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Dependence of Sudden Stratospheric Warmings on Internal and External Drivers

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Key Points:
- SSWs occur more often in QBO-E than QBO-W winters with the largest difference found if the QBO at 30 hPa of preceding autumn is used
- QBO effect on SSW occurrence strengthens (weakens) if geomagnetic or sunspot activity is low (high) or if the ENSO is in cold (warm) phase
- The highest SSW occurrence rate is found in winters with low geomagnetic activity and easterly QBO

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Abstract

A sudden stratospheric warming (SSW) is a large-scale disturbance of the wintertime stratosphere, which occurs especially in the Northern Hemisphere. Earlier studies have shown that SSW occurrence depends on atmospheric internal factors and on solar activity. We examine SSW occurrence in northern winters 1957/1958–2016/2017, considering several factors that may affect the SSW occurrence: Quasi-Biennial Oscillation (QBO), El Niño–Southern Oscillation (ENSO), geomagnetic activity, and solar radiation. We confirm the well-known result that SSWs occur more often in easterly QBO phase than in westerly phase. We show that this difference depends on how the QBO phase is determined. We find that the difference in SSW occurrence between easterly and westerly QBO winters strengthens (weakens) if geomagnetic activity or solar activity is low (high), or if the ENSO is in a cold (warm) phase. In easterly QBO phase significantly more SSWs occur during low geomagnetic activity than high activity.

Plain Language Summary

During some winters the cold polar stratosphere experiences a strong and sudden warming. These sudden stratospheric warmings (SSW) can affect greatly the surface weather in northern Europe and in North America. However, the factors that contribute to the formation of sudden warmings are not entirely known. We study how the two independent solar-related factors, energetic particles and solar irradiance, and two atmospheric internal factors, the wind in the equatorial stratosphere (QBO) and the weather system of the Pacific (ENSO), affect the occurrence of sudden warmings in the Northern Hemisphere. We confirm the earlier finding that sudden stratospheric warmings are more common in winters with an easterly QBO wind. We find that the QBO effect on SSW occurrence depends on the two solar-related factors and ENSO. Additionally, we find that the occurrence of sudden stratospheric warmings is affected by energetic particles precipitating to the Earth's atmosphere. Sudden warmings happen more often if the number of energetic particles is small. This effect is especially clear if the QBO wind is easterly. Our study helps to understand in which circumstances sudden stratospheric warmings are more or less likely to form. This information can benefit the forecasting of northern wintertime weather.

1. Introduction

A dominant pattern in the wintertime stratosphere is the polar vortex, a strong thermal westerly wind surrounding the cold pole. The polar vortex experiences large variability during winter and between winters. Planetary waves originating from the tropospheric wind patterns can propagate into the stratosphere if the stratospheric wind is westerly (Charney & Drazin, 1961), depositing their zonal momentum and thereby decelerating the polar vortex. Planetary wave activity is higher in the Northern Hemisphere than in the Southern Hemisphere because of larger mountain ranges and continent-ocean temperature contrasts (van Loon et al., 1973). Thus, the northern polar vortex is much more variable than its southern counterpart (Waugh & Randel, 1999). In the extreme cases planetary waves can initiate a temporary reversal and collapse of the polar vortex. Such events, called sudden stratospheric warmings (SSW), are accompanied by strongly enhanced downwelling of air within the polar vortex and associated warming of the polar stratosphere (Dunkerton et al., 1981; Matsuno, 1971). A midwinter SSW is a common event in the Northern Hemisphere, occurring approximately six times in a decade (Polvani et al., 2017). The polar vortex eventually breaks down during spring in a so-called final warming.

The occurrence of SSWs depends on the flux of planetary waves into the stratosphere and the state of the polar vortex (e.g., de la Cámara et al., 2017; Matsuno, 1971; Scott & Polvani, 2004). Their conditions can be affected by several factors. Two of the most influential atmospheric internal factors are the Quasi-Biennial Oscillation (QBO) and El Niño–Southern Oscillation (ENSO). QBO is a mode of wind variability in the equatorial stratosphere which involves a downward propagating zonal wind pattern, in which the equatorial zonal wind at a specific altitude reverses approximately every 14–16 months. Holton and Tan (1980) showed that the polar vortex is weaker when the QBO wind at 50 hPa pressure level is easterly. They suggested that when the QBO wind is easterly, planetary waves are diverted toward higher latitudes which makes the polar vortex weaker. The opposite is true during westerly QBO wind. This is the so-called Holton-Tan effect. Subsequently, Labitzke (1982) found that SSWs are more common in the easterly than in the westerly QBO phase.

ENSO is a climate mode in the Pacific ocean which is also known to affect the wintertime stratosphere at high latitudes. During the positive (warm; El Niño) ENSO winters the polar vortex is weaker and warmer (Garfinkel & Hartmann, 2007) and SSWs occur more frequently (Bell et al., 2009; Polvani et al., 2017) than during negative (cold; La Niña) ENSO winters. These effects of the ENSO phase result, at least, partly from altered planetary wave formation at the surface level, since the ENSO is strongly connected to the Aleutian low-pressure region. During positive ENSO phase the Aleutian low is deepened and planetary wave activity is increased, while the opposite is true in the negative ENSO phase (Garfinkel & Hartmann, 2008; Manzini et al., 2006). The effect of ENSO on polar vortex is modulated by the QBO so that the difference in polar temperature between the two ENSO phases is diminished in the easterly QBO phase (Garfinkel & Hartmann, 2007). Interestingly, the Holton-Tan effect weakens in the warm ENSO phase, making the combined effect of ENSO and QBO complicated and nonlinear (Garfinkel & Hartmann, 2007).

In addition to these internal atmospheric drivers, the Sun affects the stratosphere and polar vortex via electromagnetic radiation and energetic particle precipitation (EPP). Solar UV radiation warms the stratosphere by increased absorption of ozone. Solar irradiance follows the 11-year sunspot cycle (Fröhlich, 2006), and the direct temperature and ozone responses to this cycle are seen in the equatorial upper stratosphere (Frame & Gray, 2010; Soukharev & Hood, 2006). The effect of variable solar radiation on polar vortex is more complicated and seems to depend on the QBO phase (Camp & Tung, 2007; Labitzke & Van Loon, 1988). Labitzke and Van Loon (1988) found that the polar lower stratosphere is warmer in solar maxima than in solar minima if the QBO is westerly, while the opposite is true in the easterly QBO phase. Kryjov and Park (2007) found that in solar minima the northern polar vortex is weaker in the warm ENSO phase than in cold phase, while in solar maxima the ENSO effect on polar vortex is small and insignificant.

EPP forms reactive odd nitrogen and hydrogen oxides (NO_X and HO_X) in the polar upper atmosphere which deplete ozone. The direct effect of EPP is mostly limited to the mesosphere. However, NO_X formed by EPP can descend to lower altitudes in the polar darkness, establishing the indirect effect of EPP in the wintertime polar stratosphere (Randall et al., 2007). Several studies have shown that a high EPP activity (or geomagnetic activity as a proxy for EPP) is associated with a stronger polar vortex (e.g., Baumgaertner et al., 2011; Lu et al., 2008; Maliniemi et al., 2013, 2014, 2016; Rozanov et al., 2005; Seppälä et al., 2013; Salminen et al., 2019). Many studies (e.g., Baumgaertner et al., 2011; Langematz et al., 2003; Salminen et al., 2019) have suggested that the EPP warms the polar mesosphere and upper stratosphere, which leads to dynamical changes strengthening the polar vortex and cooling the polar lower stratosphere. The EPP effect on polar vortex also depends on QBO phase so that the effect is stronger (especially in February and March) if the QBO wind at 30 hPa is easterly (Salminen et al., 2019). Both EPP and solar radiation vary over the sunspot cycle but depend differently on the cycle phase. Whereas total and spectral solar irradiance vary in phase with the sunspot cycle, the EPP activity is enhanced by fast solar wind streams which typically maximize at Earth a few years after the sunspot maximum (Asikainen & Ruopsa, 2016; Meredith et al., 2011; Mursula et al., 2015). Gray et al. (2013) found a delayed effect related on sunspot cycle on the troposphere which maximizes a couple of years after the sunspot maximum. This delayed effect is suggested to be due to oceans which absorb increased solar radiation and release heat in following years (Scaife et al., 2013). Maliniemi et al. (2019) showed that EPP effect in the troposphere is separate from the lagged and nonlagged solar irradiance effect.

Labitzke et al. (2006) found that in westerly QBO winters more SSWs occur in solar maxima than in minima while in easterly QBO winters the situation is reversed. This supports the earlier findings of Labitzke and Van Loon (1988) concerning the dependence of polar stratospheric temperature on sunspots and QBO. So far the effect of EPP (geomagnetic activity) on SSW occurrence has not been studied. Here we study how the different factors mentioned above (QBO, ENSO, EPP, and solar radiation) affect the SSW occurrence rate. In section 2 we present the studied data sets and the methods that are used to detect SSWs. In section 3 we study SSW occurrence rates separately for the four variables. In section 4 we show SSW occurrence rates for ENSO, geomagnetic activity and solar radiation in the two QBO phases. In section 5 we present our conclusions.

2. Data and Methods

In order to study the SSW occurrence, we use here the list of SSW events in 1957–2014 provided by Butler et al. (2017) (https://www.esrl.noaa.gov/csd/groups/csd8/sswcompendium/majorevents.html). They used the method by Charlton and Polvani (2007) to detect SSWs in the northern wintertime hemisphere. An SSW event is detected when the daily zonal mean zonal wind at 10 hPa and 60°N latitude reverses to easterly in any of the northern winter months (November–March). Zonal wind must have returned to westerly for 20 consecutive days between two SSW events. After an SSW the zonal wind has to return to westerly for 10 consecutive days before the end of April, otherwise it is counted as a final warming event. We study SSWs which Butler et al. (2017) detected by using ERA-40 data set (Uppala et al., 2005) for period 1957–1978 and ERA-Interim data set (Dee et al., 2011) for period 1979–2014. Since they did not list SSWs in years 2015–2017, we searched for SSW events in winters 2014/2015–2016/2017 by using the above described detection algorithm and the ERA-Interim daily data of the zonal wind (at 60°N and 10 hPa), but we did not detect any SSW in these winters.

We use here the geomagnetic Ap index (http://isgi.unistra.fr) as a proxy for energetic electron precipitation (EEP), since this index correlates well with the observed EEP fluxes (e.g., Asikainen & Ruopsa, 2016). For the QBO index we calculate the ERA-40 (for period 1957–1978) and ERA-Interim (for period 1979–2017) zonal mean zonal wind averaged over 10°S to 10°N latitudes at 30 hPa. As a measure of ENSO we use the Niño 3.4 index (https://www.esrl.noaa.gov/psd/data/timeseries/monthly/NINO34/) which is the sea surface temperature averaged over 5°S to 5°N latitude and 120–170°W longitude range, corresponding to the region in the Pacific which is strongly affected by ENSO. As a proxy for solar radiation we use the international sunspot number version 1 (SSN1, http://www.sidc.be/silso/versionarchive), provided by WDC-SILSO of Royal Observatory of Belgium. Since SSN1 data have not been updated after May 2015, we have extended SSN1 data with SSN2 data scaled by factor 0.7, for June 2015 to December 2017.

We use December values of each variable (QBO phase, ENSO, Ap, and SSN1) in order to classify winters into high variable value and low variable value winters by comparing them to the December median value of the respective variable. For example, a winter is classified into a high-Ap group if the December Ap value is larger than the median of all December Ap values. The median December value for the studied time period for Ap is 10.5 nT, for SSN1 45.9 and for ENSO 26.4 °C. For QBO we also classify the winters by using the QBO median value, which effectively corresponds to using a deseasonalized QBO. We use QBO values of previous September for each winter, corresponding to a 3-month lead time relative to December. While the results were qualitatively the same using the December values of QBO, the September values of QBO gave the largest difference between the QBO phases. To estimate the significance of differences in SSW occurrence rates between each pair of groups we use two-tailed Fisher's exact test (Fisher, 1922). We also estimate significances of our results by using Monte Carlo simulation. We calculate the studied quantity (e.g., difference in SSW occurrence rate between two groups) with randomized data (e.g., separating winters randomly to two similar sized groups as in the studied case) 100,000 times to get a distribution for the quantity. Then we can compare the observed value to simulated values to estimate a p value (proportion of simulated values which are smaller/larger than the observed value).

3. SSW Occurrence Rate Dependence on Internal and External Variables

Figure 1 shows the number of winters with (red) and without (blue) an SSW when the winters are classified according to one of the four variables (QBO, ENSO, Ap, and SSN). It is clear that SSW occurrence depends highly on QBO phase. Out of 30 easterly QBO (QBO-E) 21 winters lead to SSW, while in westerly QBO (QBO-W) only 10 out of 30 winters include an SSW. This difference between the QBO phases is clearly significant ($p = 0.0092$) according to Fisher's exact test. This result is in accordance with the earlier finding by Labitzke (1982), and with the Holton-Tan effect: planetary waves are increasingly directed toward the polar vortex in QBO-E, leading to increased probability of SSWs. We also calculated p values for the differences in Figure 1 by using Monte Carlo simulation which gave almost the same p values as Fisher's exact test.

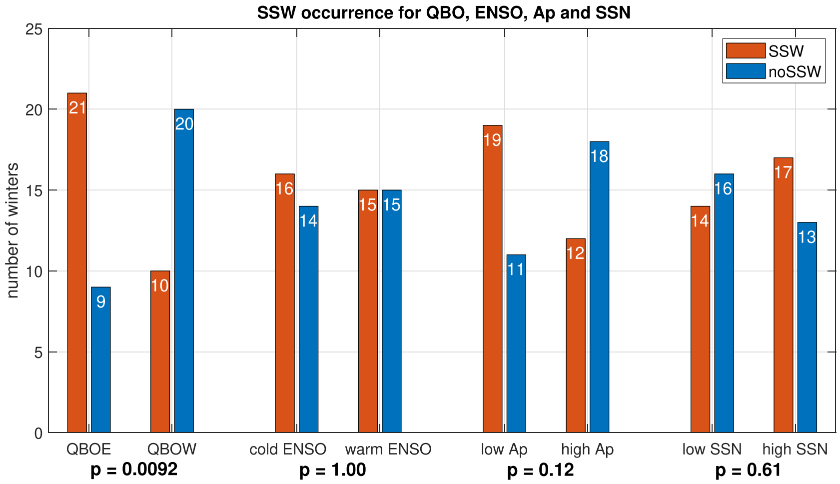

Figure 1. Number of winters with SSW (red bars) and without SSW (blue bars) in QBO-E and QBO-W (bars 1–4), in cold and warm ENSO (bars 5–8), in low Ap and high Ap (bars 9–12), and in low and high SSN (bars 13–16). The *p* value of the difference in SSW/no-SSW fraction for each set of bars is marked below the corresponding bars.

SSW occurrence does not depend on the other three variables as clearly. A similar difference is visible in Figure 1 only between low and high Ap, but even this difference is only weakly significant ($p = 0.12$). Note that significance is limited by a relatively small number (60) of winters. If the SSW occurrence rates for low and high Ap (19/30 vs. 12/30) would remain the same, the difference would be significant for some 20 more winters. The difference in SSW occurrence between low and high SSN winters is in the same direction as found by Sonnemann and Grygalashvyly (2007), although our finding of the difference does not meet our significance criterion. ENSO seems to have no significant effect on SSW occurrence. We also tried to separate the winters into three ENSO phases (cold, neutral, and warm ENSO, one out of three winters in each phase), but the differences remained small also then. These results are in disagreement with Polvani et al. (2017) who found more SSWs in warm than cold ENSO phase. Note, however, that Polvani et al. (2017) results are based on modeling and not on observations, which may explain the difference between their and our results. Butler and Polvani (2011) used NCEP/NCAR reanalysis data from 1958–2010 and found that SSWs occur as much in El Niño as in La Niña winters while in neutral ENSO winters SSWs are less likely to occur.

We also tested if the pressure level at which the QBO is determined and the lead time of QBO (relative to December) affect the difference in SSW occurrence. Figure 2 shows the difference in SSW winter fraction (ratio between SSW winters and all winters of the corresponding QBO phase) between QBO-E and QBO-W as a function of QBO lead time (*x* axis) and QBO level (*y* axis). For QBO at 30 hPa the difference is significant if the QBO phase is determined in December (corresponding to 0 value in *x* axis) or in the previous July–November (corresponding to 5 to 1 values in *x* axis). For QBO at 20 hPa, the largest and most significant differences are found when the phase is determined in previous June–September. Since the QBO pattern propagates downward in altitude, the QBO at one pressure level correlates with the QBO at a lower altitude with a certain lag. This is the reason for the significant pattern in Figure 2 moving roughly linearly across different altitudes in time. It is hard to distinguish at which pressure level QBO fundamentally affects SSW occurrence, but the most robust and significant difference ($p < 0.01$) in SSW occurrence between the QBO phases is found for August–October values of QBO at 30 hPa and June QBO at 20 hPa. Salminen et al. (2019) found that the meridional circulation into the northern polar stratosphere and the EEP effect on polar vortex are stronger in QBO-E than in QBO-W phase if the QBO at 30 hPa of previous August–September is used to determine the QBO phases.

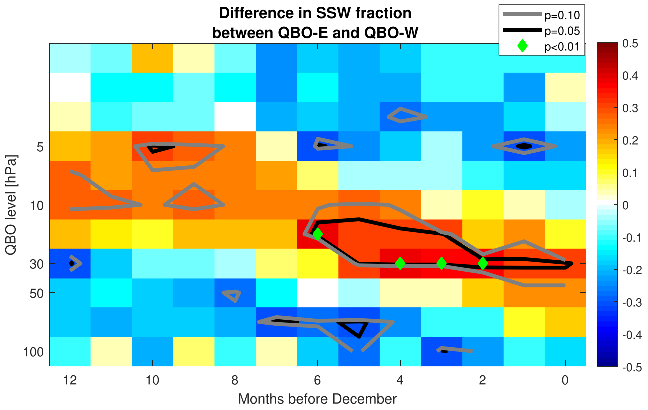

Figure 2. Difference in SSW fraction between QBO-E and QBO-W as a function of QBO lead time (*x* axis) and QBO pressure level (*y* axis). Values in *x* axis correspond to months before December. Gray contour corresponds to 90% and black contour to 95% significance level. Green diamonds correspond to values with significance level above 99%.

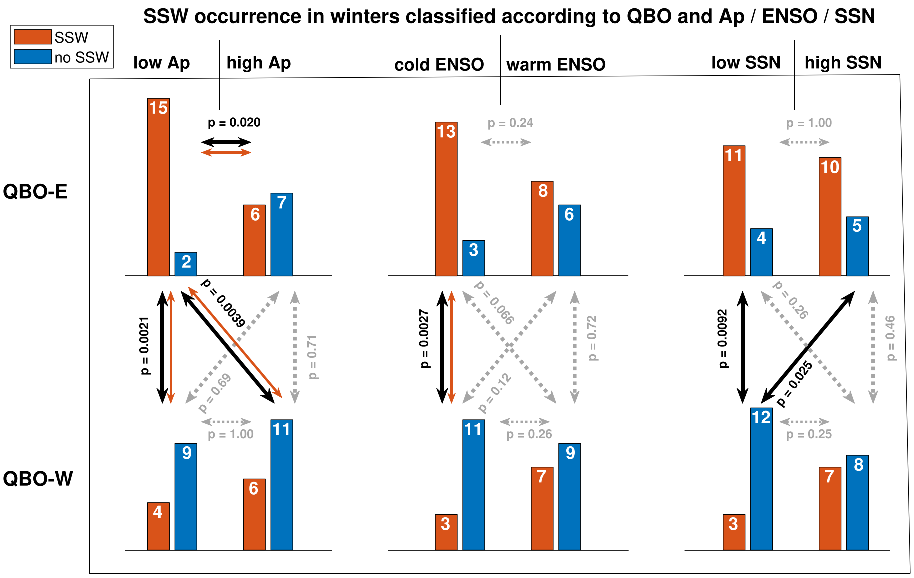

Figure 3. Number of winters with SSW (red bars) and without SSW (blue bars) in QBO-E (top) and QBO-W (bottom) phases in low and high Ap (left), in cold and warm ENSO (center), and in low and high SSN (right). The p values estimated with Fisher's exact test are marked for each difference. Differences with $p < 0.05$ are marked with black arrows, and those with $p > 0.05$ are marked with gray arrows. Differences which pass the test based on false discovery rate are marked with red arrows.

4. Combined Dependencies of SSW Occurrence

Figure 3 shows the number of winters with (red) and without (blue) SSWs in cases where winters are separated both according to QBO and one of the other variables (Ap, ENSO or SSN). The upper part of Figure 3 shows the 30 QBO-E winters separated according to Ap, ENSO and SSN, and the lower part of Figure 3 shows the same for the 30 QBO-W winters. Comparing the upper and lowers parts of Figure 3 shows that for low Ap, cold ENSO, and low SSN the differences in SSW occurrence between QBO-E and QBO-W phases are significant (note the corresponding p values in Figure 3), verifying the Holton-Tan mechanism for these conditions. These differences are quite similar to the difference between the two QBO phases in Figure 1. Note that the best prediction for SSW to occur is during QBO-E, low-Ap winters when 15 out of 17 winters lead to an SSW.

We find no significant differences between the two QBO phases, that is, no significant Holton-Tan effect, for high Ap, warm ENSO, or high SSN winters. For QBO-E the ratio of SSW to no-SSW winters is slightly below 1 for high Ap, and the corresponding difference for SSW occurrence between low Ap and high Ap is marginally significant. For warm ENSO and high SSN, the SSW to no-SSW winter ratio is larger than 1, and no clearly significant difference is found with respect to cold ENSO or low SSN cases, respectively. In fact, solar activity seems to have practically no effect on SSW occurrence ratio in QBO-E. In QBO-W phase SSW occurrence ratios for low and high Ap are almost equal. SSW occurrences in QBO-W are lower for cold than warm ENSO and for low than high SSN, but the significances of these differences are low.

Note that when the winters are separated to smaller groups according to two indices (resulting to four groups) in Figure 3, the possibility to detect a falsely significant difference is higher than when the winters are separated according to only one index (resulting to two groups). While there is only one difference to be studied between two groups, six different differences can be calculated between four groups. Wilks (2006) suggested that if there are k local significance tests (six in our case) and the false discovery rate is set to be 5% (i.e., 5% of local tests are expected to be falsely significant), the lowest p value should be lower than $0.05/k$ ($0.05/6 = 0.0083$ in our case) to be considered significant, the second lowest p value should be lower than $0.05 \times 2/k$ (0.017 in our cases), the third lowest p value should be lower than $0.05 \times 3/k$ (0.025 in our cases) and so on. The p values below 0.05 in Ap and ENSO cases shown in Figure 3 fulfill these conditions, while the lowest p value 0.0092 in the SSN case narrowly exceeds the limit of 0.0083. We can also estimate with Monte Carlo simulations whether the differences in SSW occurrence between the QBO phases in Figure 3 are significant even when the difference between QBO phases in all winters (Figure 1) is taken into account.

This can be done by, for example, randomly picking corresponding number of winters from the QBO-E and QBO-W winters (e.g., in the case of low Ap, 17 and 13 winters, respectively) numerous times and comparing the observed difference to simulated ones. According to these tests differences between QBO phases related to Ap and ENSO in Figure 3 are significant even when comparing with the overall difference between QBO phases in Figure 1.

Several studies have shown that the polar vortex is enhanced by energetic electron precipitation (e.g., Baumgaertner et al., 2011; Maliniemi et al., 2013; Seppälä et al., 2013; Salminen et al., 2019). A weak polar vortex of low Ap (EEP) times is more disturbed by planetary waves directed poleward in QBO-E phase (Holton & Tan, 1980). This explains the large number of SSW winters for combined low Ap and QBO-E. If Ap is high, the polar vortex is stronger and less vulnerable to planetary waves. Thus, the QBO effect on the polar vortex (Holton & Tan, 1980) and on SSW occurrence is weakened in high-Ap winters.

During warm ENSO winters the planetary wave activity in the stratosphere is enhanced (Garfinkel & Hartmann, 2008), and SSWs may occur regardless of QBO. Garfinkel and Hartmann (2007) suggested that the warm ENSO weakens the QBO effect on polar vortex. Our results support this suggestion, since the SSW ratio is found to be close to 1 for the two QBO phases in warm ENSO winters. In cold ENSO winters the QBO effect on SSW occurrence (four left bars of Figure 1) is even further strengthened as depicted by the SSW/no-SSW ratios (13/3 vs. 21/9 for QBO-E and 3/11 vs. 10/20 for QBO-W) and the slightly improved p value (0.0027 vs. 0.0092). A possible reason for this is that the influence of smaller planetary wave fluxes during cold ENSO is relatively more dependent on how efficiently they are guided into the polar stratosphere by QBO.

For low solar activity, the QBO effect on SSW occurrence is, similarly to low Ap and cold ENSO, further strengthened, although the p value is the same as in Figure 1 due to the smaller number of winters. These results are in accordance with earlier studies by Labitzke and Van Loon (1988), Labitzke et al. (2006), and Camp and Tung (2007) which have shown that the Holton-Tan effect operates during low solar activity. However, we do not find the similar reversal of the QBO effect (anti-Holton-Tan effect) as Labitzke et al. (2006) who found that in solar maxima most SSWs occur in QBO-W winters. This difference may result from the different definitions of QBO, solar activity or SSWs, or different time periods studied. Camp and Tung (2007) found that the polar vortex is strongest in low SSN and QBO-W winters. We found similar relationship for SSW occurrence as, out of the four cases, the SSW occurrence is lowest in low SSN and QBO-W and significantly lower than the SSW occurrence for QBO-E and low SSN ($p = 0.0092$) or high SSN ($p = 0.025$). Balachandran and Rind (1995) and Gray et al. (2004) have suggested that solar activity affects the propagation of planetary waves at low latitudes, which may explain the SSN effect on polar vortex and SSW occurrence.

As noted above, the difference in SSW occurrence between low and high-Ap winters is significant in QBO-E winters. (Maliniemi et al., 2013, 2014, 2016, 2018) and Salminen et al. (2019) found that energetic electron precipitation strengthens the polar vortex in the QBO-E phase, which means that the combined effect of Ap and QBO on SSW occurrence is similar as on the polar vortex strength. Weak EEP (low Ap) leads to a weak vortex which is vulnerable to the increased planetary wave activity of the QBO-E phase, while strong EEP (high Ap) strengthens the polar vortex and planetary waves are less likely to initiate an SSW. In QBO-W phase planetary waves are less directed to the polar vortex than in QBO-E and SSWs are rare regardless of EEP (Ap). The difference in SSW occurrence between low Ap-QBO-E winters and high Ap-QBO-W winters is also significant ($p = 0.0039$), which highlights the conclusion that the polar vortex is most vulnerable for SSWs if the QBO is easterly and EEP (Ap) is low.

5. Summary

We have studied here the dependence of SSW occurrence on QBO, ENSO, geomagnetic activity (proxy for energetic electron precipitation), and sunspots (solar activity, proxy for solar UV radiation). Our results agree with earlier studies (e.g., Labitzke, 1982; Labitzke et al., 2006) in that SSWs occur more frequently when the QBO phase is easterly. This is likely due to the fact that the planetary waves, which disturb the polar vortex and cause SSWs, are directed more poleward in the QBO-E phase (Holton & Tan, 1980). We found that the difference in SSW occurrence between the two QBO phases depends on the pressure level at which the QBO is determined (timing of QBO). The most significant difference is found when the QBO is determined at 30 hPa and the QBO phase for the following winter season is calculated during the preceding August–October.

We found that the QBO effect on SSW occurrence strengthens when EEP or solar activity is weak, or when ENSO is in cold phase. During weak EEP the polar vortex is also weak (e.g., Baumgaertner et al., 2011) and, thus, more vulnerable to QBO effect. The polar vortex is known to be weaker in QBO-E than QBO-W winters during low solar activity (Camp & Tung, 2007; Labitzke & Van Loon, 1988) and during cold ENSO (Garfinkel & Hartmann, 2007), which is in accordance with our results. We also show that the QBO effect on SSW occurrence is weakened during high EEP or solar activity or warm ENSO. This is probably due to a stronger polar vortex (high Ap) or an increased planetary wave activity or their channeling to the polar region producing SSW regardless of QBO (warm ENSO or high SSN). Earlier studies have also found that QBO effect on polar vortex weakens during high solar activity (Camp & Tung, 2007) and during warm ENSO (Garfinkel & Hartmann, 2007).

We also found that in QBO-E winters SSWs occur more commonly when Ap is low than when it is high. In fact SSW occurrence rate is highest in winters with low Ap (low EEP) and QBO-E, when SSW occurs in 15 out of 17 winters. This result agrees with earlier studies (Maliniemi et al., 2013, 2014, 2016, 2018; Salminen et al., 2019) showing that the effect of energetic electron precipitation on polar vortex is stronger in QBO-E winter months. In QBO-E winters low EEP weakens the polar vortex and SSWs occur more often, while high EEP strengthens the polar vortex and SSWs occur less. In QBO-W planetary waves are less directed poleward, which leads to a relatively strong polar vortex regardless of EEP.

SSWs lead to large variations in the wintertime surface weather, especially in Europe and North America (Baldwin & Dunkerton, 1999; King et al., 2019). King et al. (2019) showed that in Scandinavia winters with an SSW are at least 1 °C colder on average than winters without SSW and coldest temperatures after an SSW are 4–5 °C lower than climatology. Therefore, the results of this study are highly relevant for better forecasting of wintertime weather conditions and their interannual variation. However, further studies, based on both modeling and observations, are needed to examine the combined effects of these factors on the formation of SSW.

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References

Asikainen, T., & Ruopsa, M. (2016). Solar wind drivers of energetic electron precipitation. *Journal of Geophysical Research: Space Physics*, *121*, 2209–2225. https://doi.org/10.1002/2015JA022215

Balachandran, N. K., & Rind, D. (1995). Modeling the effects of UV variability and the QBO on the troposphere-stratosphere system. Part I:. The middle atmosphere. *Journal of Climate*, *8*(8), 2058–2079. https://doi.org/10.1175/1520-0442(1995)008%3C2058:MTEOUV%3E2.0.CO;2

Baldwin, M. P., & Dunkerton, T. J. (1999). Propagation of the Arctic Oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research*, *104*(D24), 30,937–30,946. https://doi.org/10.1029/1999JD900445

Baumgaertner, A. J., Seppälä, A, Jöckel, P., & Clilverd, M. A. (2011). Geomagnetic activity related NOx enhancements and polar surface air temperature variability in a chemistry climate model: Modulation of the NAM index. *Atmospheric Chemistry and Physics*, *11*(9), 4521–4531. https://doi.org/10.5194/acp-11-4521-2011

Bell, C. J., Gray, L. J., Charlton-Perez, A. J., Joshi, M. M., & Scaife, A. A. (2009). Stratospheric communication of El Niño teleconnections to European winter. *Journal of Climate*, *22*(15), 4083–4096. https://doi.org/10.1175/2009JCLI2717.1

Butler, A. H., & Polvani, L. M. (2011). El Niño, La Niña, and stratospheric sudden warmings: A reevaluation in light of the observational record. *Geophysical Research Letters*, *38*, L13807. https://doi.org/10.1029/2011GL048084

Butler, A. H., Sjoberg, J. P., Seidel, D. J., & Rosenlof, K. H. (2017). A sudden stratospheric warming compendium. *Earth System Science Data*, *9*(1), 63–76. https://doi.org/10.5194/essd-9-63-2017

Camp, C. D., & Tung, K.-K. (2007). The influence of the solar cycle and QBO on the late-winter stratospheric polar vortex. *Journal of the Atmospheric Sciences*, *64*(4), 1267–1283. https://doi.org/10.1175/jas3883.1

Charlton, A. J., & Polvani, L. M. (2007). A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks. *Journal of Climate*, *20*(3), 449–469. https://doi.org/10.1175/jcli3996.1

Charney, J. G., & Drazin, P. G. (1961). Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *Journal of Geophysical Research*, *66*(1), 83–109. https://doi.org/10.1029/JZ066i001p00083

de la Cámara, A., Albers, J. R., Birner, T., Garcia, R. R., Hitchcock, P., Kinnison, D. E., & Smith, A. K. (2017). Sensitivity of sudden stratospheric warmings to previous stratospheric conditions. *Journal of the Atmospheric Sciences*, *74*(9), 2857–2877. https://doi.org/10.1175/JAS-D-17-0136.1

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Dunkerton, T., Hsu, C-P. F., & McIntyre, M. E. (1981). Some Eulerian and Lagrangian diagnostics for a model stratospheric warming. *Journal of the Atmospheric Sciences*, *38*(4), 819–844. https://doi.org/10.1175/1520-0469(1981)038%3C0819:SEALDF%3E2.0.CO;2

Fisher, R. A. (1922). On the interpretation of χ^2 from contingency tables, and the calculation of p. *Journal of the Royal Statistical Society*, *85*(1), 87–94. https://doi.org/10.2307/2340521

Fröhlich, C. (2006). Solar irradiance variability since 1978: Revision of the PMOD composite during solar cycle 21. *Space Science Reviews*, *125*(1-4), 53–65. https://doi.org/10.1007/s11214-006-9046-5

Frame, T. H., & Gray, L. J. (2010). The 11-yr solar cycle in era-40 data: An update to 2008. *Journal of Climate*, *23*(8), 2213–2222. https://doi.org/10.1175/2009JCLI3150.1

Garfinkel, C., & Hartmann, D. (2007). Effects of the El Niño–Southern Oscillation and the quasi-biennial oscillation on polar temperatures in the stratosphere. *Journal of Geophysical Research*, *112*, L13807. https://doi.org/10.1029/2007JD008481

Garfinkel, C., & Hartmann, D. (2008). Different ENSO teleconnections and their effects on the stratospheric polar vortex. *Journal of Geophysical Research*, *113*, D18114. https://doi.org/10.1029/2008JD009920

Gray, L. J., Crooks, S., Pascoe, C., Sparrow, S., & Palmer, M. (2004). Solar and QBO influences on the timing of stratospheric sudden warmings. *Journal of the Atmospheric Sciences*, *61*(23), 2777–2796. https://doi.org/10.1175/JAS-3297.1

Gray, L. J., Scaife, A. A., Mitchell, D. M., Osprey, S., Ineson, S., Hardiman, S., et al. (2013). A lagged response to the 11 year solar cycle in observed winter Atlantic/European weather patterns. *Journal of Geophysical Research: Atmospheres*, *118*, 13405–13420. https://doi.org/10.1002/2013JD020062

Holton, J. R., & Tan, H.-C. (1980). The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. *Journal of the Atmospheric Sciences*, *37*(10), 2200–2208. https://doi.org/10.1175/1520-0469(1980)037%3C2200:TIOTEQ%3E2.0.CO;2

King, A. D., Butler, A. H., Jucker, M., Earl, N. O., & Rudeva, I. (2019). Observed relationships between sudden stratospheric warmings and European climate extremes. *Journal of Geophysical Research: Atmospheres*, *124*, 13,943–13,961. https://doi.org/10.1029/2019JD030480

Kryjov, V. N., & Park, C.-k. (2007). Solar modulation of the El-Niño/Southern Oscillation impact on the Northern Hemisphere annular mode. *Geophysical Research Letters*, *34*, L10701. https://doi.org/10.1029/2006GL028015

Labitzke, K. (1982). On the interannual variability of the middle stratosphere during the northern winters. *Journal of the Meteorological Society of Japan. Series II*, *60*(1), 124–139. https://doi.org/10.2151/jmsj1965.60.1_124

Labitzke, K., Kunze, M., & Brönnimann, S. (2006). Sunspots, the QBO and the stratosphere in the north polar region 20 years later. *Meteorologische Zeitschrift*, *15*(3), 355–363. https://doi.org/10.1127/0941-2948/2006/0136

Labitzke, K., & Van Loon, H. (1988). Associations between the 11-year solar cycle, the QBO and the atmosphere. Part I: The troposphere and stratosphere in the Northern Hemisphere in winter. *Journal of Atmospheric and Solar-Terrestrial Physics*, *50*(3), 197–206. https://doi.org/10.1016/0021-9169(88)90068-2

Langematz, U., Kunze, M., Krüger, K., Labitzke, K., & Roff, G. L. (2003). Thermal and dynamical changes of the stratosphere since 1979 and their link to ozone and CO_2 changes. *Journal of Geophysical Research*, *108*(D1), 4027. https://doi.org/10.1029/2002JD002069

Lu, H., Clilverd, M. A., Seppälä, A., & Hood, L. L. (2008). Geomagnetic perturbations on stratospheric circulation in late winter and spring. *Journal of Geophysical Research*, *113*, D16106. https://doi.org/10.1029/2007JD008915

Maliniemi, V., Asikainen, T., & Mursula, K. (2014). Spatial distribution of Northern Hemisphere winter temperatures during different phases of the solar cycle. *Journal of Geophysical Research: Atmospheres*, *119*, 9752–9764. https://doi.org/10.1002/2013JD021343

Maliniemi, V., Asikainen, T., & Mursula, K. (2016). Effect of geomagnetic activity on the northern annular mode: QBO dependence and the Holton-Tan relationship. *Journal of Geophysical Research: Atmospheres*, *121*, 10,043–10,055. https://doi.org/10.1002/2015JD024460

Maliniemi, V., Asikainen, T., & Mursula, K. (2018). Decadal variability in the Northern Hemisphere winter circulation: Effects of different solar and terrestrial drivers. *Journal of Atmospheric and Solar-Terrestrial Physics*, *179*, 40–54. https://doi.org/10.1016/j.jastp.2018.06.012

Maliniemi, V., Asikainen, T., Mursula, K., & Seppälä, A. (2013). QBO-dependent relation between electron precipitation and wintertime surface temperature. *Journal of Geophysical Research: Atmospheres*, *118*, 6302–6310. https://doi.org/10.1002/jgrd.50518

Maliniemi, V., Asikainen, T., Salminen, A., & Mursula, K. (2019). Assessing North Atlantic winter climate response to geomagnetic activity and solar irradiance variability. *Quarterly Journal of the Royal Meteorological Society*, *145*(March), 3780–3789. https://doi.org/10.1002/qj.3657

Manzini, E., Giorgetta, M. A., Esch, M., Kornblueh, L., & Roeckner, E. (2006). The influence of sea surface temperatures on the northern winter stratosphere: Ensemble simulations with the MAECHAM5 model. *Journal of Climate*, *19*(16), 3863–3881. https://doi.org/10.1175/JCLI3826.1

Matsuno, T. (1971). A dynamical model of the stratospheric sudden warming. *Journal of the Atmospheric Sciences*, *28*(8), 1479–1494. https://doi.org/10.1175/1520-0469(1971)028%3C1479:ADMOTS%3E2.0.CO;2

Meredith, N. P., Horne, R. B., Lam, M. M., Denton, M. H., Borovsky, J. E., & Green, J. C. (2011). Energetic electron precipitation during high-speed solar wind stream driven storms. *Journal of Geophysical Research*, *116*, A05223. https://doi.org/10.1029/2010JA016293

Mursula, K., Lukianova, R., & Holappa, L. (2015). Occurrence of high-speed solar wind streams over the Grand Modern Maximum. *The Astrophysical Journal*, *801*(1), 30. https://doi.org/10.1088/0004-637X/801/1/30

Polvani, L. M., Sun, L., Butler, A. H., Richter, J. H., & Deser, C. (2017). Distinguishing stratospheric sudden warmings from ENSO as key drivers of wintertime climate variability over the North Atlantic and Eurasia. *Journal of Climate*, *30*(6), 1959–1969. https://doi.org/10.1175/JCLI-D-16-0277.1

Randall, C., Harvey, V., Singleton, C., Bailey, S., Bernath, P., Codrescu, M., et al. (2007). Energetic particle precipitation effects on the Southern Hemisphere stratosphere in 1992–2005. *Journal of Geophysical Research*, *112*, D08308. https://doi.org/10.1029/2006JD007696

Rozanov, E., Callis, L., Schlesinger, M., Yang, F., Andronova, N., & Zubov, V. (2005). Atmospheric response to NO_y source due to energetic electron precipitation. *Geophysical Research Letters*, *32*, L14811. https://doi.org/10.1029/2005GL023041

Salminen, A., Asikainen, T., Maliniemi, V., & Mursula, K. (2019). Effect of energetic electron precipitation on the northern polar vortex: Explaining the QBO modulation via control of meridional circulation. *Journal of Geophysical Research: Atmospheres*, *124*, 5807–5821. https://doi.org/10.1029/2018JD029296

Scaife, A. A., Ineson, S., Knight, J. R., Gray, L., Kodera, K., & Smith, D. M. (2013). A mechanism for lagged North Atlantic climate response to solar variability. *Geophysical Research Letters*, *40*, 434–439. https://doi.org/10.1002/grl.50099

Scott, R. K., & Polvani, L. M. (2004). Stratospheric control of upward wave flux near the tropopause. *Geophysical Research Letters*, *31*, L02115. https://doi.org/10.1029/2003GL017965

Seppälä, A, Lu, H., Clilverd, M., & Rodger, C. (2013). Geomagnetic activity signatures in wintertime stratosphere wind, temperature, and wave response. *Journal of Geophysical Research: Atmospheres*, *118*, 2169–2183. https://doi.org/10.1002/jgrd.50236

Sonnemann, G. R., & Grygalashvyly, M. (2007). The relationship between the occurrence rate of major stratospheric warmings and solar Lyman-alpha flux. *Journal of Geophysical Research*, *112*, D20101. https://doi.org/10.1029/2007JD008718

Soukharev, B., & Hood, L. (2006). Solar cycle variation of stratospheric ozone: Multiple regression analysis of long-term satellite data sets and comparisons with models. *Journal of Geophysical Research*, *111*, D20314. https://doi.org/10.1029/2006JD007107

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., da Costa Bechtold, V., Fiorino, M., et al. (2005). The ERA-40 Re-analysis. *Quarterly Journal of the Royal Meteorological Society*, *131*(612), 2961–3012. https://doi.org/10.1256/qj.04.176

van Loon, H., Jenne, R. L., & Labitzke, K. (1973). Zonal harmonic standing waves. *Journal of Geophysical Research*, *78*(21), 4463–4471. https://doi.org/10.1029/jc078i021p04463

Waugh, D. W., & Randel, W. J. (1999). Climatology of Arctic and Antarctic polar vortices using elliptical diagnostics. *Journal of the Atmospheric Sciences*, *56*(11), 1594–1613. https://doi.org/10.1175/1520-0469(1999)056%3C1594:COAAAP%3E2.0.CO;2

Wilks, D. S. (2006). On "field significance" and the false discovery rate. *Journal of Applied Meteorology and Climatology*, *45*(9), 1181–1189. https://doi.org/10.1175/JAM2404.1