 65°–75°N (Figs. 3a and 3b) and zonal-mean temperature in 60°–90°N (Figs. 3c and 3d) at 10 hPa for early- (black) and late- (red) SFW years. Note that Figs. 3a and 3c are composites against the SFWODs (day 0); (b), (d) are composites against calendar days. Accompanying the onset of early-SFW events, the circumpolar westerly wind on average tends to weaken drastically around the SFWOD and reverses to easterly wind at day 0 (black; Fig. 3a). Correspondingly, the polar stratospheric temperature exhibits a drastic warming around the SFWOD (black; Fig. 3c). In contrast, around the onset date of late-SFW events, the changes of the circumpolar westerly wind and polar temperature are found to be much more gradual (red in Figs. 3a and 3c) than early SFWs (see also Black et al. 2006). As expected, in spring of early-SFW years, the circumpolar westerly wind usually weakens drastically after mid-February and becomes reversed around 16 March (black in Fig. 3b) accompanied by drastic warming in the polar stratosphere before the onset of SFWs (black in Fig. 3d). While in spring of late-SFW years, a gentle circumpolar westerly wind persists in spring months from mid-February to April, and is not reversed to an easterly wind until early May (red in Fig. 3b). The drastic change of the circumpolar westerly wind and extreme polar warming mainly occurs earlier in the preceding January (red in Figs. 3b and 3d). The central date of this warming corresponds well to the mean date of winter SSWs (Fig. 1 and Figs. 3b and 3d). This indicates that, throughout the winter and spring, weakening of the circumpolar westerlies along with a polar warming generally occurs only once in early-SFW years but may occur twice in late-SFW years. It should be pointed out that this result is quite consistent with that of Wei et al. (2007) but does not agree well with Waugh and Rong (2002), probably owing to the different criterion they used to define the SFWODs, as mentioned in section 2. Our definition of SFWOD, similar to that in Black et al. (2006) and in Wei et al. (2007), successfully isolated a later stage of the final
breakdown of the stratospheric polar vortex and thus avoided the misinterpretation of some winter SSW events as final warming events.

a. Planetary wave activity from winter to spring

Planetary wave activity in the stratosphere is one of the key dynamical forcings for polar warming events (Polvani and Waugh 2004). Next, we compare the temporal evolutions of the vertical component of Eliassen–Palm (EP) flux (Andrews et al. 1987) and anomalies by planetary waves (wavenumbers 1–3) in the extratropical (55°–75°N) stratosphere (10–50 hPa) between the early-(Figs. 4a and 4b) and late-SFW years (Figs. 4c and 4d).

In early-SFW years (Figs. 4a and 4b), EP flux by planetary waves is on average weaker at the beginning of winter but strengthens from mid-February and keeps strengthening until the onset of SFW events in mid-March. Correspondingly, anomalies of EP flux at 10 hPa exhibit large amplitude of negative-to-positive change, indicating a weaker-to-stronger planetary wave activity from mid-January to mid-March in early-SFW years (Fig. 4b). By comparing Figs. 4a and 4c and Figs. 4b and 4d, it is easy to identify that the temporal evolutions of the EP flux and its anomalies in late-SFW years are generally out of phase with those in early-SFW years. Namely, planetary wave activity in late-SFW years is usually stronger at the beginning of winter, but weakens from mid-February and keeps weakening afterward until the final breakdown of the vortex in early May. In other words, early- (late-) SFW years correspond to a quiet (turbulent) winter stratosphere followed by a turbulent (quiet) spring stratosphere. These results verify the statistical relationship between the occurrence of winter SSWs and the timing of SFWs reported in section 3.

The lack of planetary wave forcing in late-SFW springs explains the gradual changes of the stratospheric circulation accompanying the final breakdown of the polar vortex (also see Black et al. 2006; Hu et al. 2014). This also implies that, in contrast to the early-SFW events with stronger planetary wave forcing, the final breakdown of the polar vortex in late-SFW springs may be attributed mainly to seasonal change in the diabatic solar radiation, and is thus more a reflection of the natural seasonal evolution of the stratospheric polar vortex.

It can also be seen from Figs. 4b and 4d that planetary wave effects always tend to be dominated by planetary wavenumber-1, but in the winter preceding late-SFW events, the wavenumber-2 component is found to be even stronger than wavenumber 1 (Fig. 4d), suggesting that wavenumber 2 could be as important as wavenumber 1 for major SSW events (also see Martius et al. 2009; Bancelá et al. 2012). Since wavenumber 2 represents the extent of “vortex splitting” during warming events, we note that, among the eight winter SSW
events preceding late SFWs, five of them were vortex-splitting types, including the very strong splitting SSW in late January 2009 (Harada et al. 2010), as shown in Tables 1 and 2 and Fig. 1.

As already indicated in section 3, preceding those early- (late-) SFW events, it needs to be a non-SSW (SSW) winter, while non-SSW (SSW) winters may not necessarily be followed by early- (late-) SFW springs. Nevertheless, we emphasized that possibility of late (early) SFWs is much higher than early (late) SFWs after occurrence (absence) of winter SSWs. To further confirm this, similar to Fig. 4, we examined the temporal evolutions of the planetary wave forcing associated with SSW events. Figure 5a shows the composite evolution of the vertical component of EP flux anomalies around the onset dates of 35 SSW events (the SSW event in January 1958 was removed) from day −60 to day 60. It can be seen that positive EP flux anomalies appear from day −30 and then strengthen with time. After drastic strengthening from day −8, EP flux anomalies peak at day −2 prior to the SSW onset. Following that, significant negative EP-flux anomalies persist after day 8 until days 40–45, implying the suppression of planetary wave activity after SSW onset. CP07 also indicated the persistence of negative EP flux anomalies until 40 days after SSWs. Because of the persistent negative EP flux anomalies after SSWs, there is relatively weaker planetary wave activity through March and April, which therefore favors a late breakdown of the stratospheric polar vortex.

Figure 5b presents the composite difference of the vertical component of EP flux between 30 SSW years and 25 non-SSW years against calendar days. It is clear that the evolution of EP flux in Fig. 5b is quite similar to that in Fig. 4d. Namely, anomalously stronger planetary wave activity in late January of the winter is followed by anomalously weaker planetary wave activity in mid-March of the spring. The mutual reproduction of the temporal evolutions of EP flux between SSW events and SFW events further confirms that SSW (non-SSW) winters do indeed favor weaker (stronger) planetary wave activity in spring and therefore late (early) SFWs. It is known that polar stratospheric warming can be regarded as a negative NAM event (e.g., Cai and Ren 2007; Ren and Cai 2006) or the polar jet oscillation (PJO) (e.g., Hitchcock et al. 2013a,b; Kuroda and Kodera 2001), after which planetary wave activity in the stratosphere will be largely suppressed owing to the reversal of the stratospheric polar jet. The lack of wave activity in the extratropical stratosphere would continue until the recovery of the polar jet. A complete NAM or PJO cycle may last about 3–4 months between two positive events or between two negative events (Ren and Cai 2006; Cai and Ren 2007; Hitchcock et al. 2013a,b; Kuroda and Kodera 2001). This may also help to explain the general weakness of planetary wave activity and the lateness of SFWs after a (midwinter) SSW event.

b. Tropospheric precursors to winter SSW occurrence in late-SFW years

In this section, we explore the tropospheric precursors to the stratospheric warming events by focusing on the time period from early January to late March covering the warming processes of both winter SSWs and early spring SFWs. To elucidate the life cycle of the possible tropospheric precursors to winter SSWs, three time periods are selected: 6–15 January, 16–25 January, and 1–10 February, corresponding to days −20 to −11, −10 to −1, and 5 to 15, respectively, relative to the onset date of SSW events. Figure 6 shows the longitude–pressure cross sections of the composite geopotential height anomalies along the latitude band 50°–70°N for early- (left) and late- (right) SFW years in the three specified time periods. It can be seen that, in early-SFW years (left), the composite geopotential height anomalies (shading) in the troposphere are
persistently weaker and less significant than in late-SFW years (right) throughout the three time periods from early January to early February (Figs. 6a,c,e versus Figs. 6b,d,f). This indicates a relatively quiet troposphere in the winter preceding early SFWs. Associated with the less disturbed extratropical troposphere, the geopotential height anomalies in the stratosphere seem also to be relatively weaker than in late-SFW years and are mostly insignificant. Comparing the zonal distributions of the stratospheric anomalies with those of the corresponding zonal deviations of climatological means (purple lines), it can be seen that they are less in phase but mostly out of phase or orthogonal, indicating the less-intensified or weakened planetary wave activity in the stratosphere in the winter preceding early SFWs.

In contrast, the composite geopotential height anomalies in the extratropical troposphere and stratosphere during the same time periods in late-SFW years exhibit much larger amplitudes and are mostly statistically significant. Specifically, in the first time period of 6–15 January in the extratropical troposphere (Fig. 6b), positive anomaly centers appear respectively over western Eurasia (~0°) and North America (~120°W) and negative anomaly centers respectively over the North Pacific (~180°) and eastern Canada (~60°W). As a result, the stationary trough near eastern Canada (~60°W) and the Aleutian low over the North Pacific are both anomalously deepened, while the stationary ridge over western Eurasia (~0°) is anomalously strengthened, which obviously will enhance the possible upward propagation of planetary waves into the stratosphere. In previous studies, the positive anomaly center over western Eurasia has been recognized as a typical tropospheric precursor to major SSW events or a weakening of the stratospheric vortex (Garfinkel et al. 2010; Kolstad and Charlton-Perez 2011). In addition, we noted that there exists a negative anomaly center over western Siberia (~70°E) in the troposphere, but it is much weaker relative to other anomaly centers. Later, in the second time period of 16–25 January, just prior to the onset of SSW events (Fig. 6d), stronger and significant geopotential height anomalies are observed in the stratosphere,
though tropospheric anomaly signals have already diminished. More importantly, the zonal distribution of the anomalies in the stratosphere, though still wavenumber-2-like, are clearly also enhancing the climatological-mean general wavenumber-1 pattern, thus manifesting the anomalously stronger planetary wave activity in this period prior to the onset date of SSW events. After the onset date of SSW events, in the third period of 1–10 February (Fig. 6f), the geopotential height anomalies in the stratosphere become wavenumber-1-like but tend to be generally out of phase with the climatological mean field, manifesting the suppression of planetary wave activity after the occurrence of SSW events, which is also consistent with the results shown in Smith et al. (2010) and Fletcher and Kushner (2011).

The stronger tropospheric wave anomalies in the earlier period and the intensified stratospheric planetary waves later, just before the onset of winter SSW events in late-SFW years, can be seen more clearly in Fig. 7. In the earlier period of 6–15 January, as already identified from Fig. 6b, the anomalous wavenumber-1 (Fig. 7a) and wavenumber-2 (Fig. 7b) components (shading) in the extratropical troposphere below 200 hPa both exhibit a general in-phase relationship with the corresponding climatological mean components, confirming the intensified tropospheric wave activity in this period. We also note that in this period, 11–20 days before the onset of SSWs, the planetary wavenumber 1 in the stratosphere seems to be in quadrature with climatology, while the anomalous planetary wavenumber 2 at 10 hPa is still out of phase with the climatological component (Figs. 7a and 7b). In the second time period of 16–25 January (Figs. 7c and 7d), associated with the stronger geopotential height anomalies in the stratosphere and the diminished anomalies in the troposphere in Fig. 6d, the anomalous planetary wavenumber-1 components in the stratosphere are closely in phase with the corresponding climatological means. And the anomalous wavenumber-2 components also tend to intensify the climatological wavenumber-2 pattern though with a slight phase shift. In the third time period of 1–10 February, after the onset of SSWs, we see an orthogonal relationship between the anomalous stratospheric wavenumber 1.
and the climatology (Fig. 7e), accompanied by an out-of-phase relationship for the wavenumber-2 components (Fig. 7f). This indicates a suppression of planetary waves in the stratosphere after the onset of SSW events, as indicated by Limpasuvan et al. (2004) and CP07.

The results shown in Figs. 6 and 7 clearly suggest that, in midwinter of late-SFW years, significant tropospheric wave precursors appear as early as 11–20 days before the occurrence of an SSW event. Comparing Fig. 6b and Figs. 7a and 7b, we further identified that the positive anomalies over western Eurasia (≈0°) and negative anomalies over the North Pacific (≈180°) act mainly to reinforce the planetary wavenumber 1, while the negative anomalies over eastern Canada (≈60°W) act mainly to enhance the planetary wavenumber 2 in the extratropical troposphere. These earlier wave anomalies in the troposphere are obviously connected with the anomalously stronger planetary wavenumber-1 and wavenumber 2 later in the stratosphere prior to the onset of SSWs. In contrast, in midwinter of early-SFW years, wave precursor signals in the troposphere are relatively weaker or out of phase with the stationary waves, which are followed by anomalously weaker stratospheric planetary waves and thus an undisturbed stratosphere in these winters.

c. Tropospheric precursors to early SFWs

Similar to with winter SSW events, in this section we also focus on three critical time periods around the onset date of SFWs in spring: 26 February–5 March, 6–15 March, and 21–30 March, corresponding to the periods of days −20 to −11, −10 to −1, and 5 to 15, respectively, relative to the onset date of early SFWs. In Fig. 8, we display the composite geopotential height anomalies in the extratropics in the three time periods for early- and late-SFW years in parallel. First, we notice that, to a large degree, the composite mean pattern of geopotential height anomalies within the troposphere for early-SFW years (Fig. 8a) is similar to that in Fig. 6b. Namely, along the latitude band of 50°–70°N in the extratropics, positive and negative anomaly centers also exhibit a wavenumber-2-like pattern, with the two significant positive anomaly centers respectively in western and eastern Eurasia and the two significant negative anomaly centers respectively over the northeastern Pacific and eastern Canada. From the phase relationship between the anomaly centers and the climatological centers, it is clear that in this period, 11–20 days before the onset of SFW events, the wave anomalies
in the troposphere are acting to intensify the climatological planetary waves. Particularly, the positive anomaly center over western Eurasia, which acts to strengthen the western Eurasian high, was found to be already significant in the period of 16–25 February, about 21–30 days before SFWs (not shown), and could even be identified as early as in the period of 1–10 February (Fig. 6e). This suggests that the intensification of the western Eurasian high may also be considered as a precursor to spring SFW events.

Also consistent with Fig. 6d, in the second period of 6–15 March, just prior to the average onset date of SFWs, the tropospheric anomalies have remarkably diminished; however, the zonal wavenumber-1-like pattern in the stratosphere becomes strongest and most significant. Although the zonal pattern of anomalies is not exactly in phase with the climatological wavenumber-1 pattern in stratosphere, it still indicates the anomalously stronger planetary wave activity before SFW onset. After the onset of SFWs in the third period, the wavenumber-1-like pattern is weakened and the extratropical stratosphere above 20 hPa is overall dominated by positive geopotential height anomalies (Fig. 6f).

FIG. 9. As in Fig. 7, but for the periods (a),(b) 26 Feb–5 Mar, (c),(d) 6–15 Mar, and (e),(f) 21–30 Mar in early-SFW years.

In contrast, for late-SFW years, the corresponding composite geopotential height anomalies in both the troposphere and stratosphere are generally in opposite polarity to that for early-SFW years and clearly act to suppress the development of stationary ridges and troughs (Figs. 8b and 8d), representing the anomalously weaker planetary waves in late winter to early spring of late-SFW years. Consequently, in the third period of 21–30 March, the extratropical stratosphere is dominated by significant negative geopotential anomalies, which also tend to be out of phase with the climatological zonal pattern (Fig. 8f).

As in Fig. 7, we also show the anomalous zonal wavenumber-1 and wavenumber-2 components and the corresponding climatological components in the three time periods for early-SFW years in Fig. 9. Consistent with Figs. 8a and 8c, the anomalous wavenumber-1 and the wavenumber-2 components in the troposphere both tend to reinforce the climatological stationary components through the first two periods from 26 February to 15 March (Figs. 9a–d). In the stratosphere, nevertheless, while the anomalous wavenumber-1 component always acts to reinforce the climatological planetary waves in these two periods (Figs. 9a and 9c), the anomalous wavenumber-2 component is in phase with the stationary wavenumber 2 in the first period but becomes
out of phase in the second period, particularly in the upper-stratospheric layer above 70 hPa (Figs. 9b and 9d). This is different from the planetary wave activity prior to the onset of winter SSWs where planetary wavenumber 1 and wavenumber 2 are both reinforced by the anomalous planetary waves. This may imply that, unlike the winter major SSW events that usually involve both vortex location shift and vortex splitting, the occurrence of SFW events in spring seems to mainly involve vortex location shift.

d. Western Eurasian high as a tropospheric precursor to the timing of SFWs

From the diagnosis of wave activity prior to winter major SSWs in late-SFW years and that prior to early-SFW events, we can confirm that strengthening of the western Eurasian high in the troposphere could act as the most significant and robust tropospheric precursor signal to both SSWs and SFWs. Next, we further show that this tropospheric precursor could act as a significant indicator of the seasonal timing of spring SFWs. In Fig. 10, we display the seasonal temporal evolutions of the vertical EP-flux anomalies averaged in 50°–70°N in the stratosphere above 100 hPa for early- and late-SFW years (Figs. 10a and 10b). In parallel, we also display the temporal evolutions of the composite geopotential height anomalies over the western Eurasian sector (50°–70°N, 10°W–10°E) (Figs. 10c and 10d). It is evident that, in early-SFW years, the tropospheric precursor, or the strengthening of the western Eurasian high, does not occur until late February (Fig. 10c), and only after that does the EP-flux in the stratosphere become significantly stronger in early to mid-March (Fig. 10a), corresponding to the occurrence of early-SFW events. In contrast during late-SFW years, the tropospheric precursor or the strengthening of the western Eurasian high appears in early January, much earlier than in early-SFW years (Fig. 10d), and again after the precursor, the anomalously stronger EP-flux in the stratosphere appear in the period from mid- to late January (Fig. 10b), corresponding to the occurrence of the winter SSW events in late-SFW years. This clearly suggests that the linkage between the occurrence (absence) of winter SSWs and the late (early) onset of spring SFWs in the stratosphere is largely associated with the appearance of certain precursors in the troposphere, especially the strengthening of the western Eurasian high.

FIG. 10. The temporal evolutions of (a),(b) the composite vertical EP flux anomalies (wavenumbers 1–3; $10^5$ m$^2$ s$^{-2}$) at 50°–70°N in the stratosphere above 100 hPa and (c),(d) the composite geopotential height anomalies (gpm) over the western Eurasian sector (50°–70°N, 10°W–10°E) for (a),(c) early- and (b),(d) late-SFW years. Black dashes indicate the 90% and 95% confidence levels of the composite anomalies according to the $t$ test.
5. Concluding remarks

Based on the available longer reanalysis time series, we reexamined the linkage between the timing of spring SFWs and the polar vortex condition in the preceding winter in terms of the occurrence of winter SSW events. We proved a significant statistical relationship between the occurrence of winter SSWs and the seasonal timing of SFWs. We also diagnosed the related dynamical processes responsible for the linkage between these two stratospheric warming phenomena and identified the contrasting features of tropospheric precursors to the stratospheric warming events between anomalously early- and late-SFW years. The main findings can be summarized as follows:

1) Late SFWs in spring are mostly preceded by major SSW events in winter, while early SFWs are mostly preceded by non-SSW winters. Nevertheless, the occurrence (absence) of SSW events in the previous winter may not be sufficient to anticipate a late (early) SFW in the following spring because only about half of the SSW (non-SSW) winters are followed by late- (early) SFW springs. However, following SSW winters, late SFWs were found to be much more frequent than early SFWs, and meanwhile following non-SSW winters, early SFWs were found to be much more frequent than late SFWs.

2) Whether or not a late spring SFW appears following a SSW winter is largely related to the timing of winter SSW events. Winter SSW events that occur before early January may still be followed by early SFWs in spring. Winter SSW events that occur specifically during the period from late January to early February are generally followed by late-SFW events.

3) Consistent with the above findings, planetary wave activity in the stratosphere exhibits contrasting seasonal evolution features between anomalously early- and late-SFW years. Specifically, in early-SFW years, planetary wave activity is anomalously weaker in winter before mid-February but gets stronger afterward in spring and thus yields a quiet non-SSW or less-dynamical winter followed by a more-dynamical early-SFW spring. While in late-SFW years, planetary wave activity is anomalously stronger in midwinter and usually yields major SSW events around late January to early February but then becomes weaker later in spring, thus resulting in a less-dynamical late-SFW spring. This is also consistent with the notion that planetary wave activity in the extratropical stratosphere is suppressed after negative event of NAM or PJO until the recovery of the polar jet.

4) The strengthening of the western Eurasian high as a typical tropospheric precursor to both SSW and SFW warming events occurs during early to mid-January in late-SFW years but does not appear until late February to mid-March in early-SFW years. Thus, it can also act as a tropospheric precursor to the seasonal timing of SFWs.

To sum up, the significant relationship between the timing of SFWs and the occurrence of SSW events in preceding winter, proved in this study, demonstrates a clear linkage between the onset of SFWs and the preexisting condition of the stratospheric polar vortex. This linkage can be physically interpreted with the contrasting seasonal evolutions of planetary wave activity between early- and late-SFW years. The consistency of the linkage with the basic stratospheric dynamics further increases the robustness of the relationship. By identifying the contrasting features of tropospheric precursors between early- and late-SFW years, the onset of SFWs was further related to the tropospheric circulation condition in winter. It needs to be pointed out that our conclusions are insensitive to the specific criteria we applied in defining or classifying the major SSW and SFW events. Factors that may affect the timing of the tropospheric precursors, and the possible effects of early- or late-SFW events on the tropospheric circulation in spring, have not been addressed in the present paper and still require further investigation in the future.

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