Surface response to extreme events in the stratosphere under different global warming thresholds

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Motivation

Sudden stratospheric warmings (SSWs) are extreme events in the winter/spring polar stratosphere. During winter, when the polar middle atmosphere gets very cold, a strong westerly jet develops around the pole forming the polar vortex. A strong weakening of this jet, which can even lead to the breakdown of the polar vortex, i.e. to an SSW, can feed back onto the tropospheric circulation. These extreme stratospheric events **are followed by anomalies in the tropospheric annular modes** on both hemispheres (NAM and SAM) after a few weeks. This signal is quite persistent and can enhance the predictability of surface conditions.

On the NH these events occur every other year, while **on the SH there were only two events observed**: in 2002 and in 2019. In 2019 the SH polar vortex did not break down but the weakening of the vortex was strong enough for a significant surface impact. Lim et al. (2019) showed that **weak vortex years are connected to extreme heat events in Australia** which increase the risk of wild fires. It is therefore of great importance to assess how likely such stratospheric extreme events are in the near and far future.

Here, we investigate the occurrence and surface impacts of such extreme stratospheric events for different global warming thresholds.

Model Experiments and Methods

We performed AMIP-like experiments with ECHAM6 T63/L95 (incl. JSBACH) using daily SST and SIC forcing based on ERA5 data for different scenarios: **Historical**, **2018** (present state), **1.5 K**, **2 K**, **3 K** and **4 K global warming (GW)** levels with respect to pre-industrial temperatures.

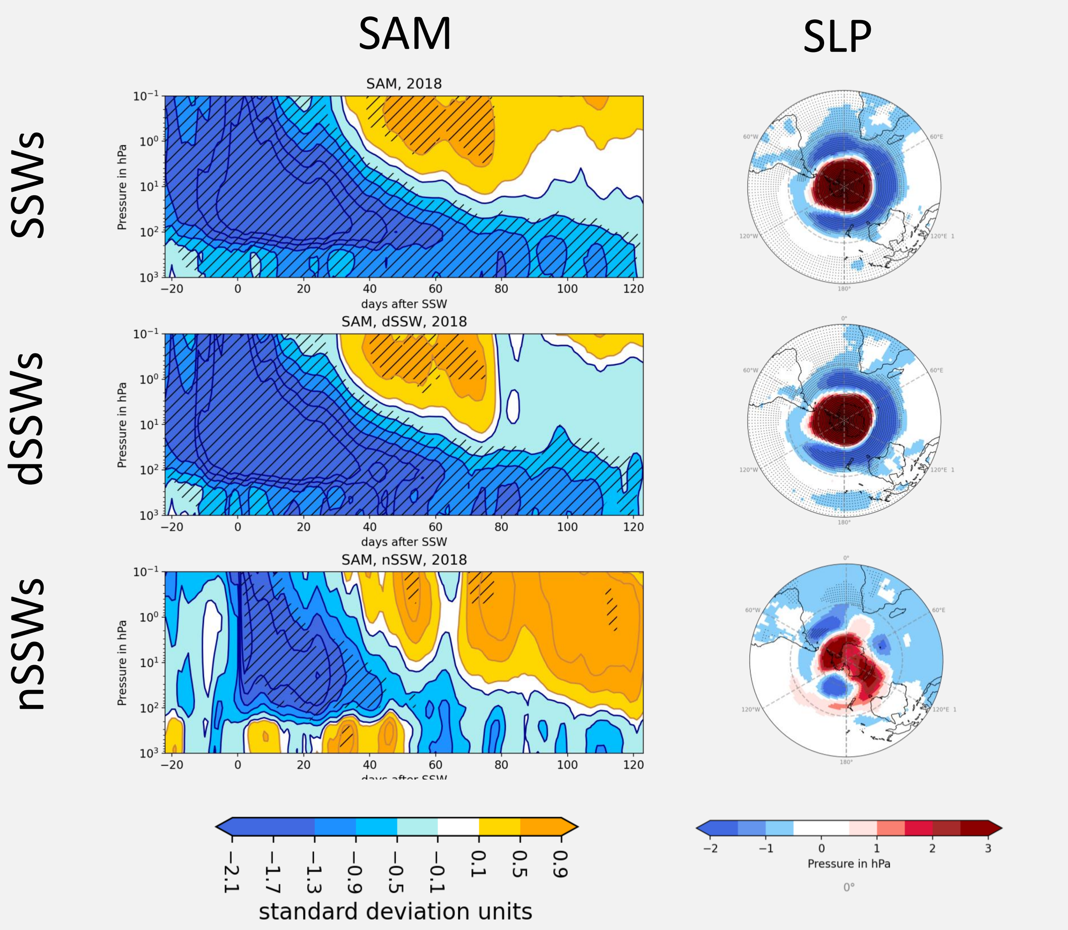
Historical experiment	Transient 1980 to 2019 forcing conditions in the atmosphere and the surface, historical forcing until 2014 and after that following the SSP8-5.8 CMIP6 scenario; 5 ensemble members.
2018 experiment	Perpetual 2018 conditions in the atmosphere and the at the surface; 292 model years.
GW experiments	Perpetual atmospheric and surface conditions that apply to the given warming levels under SSP5-8.5 conditions. To design the SST and SIC forcing, warming levels were calculated from a coupled FOCI simulation (Matthes et al. 2020) following the SSP8-5.8 scenario. SST trends from 2018 until the individual warming levels (+/- 15 years) were added to the daily 2018 SST field based on ERA5 data up to 60° latitude. Poleward of that the forcing converges to the model SIC and SSTs. We ran about 200 model years per warming threshold.

Extreme events in the stratosphere are defined to occur when the zonal mean zonal wind at 60°S and 10 hPa decreases to 20 m/s at least (Rao et al. 2020). For simplicity we call these events **SSWs**. To separate SSWs from the final warmings (the return to the summer circulation), the zonal mean zonal wind has to return to values larger than 20 m/s for at least 10 consecutive days before the final breakdown of the polar vortex.

SSW characteristics and surface impact

Following the method of Karpechko et al. (2017) for the NH, we defined downward propagating (dSSWs) and non-downward propagating (nSSWs) events based on the Southern Annular Mode (SAM) at 1000 and 150 hPa. We show that this method is also applicable to the weaker SSW definition that we applied for the SH warming events. The surface anomalies in SSW years is shown for all experiments and dSSWs in more detail.

SSW downward propagation



Long-lasting SAM anomaly within the stratosphere with an effect on the surface SAM up to 120 days after the start of the events.

Significant surface impacts of the SSWs mainly result from the dSSWs.

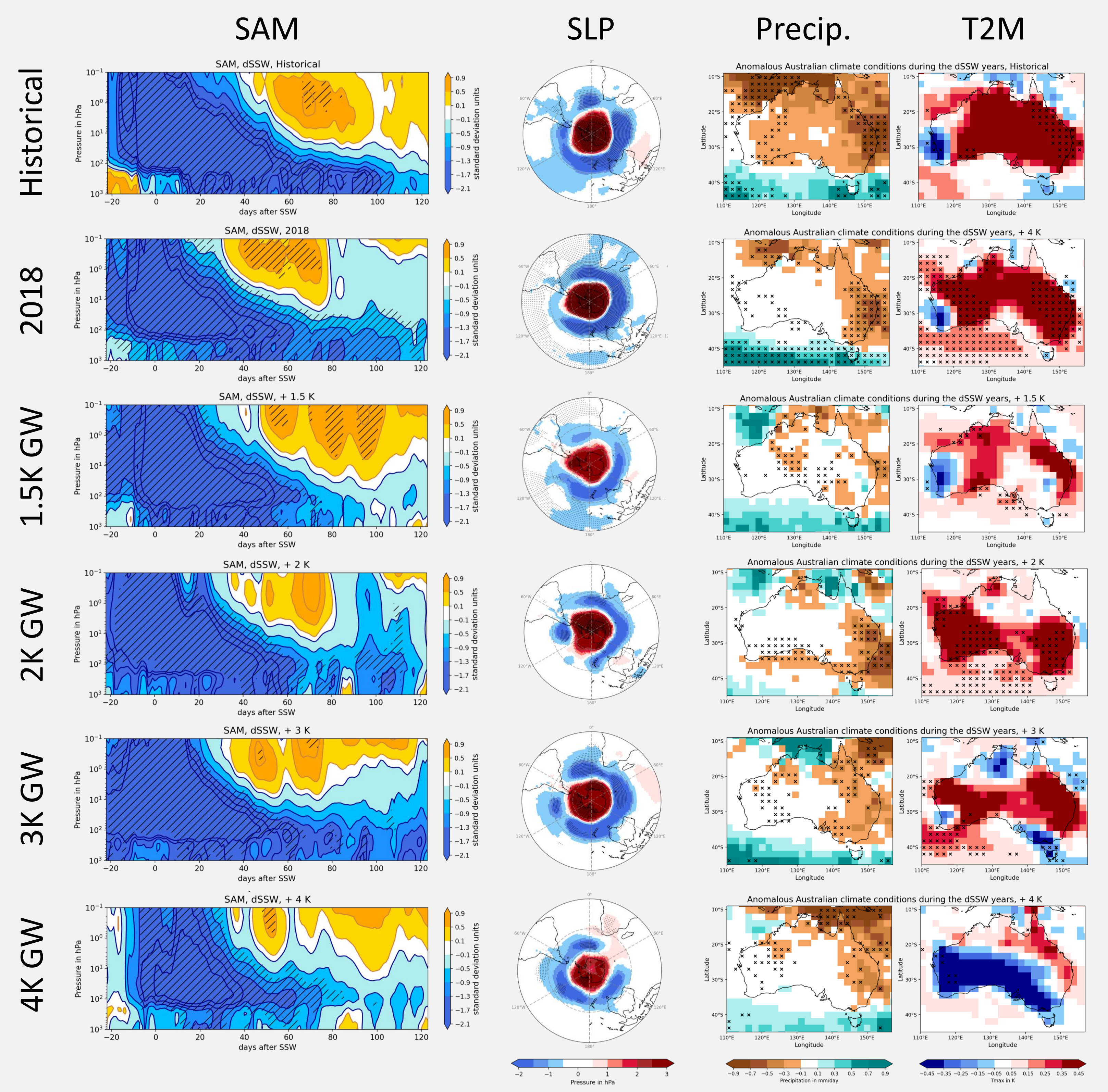
The SAM and sea level pressure (SLP) anomalies after SSWs are shown for the 2018 experiments. We use the 2018 experiment as an example here since it has the best statistics. However, the difference between dSSWs and nSSWs are similar for the other experiments as well.

SSW frequencies

Experiment	Model Years	SSWs/decade	dSSWs/decade	nSSWs/decade	dSSWs/nSSWs
Historical	200	0.70	0.50	0.20	2.50
2018	294	0.99	0.82	0.17	4.80
1.5 K global warming	203	0.69	0.54	0.15	3.67
2 K global warming	204	0.74	0.29	0.44	0.67
3 K global warming	203	0.54	0.34	0.15	2.33
4 K global warming	193	0.67	0.41	0.26	1.60

The number of SSWs per decade peaks for the 2018 setting and roughly decreases with global warming levels afterwards. A cut seems to occur at 2K warming, where the number of nSSWs gets larger than that dSSWs. The ratio of dSSWs/nSSWs decreases with the global warming level.

dSSW surface impact under different global warming levels



Surface response in SSW years well represented in our model runs under historical and present day climate conditions

Decrease in significance for 1.5 K GW

Slight changes in the surface response pattern for 2K and 3K warming. Significance reduces under 3K warming.

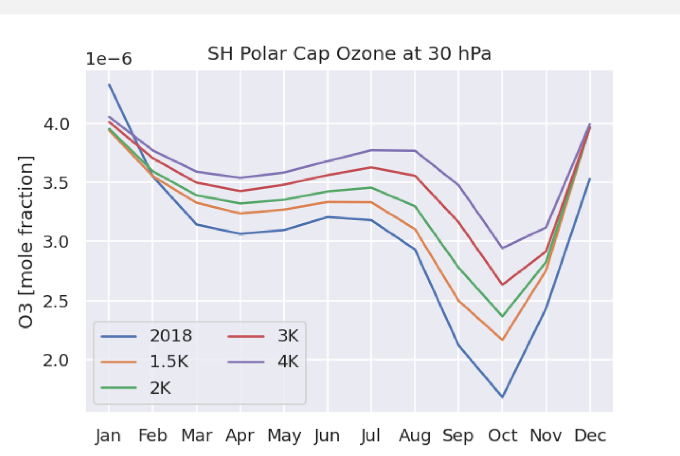
Surface response under 4K warming changes.

The SAM, SLP, precipitation (Precip.), and 2m air temperature (T2M) anomalies after the onset of the dSSWs (SAM) and for the October to December season in dSSW years vs. all years (for all other variables) in the different experiments. GW = global warming.

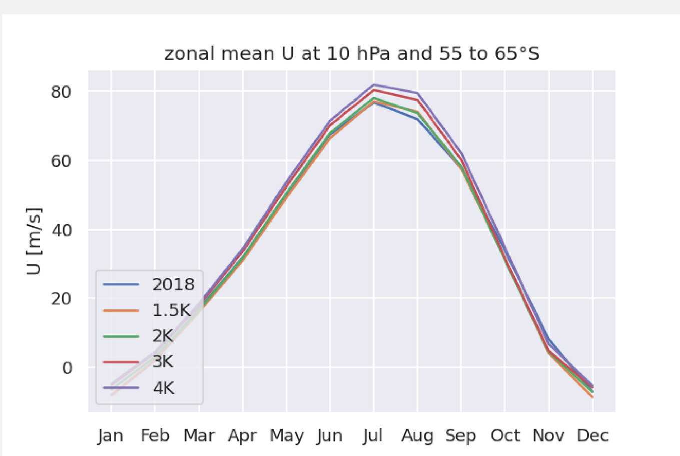
What is causing the difference in SSW occurrence under global warming?

Ozone recovery counteracts the GHG increase that is projected within the SSP5-8.5 scenario. While the polar cap ozone increases continuously with warming levels, the strength of the stratospheric jet between 55 and 65°S at 10 hPa increases and the polar cap temperatures at 30 hPa keep decreasing especially during July, August and September. The background state of the polar vortex is very important for the onset of SSWs (e.g., Jucker et al. 2021).

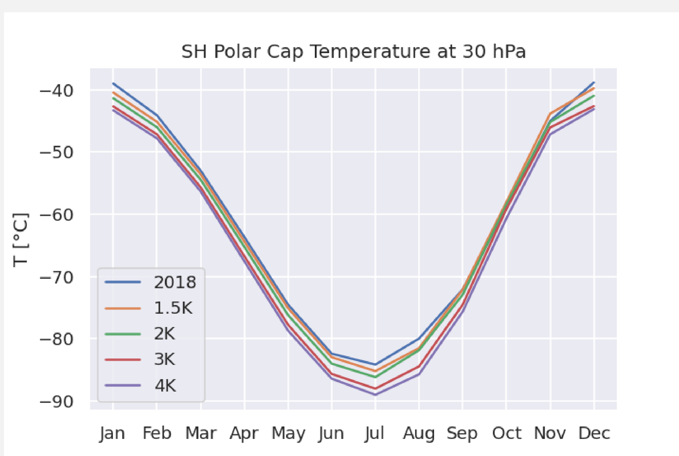
Ozone recovery



Strengthening of the polar vortex



Polar cap cooling



Outlook/Discussion

Occurrence of SSWs and surface response suggest that there is a change in the SH STC at about 2K warming. This might be due to the interplay between GHG increase and Ozone recovery and is probably model dependent. The effect on upward wave propagation still has to be investigated.

The effect of interactive chemistry on the GHG – Ozone interplay would be an interesting subject for future studies. Also with respect to the fact that ozone recovery might be underestimated in the CMIP6 forcing for the SSP5-8.5 scenario (Revell et al. 2022).

References

Jucker et al., 2021: How Frequent Are Antarctic Sudden Stratospheric Warmings in Present and Future Climate? *Geophys. Res. Lett.*, **48**, 1–9, doi:10.1029/2021GL093215.; **Lim et al., 2019**: Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex. *Nat. Geosci.*, **12**, 896–901, doi:10.1038/s41561-019-0456-x.; **Matthes et al., 2020**: The Flexible Ocean and Climate Infrastructure version 1 (FOCI1): mean state and variability. *Geosci. Model Dev.*, **13**, 2533–2568, doi:10.5194/gmd-13-2533-2020.; **Rao et al., 2020**: The Southern Hemisphere Minor Sudden Stratospheric Warming in September 2019 and its Predictions in S2S Models. *J. Geophys. Res. Atmos.*, **125**, 1–19, doi:10.1029/2020JD032723.; **Revell et al., 2022**: Influence of Ozone Forcing on 21st Century Southern Hemisphere Surface Westerlies in CMIP6 Models. *Geophys. Res. Lett.*, **49**, 1–9, doi:10.1029/2022GL098252.

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