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Estimating the Frequency of Sudden Stratospheric Warming Events From Surface Observations of the North Atlantic Oscillation

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Key Points:
- Two thirds of SSW events are followed by a persistent negative NAO and/or a switch to a negative NAO at the surface
- Winter surface NAO anomalies commonly observed after SSW events are preceded by a SSW in less than 25% of all cases
- The "SSW drought" in the 1990s coincides with the longest absence of NAO events since 1850

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Abstract Sudden stratospheric warming (SSW) events can exhibit long-lasting surface impacts that promise improvements in medium-range to seasonal predictability. Their surface impact is dominated by the negative phase of the North Atlantic Oscillation (NAO). Hence, the question arises if stratospheric variability, and in particular the frequency of SSW events, can in turn be estimated from surface NAO conditions. This is especially relevant for the period before frequent upper air observations became available, while daily surface observations of the NAO date back to 1850. The surface impact is here quantified by NAO characteristics that are commonly observed after SSW events: a switch from a positive to a negative NAO and an extended persistence of the negative NAO, termed *NAO events*. Two thirds of SSW events are found to be followed by either a persistence or switch NAO event, and a quarter of SSW events are followed by both. On the other hand, less than 25% of winter surface NAO events are preceded by a SSW event. Based on these findings, an index purely based on surface NAO observations is derived that estimates SSW frequency for the satellite era and extends it back to 1850, indicating that decadal stratospheric variability was present for the entire time series, with no significant trend. The minimum in SSW frequency in the 1990s is found to be coincident with the longest absence of NAO events since 1850, indicating that the early 1990s may constitute the longest absence of SSW events for the 150-year record.

Plain Language Summary Extreme events in the stratosphere, so-called sudden stratospheric warming (SSW) events, have long-lasting impacts on the weather over the North Atlantic that can be characterized by variability in the North Atlantic Oscillation (NAO). While daily observations of the NAO date back to 1850, estimates of SSW event frequency only go back to the 1950s. This study explores to what extent the frequency of SSW events can be estimated from surface NAO variability as a first step toward reconstructing SSW frequency before the 1950s. It is found that characteristic effects in the surface NAO that typically occur after SSW events are only associated with SSW events in about a quarter of all cases. Nevertheless, an index can be generated entirely based on surface information that can to a good extent reproduce the SSW frequency for the period for which information for the stratosphere is available. Extending the index back to 1850 indicates that the frequency of SSW events exhibited decadal variability, as observed in the second half of the twentieth century. It is also found that the early 1990s, a period where very few SSW events were observed, was likely the longest absence of SSW events since 1850.

1. Introduction

Sudden stratospheric warming (SSW) events account for the most extreme changes on daily to weekly timescales in the extratropical winter stratosphere. The stratospheric anomaly descends into the lower stratosphere through wave-mean flow interaction (Plumb & Semeniuk, 2003) and can persist there for several weeks to months, in so-called polar jet oscillation events (Hitchcock, Shepherd, Yoden, et al., 2013; Hitchcock, Shepherd & Manney 2013; Kuroda & Kodera, 2004). A downward impact of the stratospheric signal to the troposphere can occur through a range of mechanisms involving both synoptic-scale and planetary-scale waves (Domeisen et al., 2013; Hitchcock & Simpson, 2014; Smith & Scott, 2016; Song & Robinson, 2004); for a summary of the mechanisms see Tripathi et al. (2015) and Kidston et al. (2015). Compositing with respect to SSW events yields a surface response in the form of a negative signature of the Arctic Oscillation (Baldwin & Dunkerton, 2001). This response tends to focus on the North Atlantic and imprints onto the negative phase of the North Atlantic Oscillation (NAO), while the North Pacific is less strongly affected (Figure 4 in Butler et al., 2017; Greatbatch et al., 2012). The associated surface weather impacts include cold air outbreaks in Northern Europe (Kolstad et al., 2010) and increased precipitation in the Mediterranean (Butler et al., 2017). The detection of these surface impacts has led to an increased interest in SSW events with the aim to improve North Atlantic predictability at subseasonal to seasonal timescales (Beerli et al., 2017; Butler et al., 2016, 2019; Domeisen et al., 2015; Jia et al., 2017; Karpechko, 2015; Scaife et al., 2016; Sigmond et al., 2013). On weather time scales, the NAO exhibits predictability on weather time scales of about a week, with a theoretical limit of about 3 weeks (Buizza & Leutbecher, 2015; Domeisen et al., 2018). On seasonal and longer time scales a skillful prediction of the winter NAO is possible when utilizing the effect of remote influences including the stratosphere (Dobrynin et al., 2018; Dunstone et al., 2016; Scaife et al., 2016).

A range of studies has classified SSW events and their surface impacts, with respect to their geometry, that is, split and displacement events (Maycock & Hitchcock, 2015; Mitchell et al., 2013), their evolution, that is, absorbing and reflecting events (Kodera et al., 2016), and based on their lower stratospheric and surface response (Karpechko et al., 2017, hereafter K17). Runde et al. (2016) find that 20% of extreme stratospheric vortex events exhibit a surface response for a classification of stratospheric extreme events that includes strong vortex events and minor sudden stratospheric warmings. For classifications that are restricted to SSW events, roughly half of all observed events are found to exhibit a surface signature (see Table 1 in K17). However, these SSW classifications differ significantly in terms of which SSW events they find to exhibit a downward impact. Despite the strong dependence of the surface impact on the exact definition, it is clear that a surface impact can be expected for a large range of SSW events. The question arises if stratospheric variability, and in particular the occurrence of SSW events, can be inferred from surface NAO observations. This is particularly relevant before the satellite era, since different reanalysis products for this period yield significant discrepancies in stratospheric variability (Badin & Domeisen, 2014a, 2014b) and SSW occurrence (Butler et al., 2017). For the satellite era, Reichler et al. (2012) find strong decadal variability in SSW occurrence. While SSW events on average occur about 6 times per decade (Charlton & Polvani, 2007), reanalysis products agree that no SSW event occurred for the nine winters from 1989/1990 to 1997/1998 (Butler et al., 2017), the longest absence of SSW events observed for the satellite era. For future projections, McLandress and Shepherd (2009) predict an increase in SSW events when not adapting the SSW definition to changes in the mean state, while newer studies find no robust evidence of changes in the frequency of SSW events (Ayarzagüena et al., 2018). For the past, in particular before the 1950s, it remains unclear to what extent SSW frequency might have experienced changes. While several reanalysis products date back before more frequent radiosonde observations were available in the 1950s, these often contain significant biases (Wartenburger et al., 2013) and lack sufficient stratospheric variability: As an example, the Twentieth Century Reanalysis (Compo et al., 2011) that is based on an assimilation of surface pressure fields and dates back to 1871 exhibits only a single SSW event between 1958 and 2013 as compared to the 35 (in the NCEP-NCAR I reanalysis, Kalnay et al., 1996) to 37 (in the JRA-55 reanalysis, Kobayashi et al., 2015) SSW events in other reanalysis products for the same period (Butler et al., 2017). While the frequency of SSW events is not reliably reproduced in products that extend before the 1950s, estimates for the daily variability of the NAO exist back to 1850 (Cropper et al., 2015). The fact that many SSW events exhibit a surface response therefore allows for the potential to reconstruct—while not the full stratospheric variability—at least an estimated frequency of SSW events.

Inferring stratospheric variability from surface observations is complicated by the fact that surface conditions similar to the ones observed after SSW events can arise without a stratospheric forcing. While significant deviations from the mean state of the NAO are observed after SSW events both in terms of the sign and persistence of the NAO response, episodes of an anomalous or persistent NAO signature can also be brought about by a range of internal tropospheric processes (Barnes & Hartmann, 2010; Drouard et al., 2013; Drouard et al., 2015; Rivière & Drouard, 2015; Woollings et al., 2016) and tropospheric remote influences from, for example, El Niño Southern Oscillation (Jiménez-Esteve & Domeisen, 2018) and the Madden-Julian Oscillation (Lin et al., 2015). This study analyzes to what extent it is indeed possible to infer stratospheric variability from surface NAO conditions with a focus on the occurrence of SSW events with a downward impact. Section 2 introduces the data sets and the methods used to analyze the time series. Sections 3 and 4 detail the findings of the study, and section 5 provides a discussion of the results.

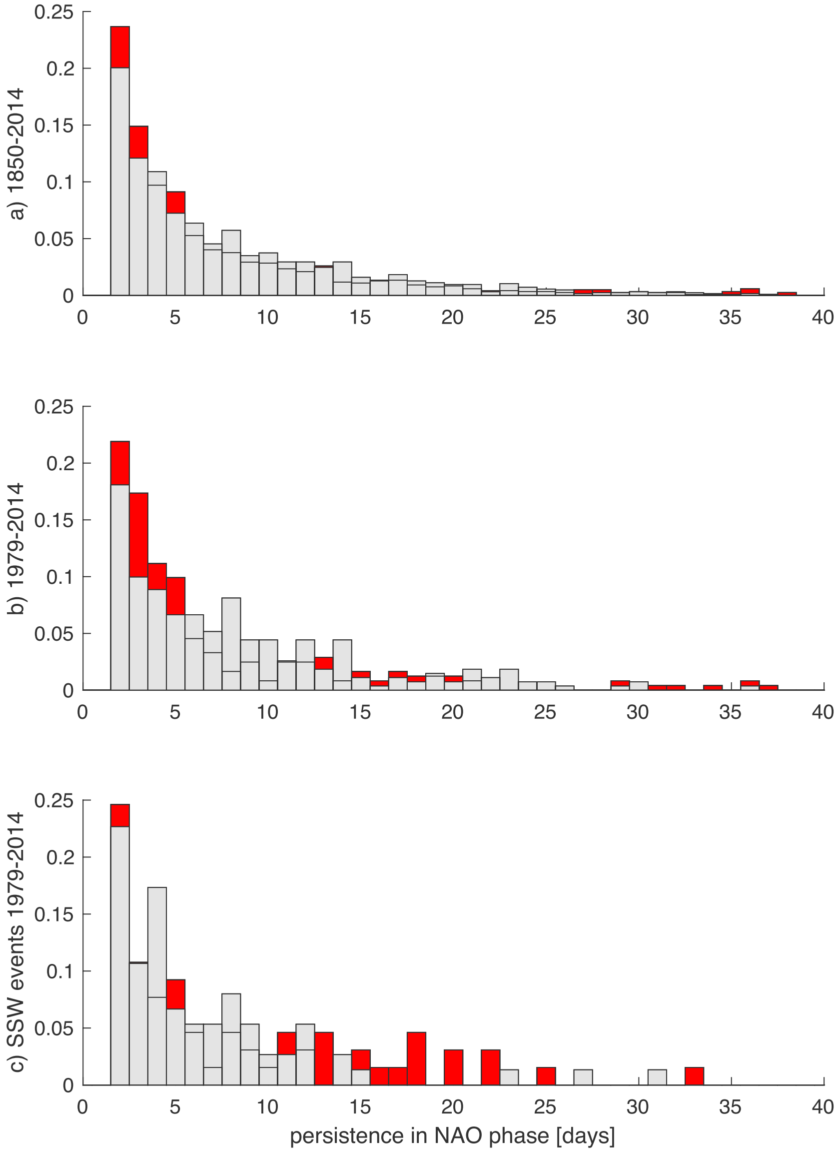

Figure 1. Histogram of the persistence (days) longer than 1 day in a positive (light gray) versus negative (red) North Atlantic Oscillation (NAO) phase for winter (December–March) for (a) the full NAO time series 1850–2014, (b) the NAO time series for 1979–2014, (c) the days 8 to 52 after the occurrence of a sudden stratospheric warming (SSW) event for 1979–2014. Additional horizontal bars inside the gray bars indicate the height of the red bars where the gray bars are taller than the red bars. All distributions are normalized for comparison.

2. Methodology

2.1. Data

A station-based daily NAO time series is available from 01 January 1850 to 15 May 2014 (Cropper et al., 2015), based on daily sea level pressure observations from stations in Iceland and the Azores. The reconstruction is homogenized with data from the Twentieth Century Reanalysis Project (Compo et al., 2011) and European Mean Sea Level Pressure (Ansell et al., 2006). The NAO index does not exhibit a linear trend (Domeisen et al., 2018) and is normalized by its standard deviation. Other reconstructions of the NAO for the period before 1850 do not exhibit daily resolution (e.g., Jones et al., 1997; Luterbacher et al., 1999, 2001) and are therefore not used here due to the need for daily resolution for the analysis performed here.

For the SSW event dates, the consolidated list of ERA40 (Uppala et al., 2006) (1958–1978) and ERA-interim (1979–2014) from Butler et al. (2017) is used. For 01 January 1979 to 31 December 2014, ERA-interim reanalysis data (Dee et al., 2011) for zonal wind at 10 hPa and 60°N, 500-hPa geopotential height, and polar cap

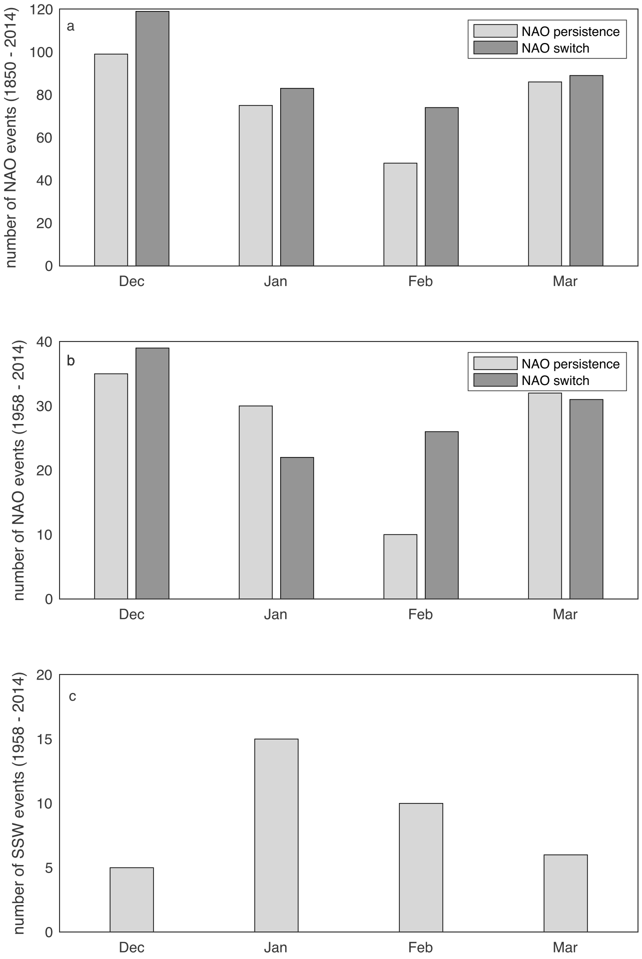

Figure 2. The total number of North Atlantic Oscillation (NAO) events per winter month for (a) 1850–2014 and (b) 1958–2014; (c) the total number of sudden stratospheric warming events per month for 1958–2014.

temperature at 150 hPa are used for comparison. Polar cap temperature is averaged from 60–90°N after weighting by the cosine of latitude to account for the decreasing area with increasing latitude and the seasonal cycle is removed. All data are restricted to winter (December–March), since this is the period when a SSW surface impact can be expected. While final stratospheric warming events occurring in March–May tend to have surface impacts as well, they are found to not project onto the NAO to the same degree (Black & McDaniel, 2007; Sheshadri et al., 2014). In particular, final warmings with an onset in the midstratosphere show a more negative NAO pattern than final warmings with an onset in the upper stratosphere (Hardiman et al., 2011). Due to the distinct behavior of final warmings as compared to SSW events, final warmings will not be considered here and will be investigated separately.

2.2. Definition of NAO Events

The most prominent surface NAO characteristics observed after SSW events are (1) an increased persistence of the negative NAO phase, and (2) a drop from a positive to a negative NAO. These are here translated into two criteria for characterizing the downward impact of SSW events by defining (1) a *NAO persistence* criterion and (2) a *NAO switch* criterion. A surface impact criterion based on persistence has already been developed in K17, which is here used as a basis for the definition of the persistence criterion. While K17 uses lower stratospheric temperature at 150 hPa and the Northern Annular Mode (NAM), these indices are not available back to 1850. The criterion is therefore here modified to only include surface conditions and to use the NAO instead of the NAM, which can be justified by the focus of the surface response on the North Atlantic. This yields the following NAO persistence criterion:

Table 1

Classification of the Observed SSW Events Into Events That Are Followed by a Downward Response (According to K17), a NAO Persistence or a NAO Switch Event

SSW central date	Downward SSW	NAO persistence	NAO switch
31.1.1958		x	-
17.1.1960		x	-
28.1.1963		x	-
16.12.1965		x	x
23.2.1966		x	-
7.1.1968		x	-
28.11.1968		x	x
13.3.1969		-	-
2.1.1970		x	x
18.1.1971		x	-
20.3.1971		x	-
31.1.1973		-	-
9.1.1977		x	-
22.2.1979	x	x	-
29.2.1980	x	x	x
4.3.1981	-	x	-
4.12.1981	x	x	x
24.2.1984	x	x	x
1.1.1985	x	x	x
23.1.1987	x	x	-
8.12.1987	-	-	-
14.3.1988	-	x	-
21.2.1989	-	-	-
15.12.1998	-	-	-
26.2.1999	x	-	x
20.3.2000	-	x	x
11.2.2001	x	x	x
30.12.2001	-	-	-
18.1.2003	-	-	-
5.1.2004	x	x	x
21.1.2006	x	x	x
24.2.2007	-	-	-
22.2.2008	-	-	-
24.1.2009	x	-	x
9.2.2010	x	x	-
24.3.2010		x	x
7.1.2013	x	-	-

Note. The SSW central event dates are based on ERA40/ERAinterim data according to Butler et al. (2017). Where ERA40 and ERAinterim do not agree, the SSW event date from ERAinterim is used. The columns indicate the classification into downward SSW events in K17 for the satellite era, the surface impact of SSW events in terms of the occurrence of a NAO persistence or switch event. The presence of an event is indicated by an “x,” the absence of an event is indicated by “-”. If no classification is available for an event, it is left blank. Note that the event on 24.3.2010 was not classified in K17. Dates are formatted as day.month.year. SSW = sudden stratospheric warming; NAO = North Atlantic Oscillation.

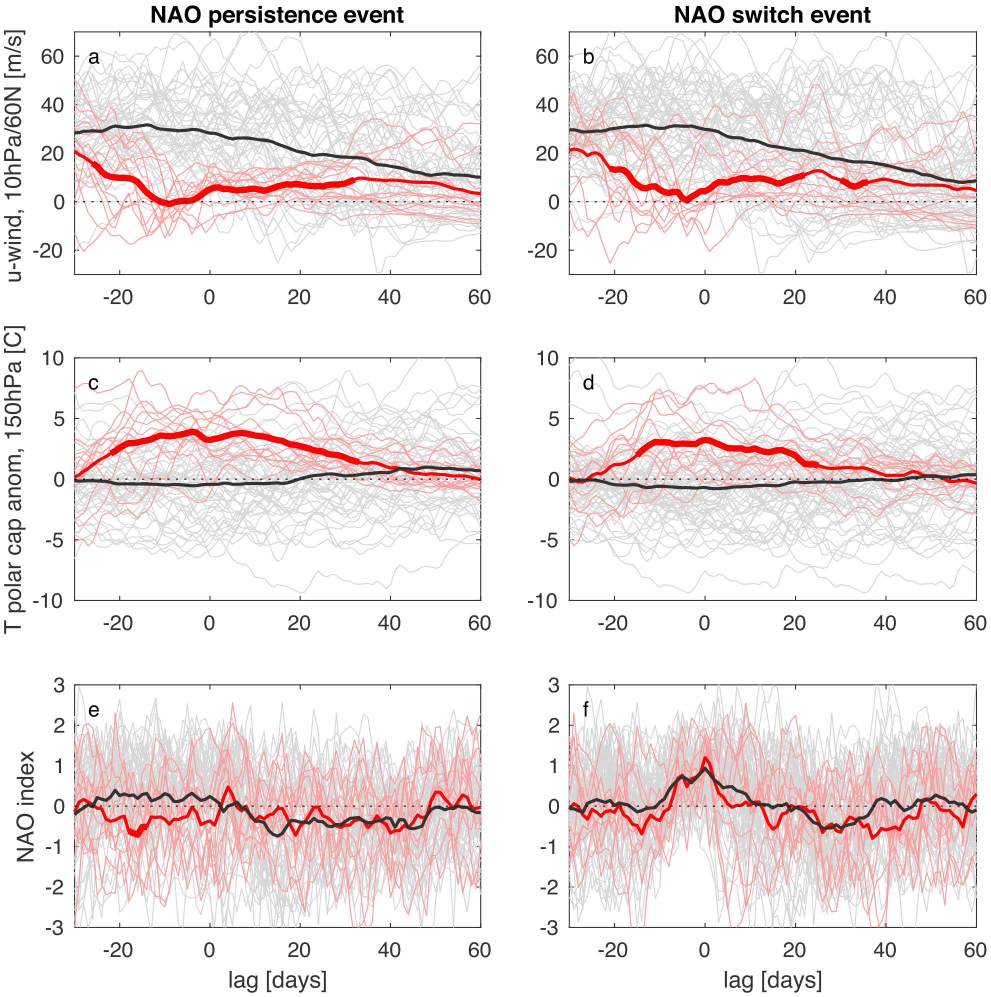

Figure 3. Composite of (a, c, and e) North Atlantic Oscillation (NAO) persistence and (b, d, and f) NAO switch events for (a and b) zonal mean zonal wind at 10 hPa/60°N [m/s], (c and d) polar cap average temperature anomalies at 150 hPa [°C], (e and f) the NAO index for winters (DJFM) between 1 January 1979 and 31 December 2014 as a function of lag [days] with respect to the NAO event. Thin red lines indicate composites that experience a SSW event (based on a wind reversal at 60°N and 10 hPa) in the first 30 days of the composite (lags −30 to −1), while thin gray lines indicate composites that do not experience a SSW event during this period. The bold black line indicates the average of the cases without a SSW event (i.e., the thin gray lines), while the red line indicates the average of all composites with a SSW event (i.e., the thin red lines). The bolder parts of the bold red line for u and T indicate values that are significantly different from the average of the full composite (i.e., the average over both the thin gray and red lines) according to a *t* test at the 5% significance level.

(1) NAO persistence criterion. For days 8–52 after the central date of a SSW event, (i) the NAO index averaged over this 45-day period must be negative, and (ii) the fraction of days within this 45-day period has to be greater than 50%. A NAO persistence event can be detected immediately again after this 45-day period (i.e., on day 53 after the central date of the SSW event). For periods without a SSW event, this criterion is evaluated for each 45-day period.

SSW events also tend to be followed by a switch of the NAO index toward its negative index state. Charlton-Perez et al. (2018) find a significant increase in the probability of a switch to a negative NAO after weak stratospheric vortex events. As an example, after the SSW event on 12 February 2018, the NAO started dropping 10 days after the SSW and decreased from above 1 to below −1 in a single week.

(2) NAO switch criterion. This criterion is based on a drop of the NAO by more than 1 standard deviation between the averages over two 11-day periods that are separated by a minimum of 1 and a maximum of 19 days. The average of the surface NAO over the first (second) 11-day period has to be positive (negative). A new event cannot be detected within 30 days of the first period, which is the maximum extent of the

Table 2
Total Number of Events for (a) NAO Persistence Events, (b) NAO Switch Events, and (c) SSW Events for the Periods Indicated in the Left Column for Total Number (Middle Column) and Number of Events per Winter (DJFM; Right Column)

Event	Number of events	Events/Winter
(a) NAO persistence events		
1850–2014 (164 winters)	308	1.88
1979–2014 (35 winters)	60 (following SSW: 14)	1.71 (following SSW: 0.40)
(b) NAO switch events		
1850–2014	365	2.23
1979–2014	72 (following SSW: 11)	2.06 (following SSW: 0.31)
(c) SSW events		
1979–2014	24 (downward: 13)	0.69 (downward: 0.37)

Note. The number in brackets for (a,b) indicates the number of events that follow SSW events. The number in brackets in (c) indicates the number of SSW events with a downward impact according to K17. DJFM = December–March; SSW = sudden stratospheric warming; NAO = North Atlantic Oscillation.

second period. A sensitivity analysis indicates that extending the wait time between the 11-day periods to 21 days does not alter the results. An increase in the magnitude of the switch results in fewer identified events, which is not surprising. For NAO switch events associated with SSW events, the first period is the 11-day period before the SSW event including the day of the SSW event.

3. Behavior and Statistics of NAO Events

As a first step, further analysis on the occurrence of the negative phase of the NAO is provided, since this is the expected response for both the NAO persistence and switch criteria. The daily NAO exhibits negative skewness, indicating that the negative phase occurs more frequently (Domeisen et al., 2018; Woollings et al., 2010).This however does not give an indication of the persistence in a particular phase. In the climatology for both the satellite era (starting in 1979) and the full time series (starting in 1850), NAO persistence is therefore examined in more detail (Figure 1). Short persistences of 2–5 days are more common for the negative NAO phase, while persistences of 6–12 days are more common for the positive NAO phase (Figures 1a and 1c). It is now tested if a more persistent negative NAO indeed holds as a signature of SSW events for the part of the data set where information about SSW events is available, that is, for the satellite era starting in 1979. After SSW events, negative NAO persistence events are more common as compared to positive NAO persistence events for persistences of 11–22 days (Figure 1c). The differences between the positive and negative NAO persistence distributions are significant according to a Kolmogorov-Smirnov test at the 1% level for both the satellite era and the full time series (Figures 1a and 1b). The differences in the distributions between positive and negative NAO after SSW events are not significant, likely due to the smaller sample size. However, the overall distribution of NAO persistence events after SSW events is significantly different from its climatology (1979–2014) at the 1% level (Figures 1b and 1c).

A further question that arises is the seasonality of the defined NAO events. NAO switch events tend to be more frequent than persistence events for the full time series (1850–2014), while this is only true for December and February for the shorter record (1958–2014) for which information on SSW occurrence is available (Figure 2). Both types of NAO events occur more frequently in early and late winter as compared to midwinter. This is an indication for the occurrence of NAO events independently of SSW events, which have a different seasonality with a peak in midwinter (Figure 2c), hence, more NAO events in midwinter (January/February) are associated with SSW events than in early or late winter.

While both the persistence and switch criteria are motivated based on the typical response to SSW events, they both exclusively use information based on surface quantities. Another way of evaluating if NAO events are indeed associated with SSW-like behavior is therefore to evaluate them with respect to their corresponding stratospheric variability. Figure 3 shows a composite of stratospheric winds at 10 hPa/60°N, polar cap temperature anomalies at 150 hPa, and the surface NAO for the identified NAO events. For all criteria, the stratospheric wind decreases during the NAO event, and the lower stratospheric temperature increases. This

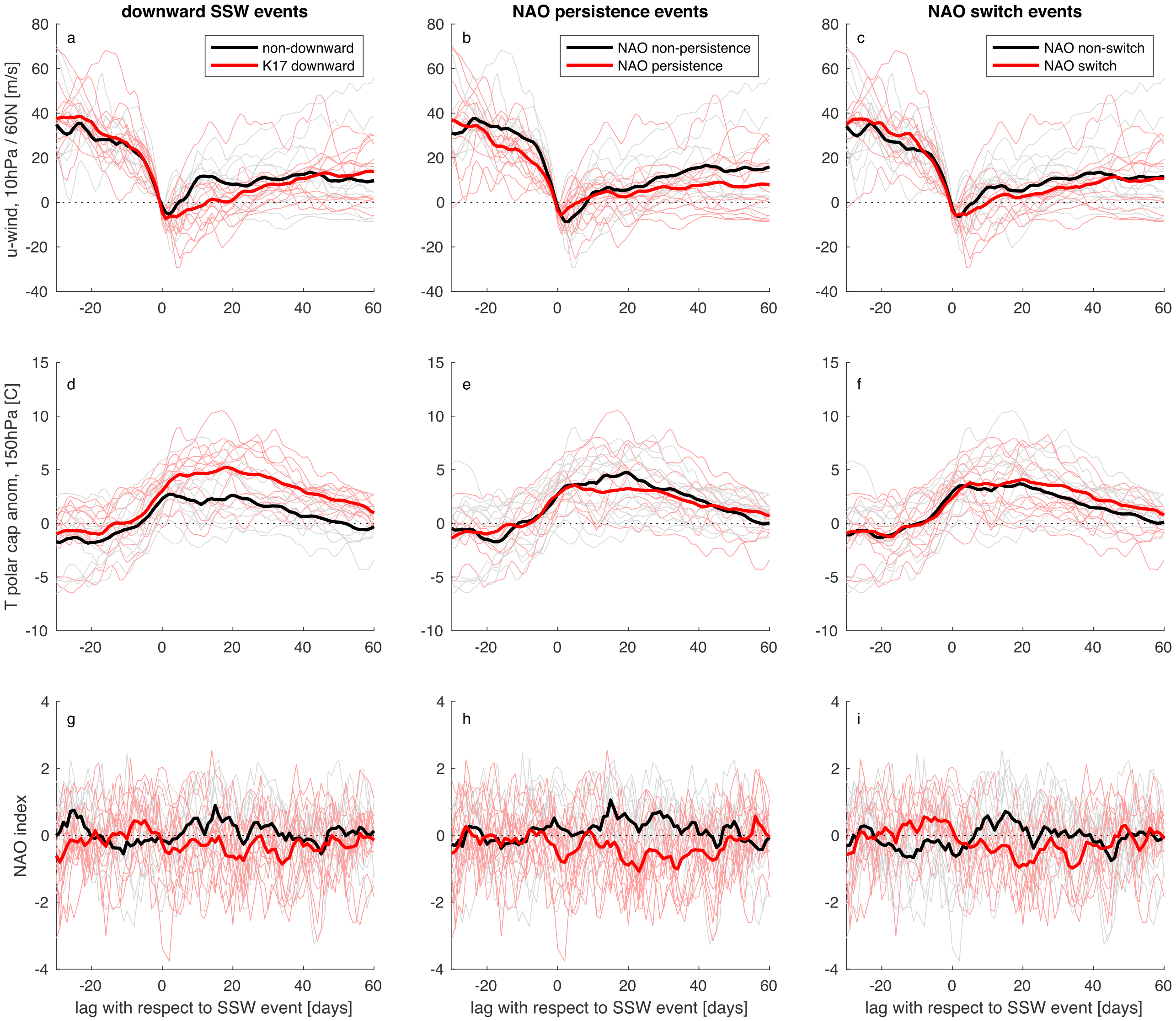

Figure 4. Composite of all sudden stratospheric warming (SSW) events during the satellite era 1979–2014 as listed in Table 1 for (a–c) zonal mean zonal wind at 10 hPa/60°N [m/s], (d–f) polar cap averaged temperature anomalies at 150 hPa [C], and (g–i) the surface North Atlantic Oscillation (NAO) from the Cropper time series. The SSW events are divided up by (a, d, and g) the K17 criterion into events with and without a downward impact, (b, e, and h) the presence of a NAO persistence event, and (c, f, and i) the presence of a NAO switch event.

effect can be observed particularly strongly for the NAO events that are preceded by a SSW event at negative lags (red lines), while a weak deceleration of the winds and increase in temperature can also be observed for events not associated with a SSW event. Several of the events that are not associated with a SSW event (gray lines) may be associated with minor SSW events or major SSW events at positive lags (note that only NAO events with SSW events at negative lags contribute to the red lines in Figure 3), while some NAO events that are not associated with a deceleration of the stratospheric winds or an increase in temperature may be due to internal tropospheric dynamics.

4. Association of NAO Events With SSW Events

It is now evaluated to what extent NAO events are indeed associated with SSW events. Table 1 shows the results for SSW events with a downward impact and surface NAO events for the SSW events classified by Butler et al. (2017) for the ERA40/ERAinterim reanalysis. For 1958–2014, NAO persistence events follow 25 of the 37 SSW events identified in the reanalysis. The NAO persistence criterion yields the same result (i.e., downward or nondownward effect) for 17 of the 23 SSW events identified in K17. Note that while

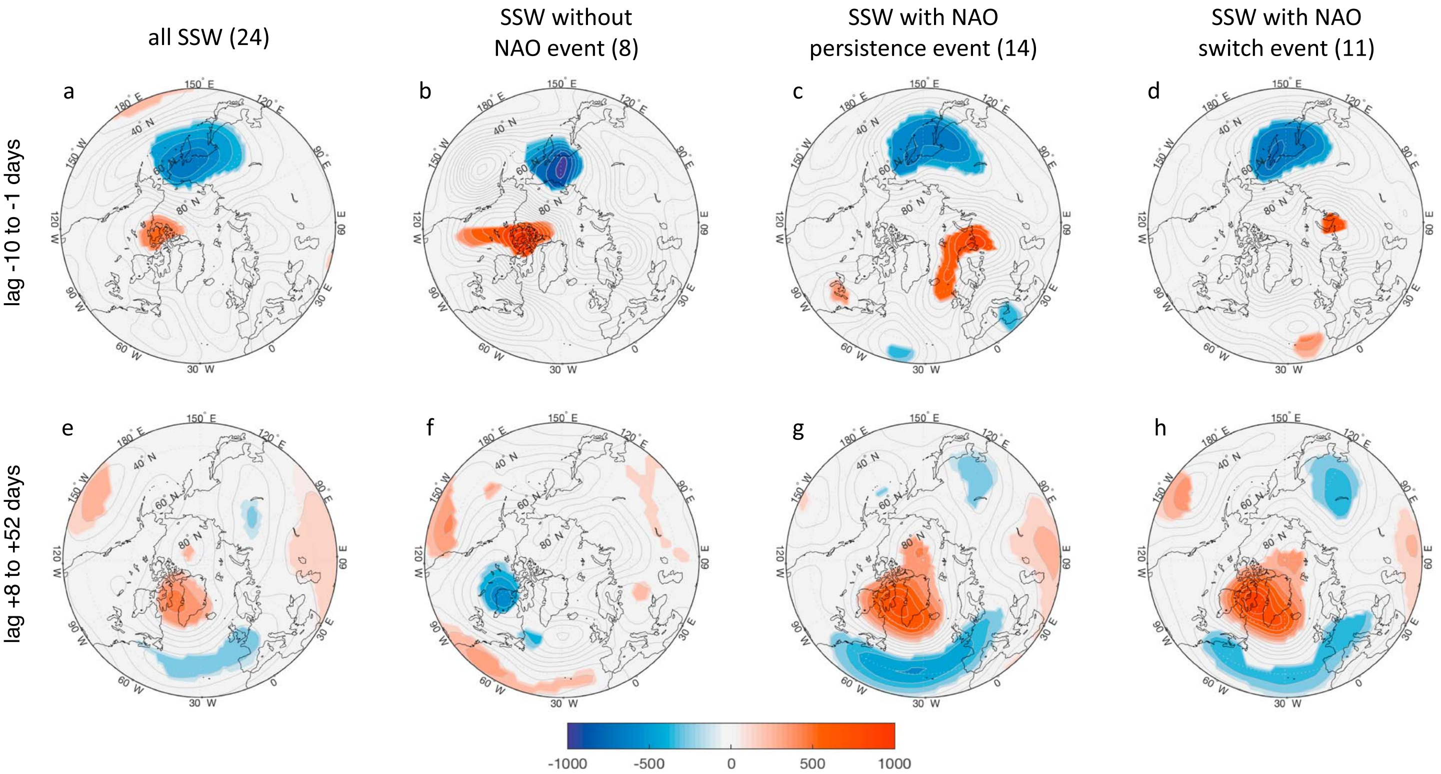

Figure 5. Composite of 500-hPa geopotential height anomalies [m] from ERAinterim for 1979–2014 for (a and e) all sudden stratospheric warming (SSW) events, (b and f) all SSW events that exhibit neither a North Atlantic Oscillation (NAO) persistence nor a switch event, (c and g) all SSW events that exhibit a NAO persistence event, (d and h) all SSW events that exhibit a NAO switch event as listed in Table 1 averaged over (a–d) the 10 days before the SSW event and (e–h) the days 8 to 52 after the SSW event. Values significant at the 5% level according to a *t* test are shaded, nonsignificant values are indicated by contour lines. The number in brackets indicates the number of events used for the composites. The contour interval is 100 m.

the 24 SSW events between 1979 and 2014 from Butler et al. (2017) are listed here, the event on 24 March 2010 has not been classified in K17. As a sensitivity test, tightening criterion (ii) defined in section 2.2 for the NAO to be below zero for at least 26 instead of at least 23 days (i.e., more than 50% of the days out of a period of 45 days) yields agreement for 18 of the 23 SSW events identified in K17. The criterion is robust to further sensitivity tests and is kept at 23 days for consistency with K17. NAO switch events are found after 14 of the 37 SSW events, and the switch criterion also yields the same result (i.e., downward or nondownward effect) for 17 of the 23 SSW events identified in K17, like the persistence criterion. The persistence and switch criteria occur simultaneously for 20 of the 37 SSW events. Overall, 16 of the 24 SSW events in ERAinterim, that is, two thirds of all SSW events, exhibit either a NAO persistence event, a NAO switch event, or both. No clear connection between the occurrence of NAO events and wave 1 versus wave 2 SSW events, absorbing/reflecting SSW events, or polar jet oscillation events could be identified. The here defined NAO events tend to be more frequent than SSW events (Table 2). NAO switch events exhibit a higher frequency of more than two events per winter. A 23.3% of NAO persistence events and 15.3% of switch events are preceded by a SSW. A slightly lower frequency of events is observed during the satellite era as compared to the full time series for all NAO events.

In order to examine the behavior of SSW events that are followed by the different NAO events, Figure 4 shows the evolution of stratospheric winds, lower stratospheric polar cap temperature anomalies, and the surface NAO index for all SSW events in the satellite era. By definition, a difference can be observed in the surface NAO index for persistence and switch events (red lines in Figures 4h and 4i) as compared to SSW events that do not fulfill these criteria (gray lines), and in the lower stratospheric polar cap temperature for downward versus nondownward events as defined in K17 (Figure 4d). Overall, the SSW events that exhibit a surface NAO response tend to have a more persistent deceleration of the zonal wind at 10 hPa and 60°N of more than 2 (1.5) months for NAO persistence (switch) events. NAO switch events also exhibit a stronger warming of the lower stratosphere, as opposed to NAO persistence events (Figures 4e and 4f). The analysis

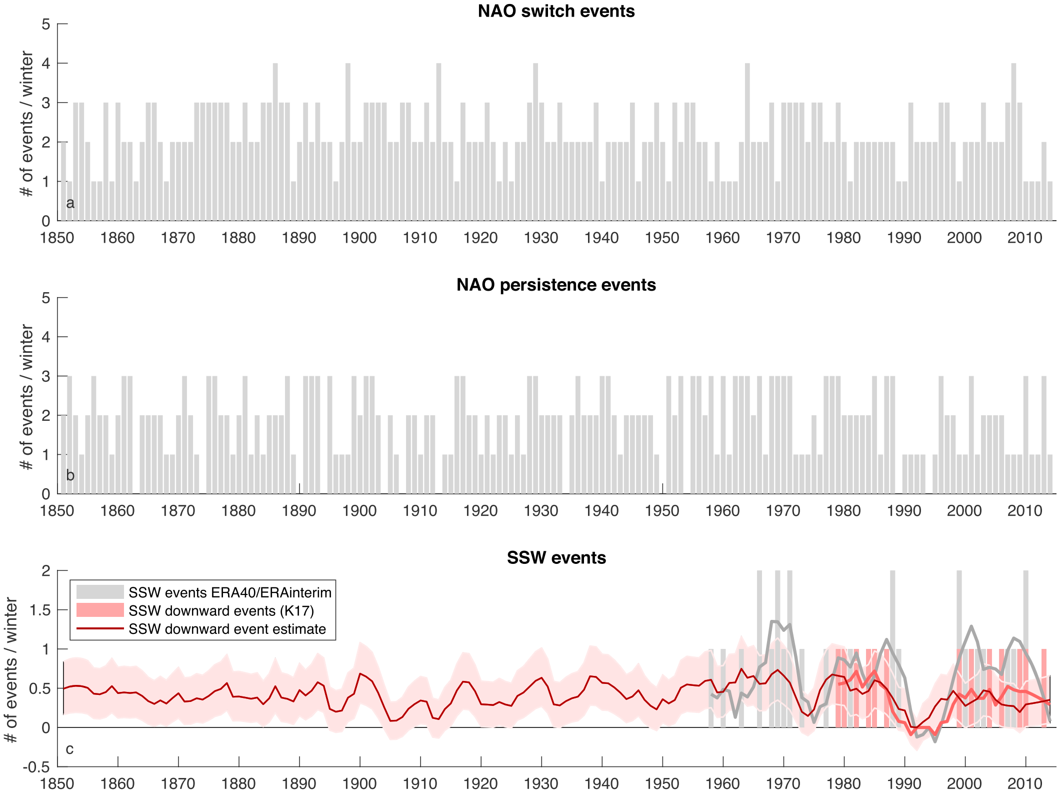

Figure 6. The number of North Atlantic Oscillation (NAO) events per winter (DJFM) from 1850/51 to 2013/14 for (a) NAO switch events and (b) NAO persistence events. The indicated year corresponds to January of the displayed winter. Panel (c) indicates the number of sudden stratospheric warming (SSW) events per winter (gray bars) according to a combination of ERA40 and ERA-interim data (1958–2014) and the number of downward SSW events classified in K17 for 1979–2014 (red bars). The gray and light red lines indicate the smoothed frequency of occurrence for the respective time series (underlying bars). Smoothing was applied using a Savitzky-Golay filter of degree 2 and an averaging window of 10 years. The dark red line indicates an estimate of downward SSW events, while the shading indicates the uncertainty given by the 95th percentile (see text for details).

confirms that NAO events—although they were specifically identified as features typically observed after SSW events—can frequently occur without a SSW event. A NAO response unique to SSW events could not be identified.

In order to obtain an estimate of potential differences in the tropospheric precursors to SSW events that are followed by NAO events, the midtropospheric anomalies of geopotential height at 500 hPa are analyzed before and after SSW events as a function of the associated NAO events. When compositing all SSW events in the satellite era, the major features are the well-known signals consisting of a strengthened Aleutian low-pressure system before the SSW event and a negative NAO signature after the event (Figures 5a and 5e, compare, for example, to Butler et al., 2017), while a weak positive NAO pattern dominates after SSW events that do not exhibit a NAO persistence or switch event (Figure 5f). For SSW events that are followed by a NAO event, the negative NAO response over the North Atlantic increases in strength for both types of NAO events (compare Figures 5e to 5g and 5h). The patterns before the SSW events all exhibit a strong Aleutian low-pressure system covering the SSW precursor region identified in Garfinkel et al. (2012). A significant Siberian high-pressure anomaly can be observed for the SSW events followed by a NAO event, which is consistent with White et al. (2019), who found the Siberian high to be a characteristic of SSW events with a downward impact. The positive and negative anomalies over Siberia also both emerge in a cluster analysis of SSW precursors (Bao et al., 2017). This is further confirmed by comparing with the precursors to SSW events that are not followed by a NAO event and instead exhibit a Siberian trough and a European blocking pattern, though these patterns are not significant at the 5% level (Figure 5b). SSWs not followed by a NAO event in addition exhibit an anomalous ridge over northwestern Canada that is significant at the 5% level. The precursor pattern in the North Atlantic region also differs between SSW events that are followed by

Table 3
Correlations Between the Smoothed Time Series of NAO Event Occurrence in Figure 6 and the SSW Events Listed in Table 1 and the Downward SSW Events From K17

Event	NAO persistence	NAO switch
SSW events (1958–2014)	0.37*	0.10
SSW downward events (1979–2014)	0.72*	−0.01

*Correlations significant at the 5% significance level according to a *t* test.

persistence versus switch events: NAO switch events are by definition preceded by a positive NAO pattern with a negative geopotential height anomaly over Greenland and a positive anomaly in the eastern North Atlantic (Figure 5d). NAO persistence events are instead preceded by a blocking over Scandinavia and a trough over the central North Atlantic (Figure 5c).

The final goal of this study is to extend the NAO event time series back to 1850 and thereby infer the frequency of SSW events with a downward impact on the NAO under the assumption that the relationship between the NAO and the stratosphere did not change since 1850. Figures 6a and 6b shows the number of NAO events per winter for 1850 to 2014. The NAO time series is consistent with the frequency and persistence of the negative NAO pattern found in Matsueda and Palmer (2018), in particular the less frequent occurrence of the negative NAO pattern in the early 1990s and the more frequent occurrence of the negative NAO in the 1980s and the 2000s. The NAO persistence index (Figure 6b) exhibits a similar evolution as the long-term variability in downward SSW events (light red line in Figure 6c) during the satellite era. Especially the frequent occurrence of downward SSW events in the 1980s and the 2000s are well represented, indicated by the increased number of NAO persistence events in these decades.

Table 3 gives the correlation between the smoothed indices of the SSW and downward SSW time series (Figure 6d) and the NAO event time series (Figures 6a and 6b). A high correlation between the NAO persistence events and the SSW downward events from K17 as compared to the other criteria can be expected due to the definition of the downward SSW events in K17 using a persistence criterion. Since no stratospheric information is taken into account for the here defined NAO persistence criterion (except for conceiving the definition in the first place), a significant correlation is not straightforward, especially since the downward SSW events from K17 are not identical with the events identified using the persistence criterion in this study (as shown in Table 1). The comparison of all SSW events (1958–2014) is a more robust test and shows a lower but significant correlation. NAO switch events do not show a significant correlation with SSW frequency, although they tend to follow SSW events, and although they agree with the downward impact definition from K17 for the satellite era for the same number of events as the persistence criterion (Table 1). The NAO switch time series exhibits a similar increase in the early 1970s as the SSW events, but many other features, such as the minimum in the 1990s, are not represented in the time series (Figure 6a). Both NAO indices exhibit strong decadal variability but no significant trend. Local minima in the frequency of NAO events occur throughout the time series, suggesting a temporary absence of SSW events. Interestingly, the early 1990s constitute the most persistent absence of NAO persistence events, coincident with the lack of SSW events in the stratosphere, indicating that the lack of SSWs might have been associated with a weaker surface response of the stratosphere during this period. In order to test this further, the frequency of downward SSW events is estimated based on a linear regression on the smoothed time series of the NAO persistence events for the known part of the downward SSW time series (1979–2014) based on the positive correlation shown in Table 3. A bootstrapping approach with 1,000 subsamples consisting of 30 random samples out of the 35 available years is used to determine the 5th and 95th percentiles of the regression coefficients, which is then used to compute the uncertainty of the estimate (shown by the shading in Figure 6c). The estimate of downward SSW events shows significant decadal variability but no significant trend. The SSW event estimate reaches its lowest value over the entire time period 1850–2014 in 1992, that is, during the well-known SSW “drought” in the 1990s. This reconstruction suggests that this persistent absence of SSW events may have been unprecedented in the past 150 years. Note that this reconstruction can only account for SSW events that exhibit a downward impact on the NAO, and given the results from Table 2 it is likely that the actual number of SSW events during this period was higher than indicated by the estimate in Figure 6c, as during the period 1979–2014 only 13 out of 24 SSW events indeed had a downward impact. While a full representation of the stratospheric variability is not possible only based on surface quantities, the surface NAO can nevertheless give a reasonable estimate of stratospheric variability.

5. Summary and Discussion

This study analyzes the relationship between surface anomalies in the NAO and SSW events. While a long record of the NAO is available back to 1850 from Cropper et al. (2015), the SSW event frequency is not known before the 1950s. The known relationship between SSWs and the NAO during the satellite era provides a pathway toward reconstructing SSW frequency back to 1850. The characteristic response of the NAO to SSW events is quantified as a prolonged persistence of the negative NAO phase and a switch from a positive to a negative NAO phase, termed NAO events. Two thirds of the SSW events during the satellite era are followed by either one or both of these NAO events. On the other hand, NAO events are found to not be unique to the period after SSW events, and less than 25% of the identified NAO events are preceded by a SSW event. NAO events that are not preceded by stratospheric anomalies are believed to be generated through tropospheric internal variability, though some of the identified NAO events without a preceding major SSW event may potentially be associated with minor SSW events or other stratospheric forcing. In terms of their classification of a NAO surface impact, 74% of the SSW events agree with the downward impact classification developed in Karpechko et al. (2017) that also uses lower stratospheric anomalies. Unlike SSW events, NAO events exhibit a local minimum in midwinter, with more events in early and late winter, indicating a more frequent association of NAO events with SSW events in midwinter. SSW events that are followed by a NAO event exhibit different tropospheric precursor patterns during the 10 days preceding the SSW event, with a significant positive geopotential height anomaly over Siberia as opposed to events that are not followed by a NAO event and opposite anomalies over the Arctic in the region of Northern Canada and Greenland. This suggests that the Siberian high acts as a precursor for SSW events with a downward effect, consistent with White et al. (2019).

NAO events are computed for the full time series back to 1850, showing that NAO persistence and switch events have not experienced a significant change in frequency and no significant trend since 1850. The NAO persistence criterion yields a significant correlation with the number of SSW events, while the NAO switch criterion does not yield a significant correlation with SSW frequency, despite their frequent occurrence after SSW events. The connection between SSW frequency and persistent NAO events leads to the conclusion that SSW events may have exhibited a similar frequency as in today's climate over a period covering almost two centuries. Local minima in the NAO index can be observed, for example, for the early twentieth century until 1920. It is interesting to note that the early 1990s constitute the longest observed period of absence of NAO persistence events in the long-term record. This period also constitutes the most persistent absence of SSW events in the satellite era. A reconstruction of the SSW frequency based on NAO persistence events indicates that the early 1990s may constitute the longest absence of SSW events in the long-term record back to 1850.

It is important to note that the above conclusions are based on the assumption that the relationship between the NAO and SSW events has not changed since 1850. This assumption is challenged by the possible existence of trends in either of the two time series, for example, the projected cooling trend in lower stratospheric temperature with climate change (e.g., Rind et al., 1998). In addition, long-term changes in the NAO (Shindell et al., 1999), Arctic stratospheric ozone (Calvo et al., 2015; Ivy et al., 2017; Karpechko et al., 2014; Smith & Polvani, 2014), or Arctic sea ice (Sun et al., 2015) may affect the relationship between the NAO and the stratosphere. Apart from external forcing, internal stratospheric variability may for a large part be responsible for the observed variability in SSW frequency: Butchart et al. (2000) find in a modeling study that the frequency of SSW events more strongly depends on internal atmospheric variability as opposed to trends in greenhouse gases or sea surface forcing for the period 1992–2051. This suggests that the majority of the observed variability is forced naturally.

In summary, the long-term changes in SSW frequency can be approximated from surface NAO persistence observations, although these are not uniquely tied to SSW events. Based on this relationship, the occurrence of SSW events is estimated to have experienced decadal variability comparable or slightly weaker to today's climate and no significant trend since 1850. The minimum in SSW occurrence in the 1990s coincides with the most extreme minimum in the reconstructed SSW time series, indicating that the 1990s may constitute the most significant absence of SSW events since 1850.

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