Solar-related and internal drivers of the northern polar vortex

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Background: Solar-related drivers

The Sun and solar wind affect the Earth's atmosphere and climate via two independent drivers:

1. Solar radiation
   - Solar irradiance varies in concert with the sunspot cycle.
   - Largest variability in short wavelengths, e.g., in ultraviolet range.

2. Particle precipitation
   - The most important precipitating particles are magnetospheric energetic electrons.
   - Energetic electron precipitation (EEP) maximizes a few years after the sunspot (and solar irradiance) maximum

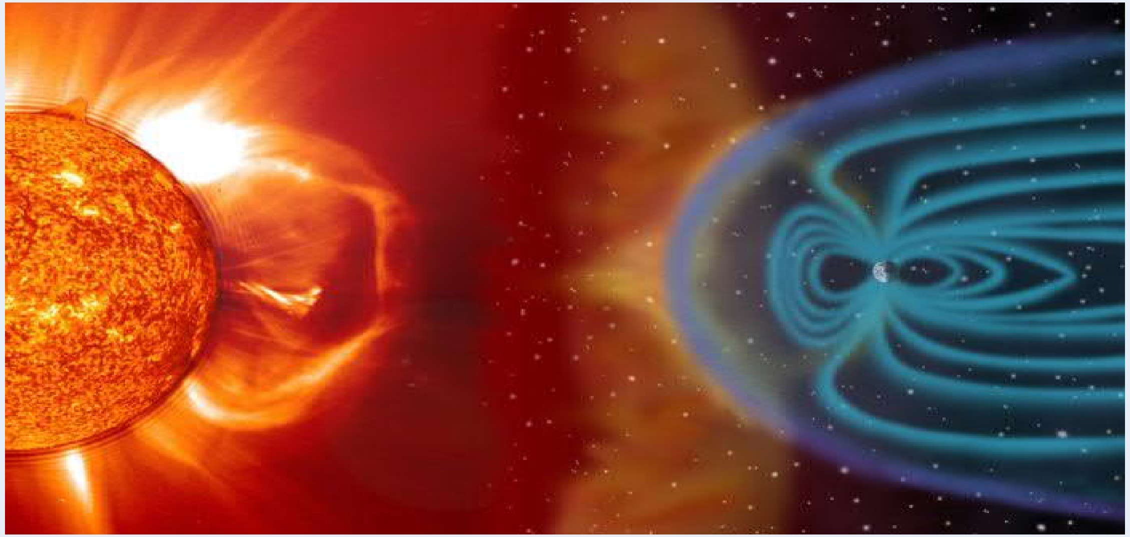
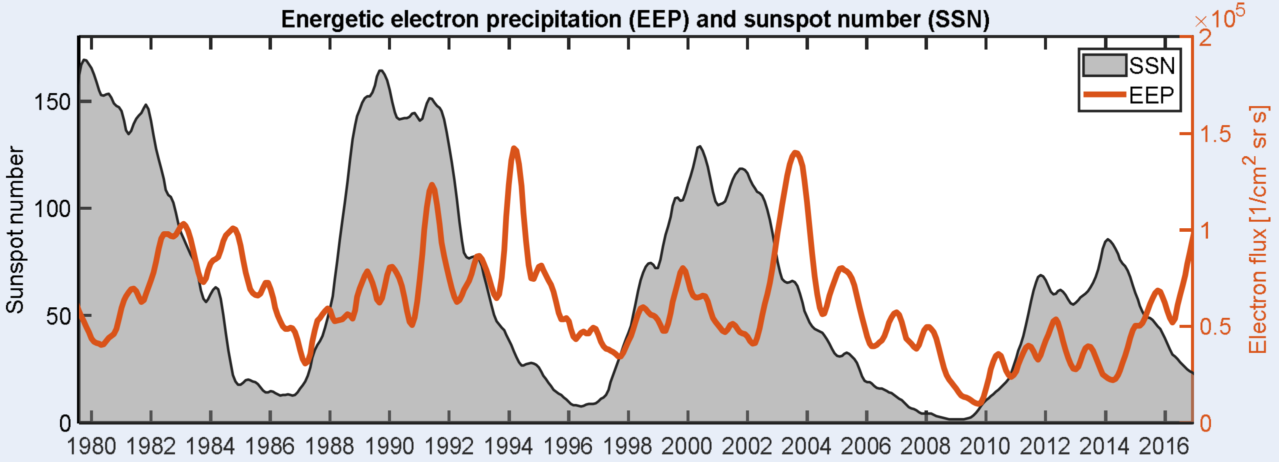


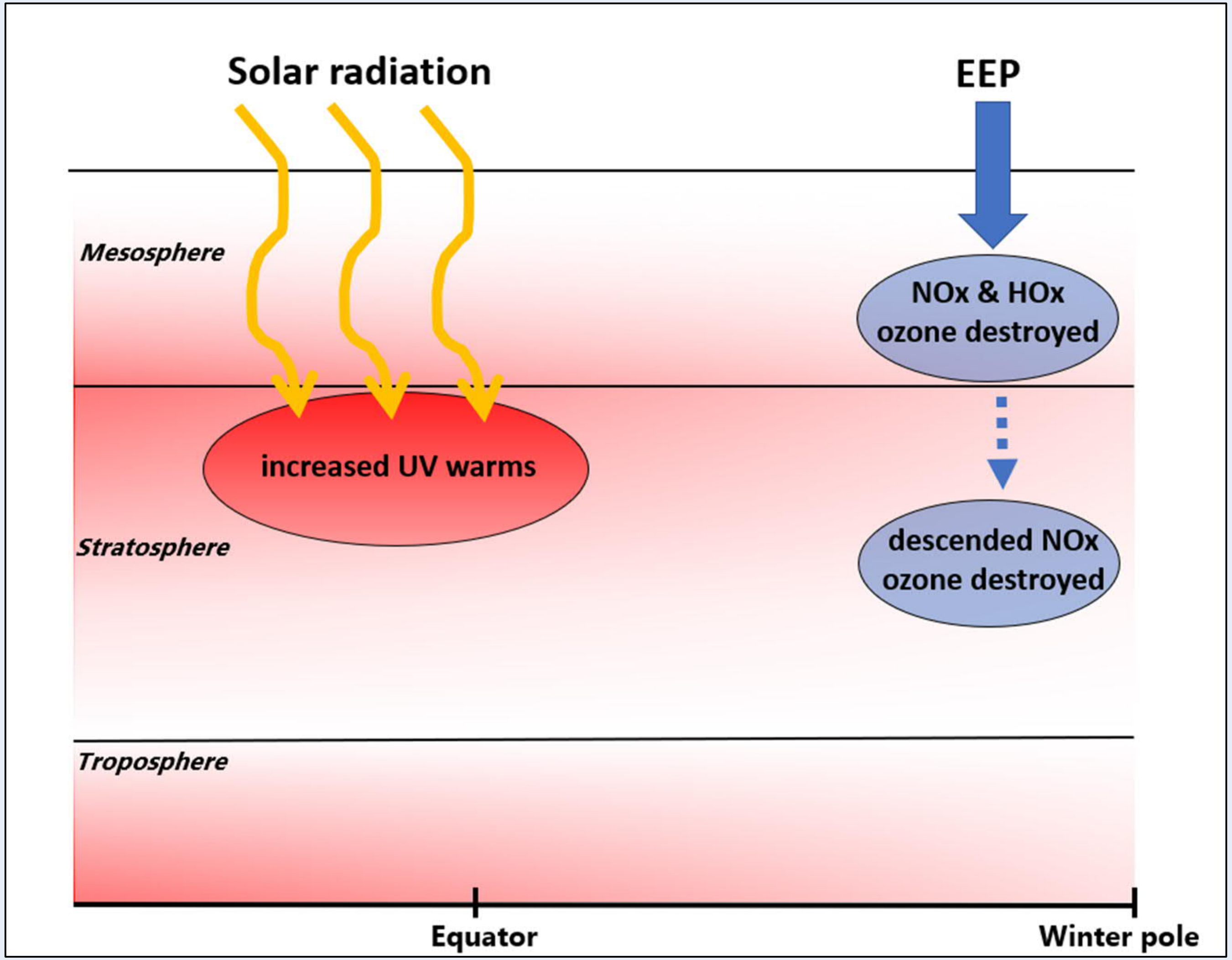
Illustration of the Sun-Earth system. The Earth is surrounded by magnetosphere.
Credit: NASA [www.nasa.gov]



Energetic electron precipitation (red) and sunspot number (black). Data are 13-month running averages

Background: Solar-related drivers

Variations in solar radiation affect most optimally at the low-latitude stratosphere where solar UV radiation is absorbed by ozone.



Effects of the two solar drivers: solar radiation and energetic electron precipitation

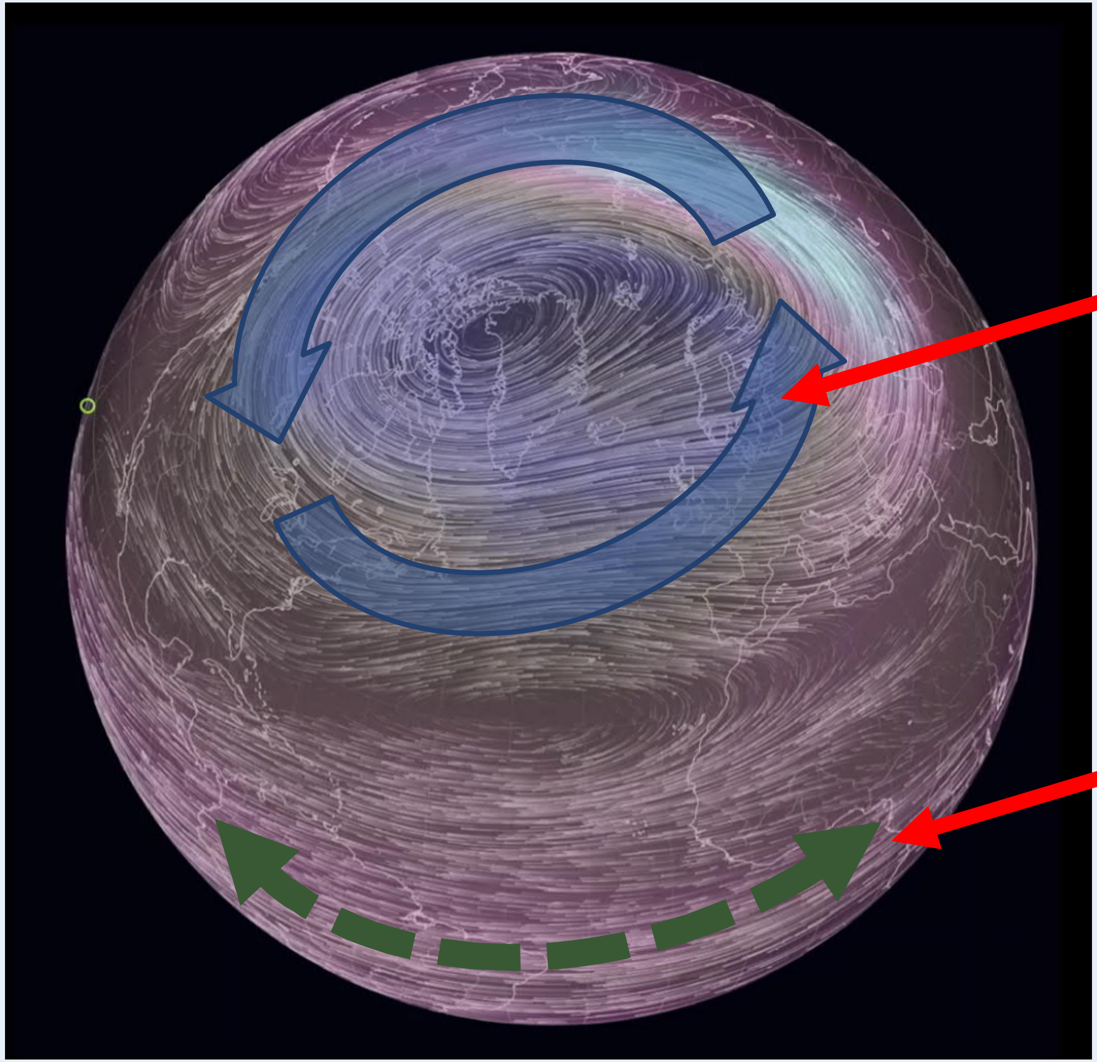
Energetic electron precipitation is focused on the high-latitude mesosphere and upper stratosphere.

EEP forms reactive NOx and HOx compounds which destroys ozone.

During winter EEP-NOx descend to lower altitudes

- ➢ Indirect EEP effect

Background: Wintertime stratosphere



Temperature (color) and winds (lines) in the northern winter stratosphere
[https://earth.nullschool.net/]

Polar vortex, a westerly wind jet, forms around the cold polar region in the stratosphere during winters. In the northern hemisphere the polar vortex varies during the winter considerably as it is disturbed by planetary waves.

Planetary waves can initiate a sudden stratospheric warming (SSW), in which polar vortex is momentarily collapsed and reversed.

Quasi-Biennial Oscillation (QBO) is a wind mode in the equatorial stratosphere in which the wind changes its direction every 14-16 months (easterly/westerly). The QBO phase affects the propagation of planetary waves so that planetary waves are diverted more poleward and polar vortex is weaker in the easterly QBO phase [Holton and Tan, 1980].

Background: Drivers of the polar vortex

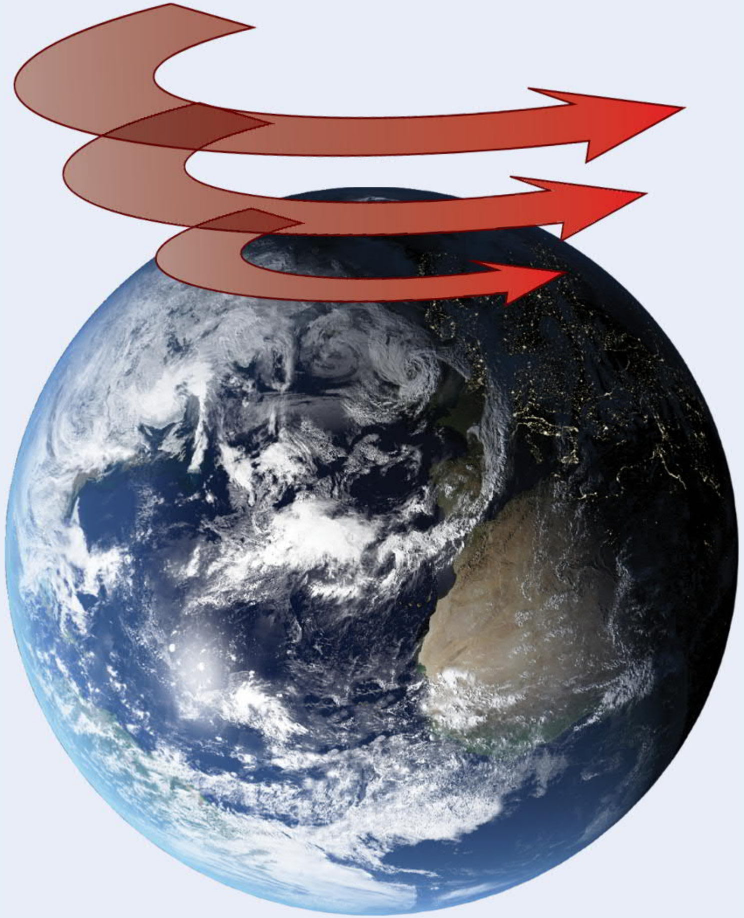
Several drivers modulate the polar vortex in the northern hemisphere

Solar-related drivers

- Solar radiation
  [Labtizke and van Loon, 1982]
- Particle precipitation
  [Rozanov et al., 2003; Salminen et al., 2019]

Terrestrial drivers

- QBO wind mode
  [Holton and Tan, 1980]
- ENSO climate mode
  [Garfinkel and Hartmann., 2007]



Variations of the northern polar vortex propagate down to the lower atmosphere causing variations in the surface weather, especially in the Arctic region. Therefore, polar vortex is an important factor to mediate the solar-related effects on the climate [Maliniemi et al., 2019].

In this study we examine how different drivers affect the SSW occurrence.

SSW/no SSW winter distributions

We examine how the occurrence of sudden stratospheric warmings depend on the two terrestrial drivers (QBO, ENSO) and two solar-related drivers (EEP, solar irradiance). We study winters 1957/1958 – 2016/2017. SSWs are identified by using the ERA-40 (1957-1978) and ERA-Interim (1979-2017) data. List of SSWs are found in https://www.esrl.noaa.gov/csl/groups/csd8/sswcompendium/majorevents.html

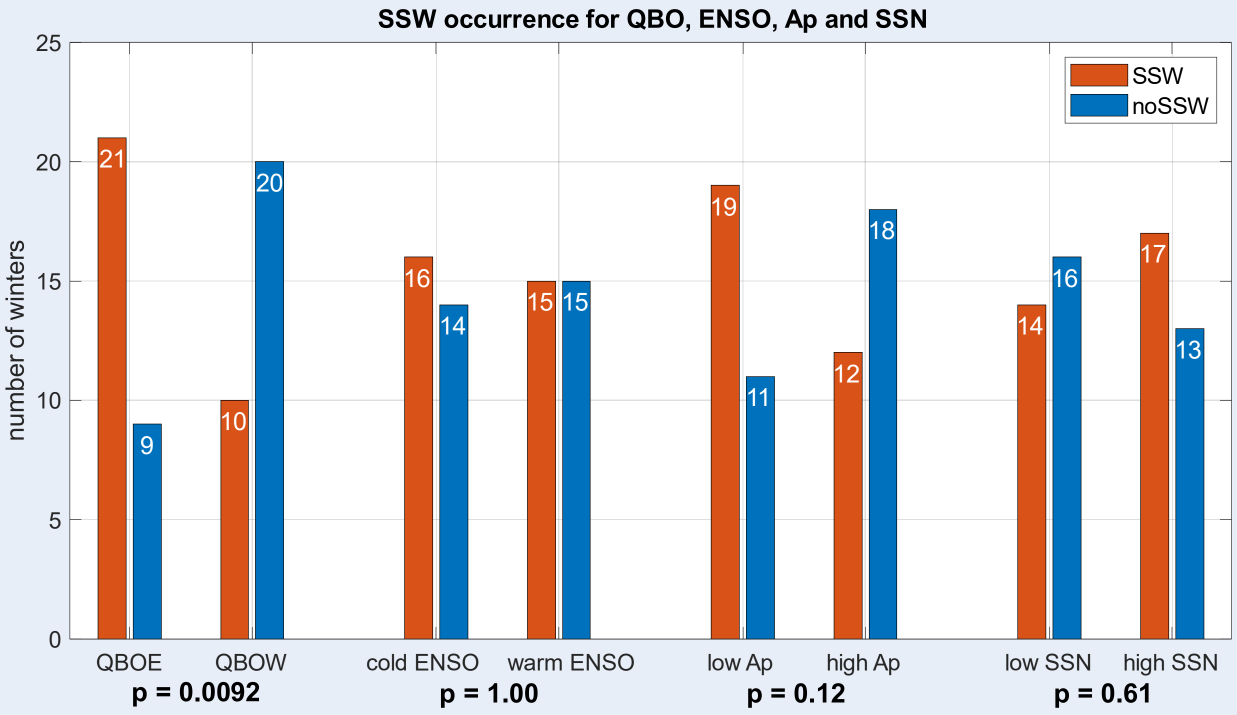
⇒ 31 winters with SSWs, 29 winters without an SSW

Then we separate winters to

- QBO-E and QBO-W (QBO at 30 hPa)
- cold and warm ENSO
- low and high Ap (geomagnetic activity/EEP)
- low and high sunspot number (solar irradiance)

We use December values for each variables except for QBO we use value of preceding September. The separation is based on the median value of each variable.

Significances of differences in SSW occurrence are calculated with Fisher's exact test.



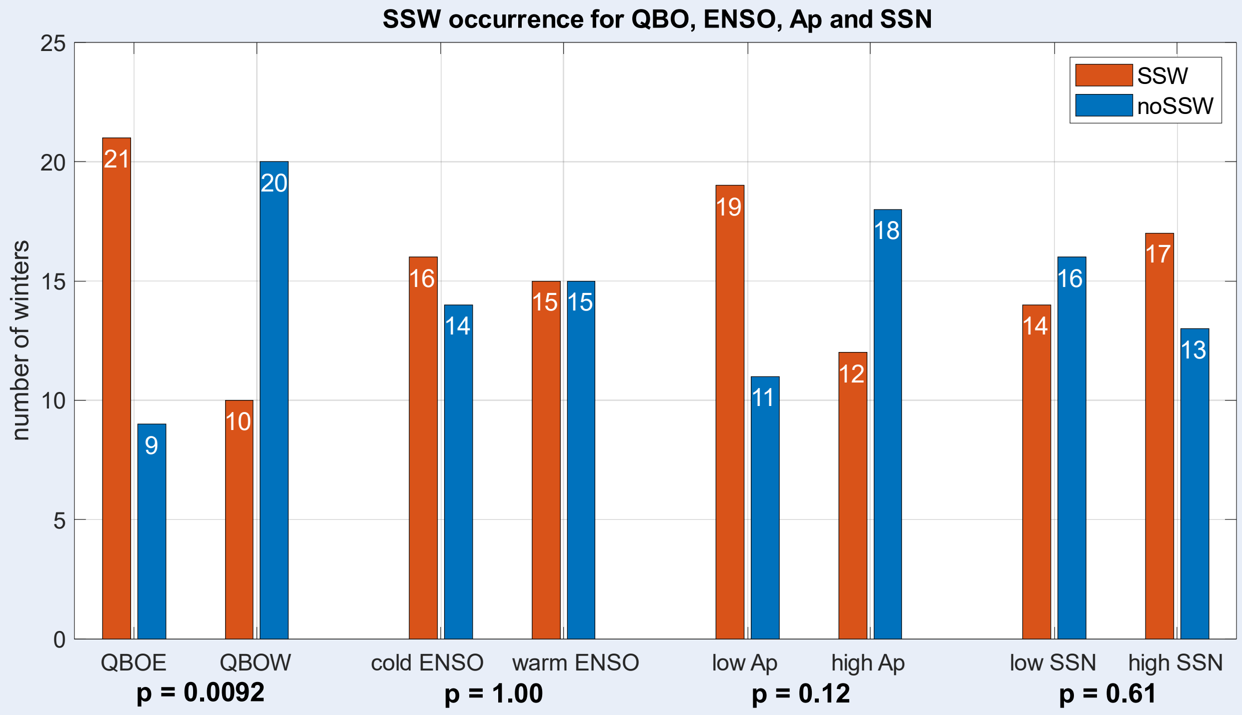
Number of winters with SSW (red bars) and without SSW (blue bars) in QBO-E and QBO-W (bars 1-4), in cold and warm ENSO (bars 5-8), in low and high Ap (bars 9-12), and in low and high SSN (bars 13-16). [Salminen et al., 2020]

SSW/no SSW winter distributions

SSWs are more common in QBO-E winters (SSW in 21 of 30 winters) than in QBO-W winters (10/30) (p = 0.0092).

SSW occurrence is also higher in low Ap winters (19/30) compared to high Ap winters(12/30), but this difference is only marginally significant (p = 0.12).

Differences in SSW occurrence are only minor between cold and warm ENSO winters, and between low and high SSN winters.



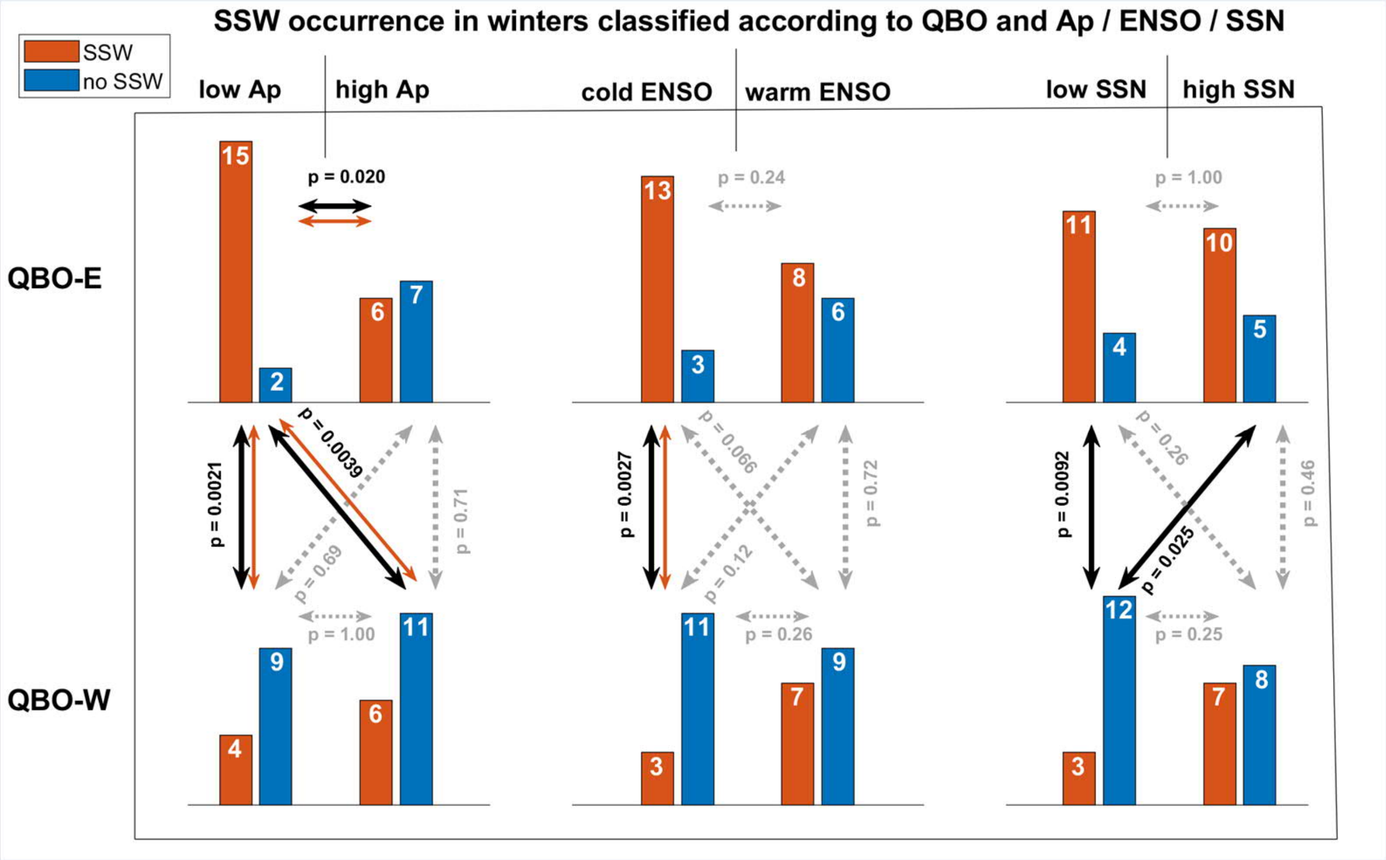
Number of winters with SSW (red bars) and without SSW (blue bars) in QBO-E and QBO-W (bars 1-4), in cold and warm ENSO (bars 5-8), in low and high Ap (bars 9-12), and in low and high SSN (bars 13-16). [Salminen et al., 2020]

SSW/no SSW winter distributions

We also studied how SSW / no SSW winters are distributed when the winters are separated to four phases according to two factors: QBO and either Ap, ENSO or SSN.

SSWs are more common in QBO-E than in QBO-W winters in all studied cases. However, the difference in SSW occurrence between QBO phases is significant in low Ap, low SSN and cold ENSO winters, while in high Ap, high SSN and warm ENSO winters the difference is small and insignificant.

In QBO-E, SSWs are more common in low Ap winters than in high Ap winters ($p = 0.020$). Of all studied cases, SSWs are most common in winters with low Ap and easterly QBO (15 of 17 winters with a SSW).



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). Differences which are significant ($p < 0.05$) are marked with bold black arrows and those which pass the test based on false discovery rate [Wilks, 2006] are marked with red arrows. [Salminen et al., 2020]

Discussion and conclusions

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SSWs occur more often in QBO-E than QBO-W winters.

- Planetary waves are directed poleward in QBO-E [Holton & Tan, 1980]

The QBO effect on SSW occurrence is stronger in winters with low geomagnetic activity, low sunspot activity or cold ENSO.

- High geomagnetic activity is associated with stronger polar vortex [Rozanov et al., 2003; Salminen et al., 2019].
- ENSO [Manzini et al., 2006] and solar irradiance [Gray et al., 2004] affect the formation and propagation of planetary waves.

In QBO-E SSWs are more common in low geomagnetic activity winters than in high geomagnetic activity winters. The highest SSW occurrence rate is winters with easterly QBO and low Ap (15/17 winters with SSW).

- Ap effect is stronger in QBO-E [Maliniemi et al., 2013, Salminen et al., 2019].

Salminen, A., Asikainen, T., Maliniemi, V., & Mursula, K. (2020). Dependence of sudden stratospheric warmings on internal and external drivers. Geophysical Research Letters, 47, e2019GL086444. doi: 10.1029/2019GL086444

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