

Answer to Reviewers

Thank you for your valuable comments that helped to improve our manuscript. We address the specific comments below and hope that the revised version of the manuscript meets your demands.

Best regards,

In behalf of all the co-authors,
Sabine Bischof

Reviewer 1

Comments on “Southern Hemisphere Sudden Stratospheric Warmings Continue to Be Relevant Under Global Warming” by Bischof et al.

Summary

This study uses a model to study the possible changes of the sudden warming in different scenarios at the present-day, historical, and different warming states. The SSW frequency in the southern Hemisphere is very low, and only one major SSW occurs in the Southern hemisphere based on the ERA5 since 1940. Even the data after 1979 are used to assess the SSW frequency, the frequency is once from 1979 now. The frequency is 1/45 once per year. However, the frequency in the model is much higher. This inconsistency should be included in the paper.

Major comments:

1. The significance of this study should be emphasized. Since the SSW is much rarer in the Southern Hemisphere than in the Northern Hemisphere, and the significance is relatively low. Since 1979, only one major SSW was observed in the Southern Hemisphere. Whether there will be a second major SSW in the future is a big problem. Therefore, the significance of this study is low.

We would disagree with the comment that the significance of this study is low. We include a more thorough motivation now in the beginning of the manuscript to underline this. Although only one major SSW was ever observed in the SH, there has been a minor SSWs in 2019, that significantly contributed to surface heat events as also stated in the original version of the manuscript (Lim et al., 2021, 2020). Further, especially in recent years the polar stratospheric vortex seems to get more variable, with an increasing trend in weaker warmings (Kwon et al., 2020; Zi et al., 2025). We rewrote parts of the introduction and include more details also on weaker events to further highlight the importance of stratospheric warmings also in the SH (lines 16-47). Apart from Australia, our study also highlights the potential vulnerability of southern Africa to stratospheric warmings under intermediate warming levels. The finding, that SSWs can still occur under intermediate warming levels valuable for the Australian as well as for the southern African weather prediction.

2. The SSW frequency in the models have been comprehensively assessed by other studies, which should be included. Compared with the state-of-the-art models, we did not see the simulation level of the used model FOC1. Is this model also a CMIP6 model, and is the simulation skill is good enough to study the stratosphere and the Southern Hemisphere? The assessment of this study with ERA5 shows a

big difference and even bias. How will the author attribute this bias? Is it necessary to correct the simulation before using the simulation data?

FOCI1 is not a CMIP model, it is therefore not included in the multimodel assessment studies; however, we use AMIP-like simulations in this manuscript, which are based on ECHAM6.3, which is the atmospheric component of the MPI-ESM1.2 contribution to CMIP6 (Mauritsen et al., 2019). The ability of the different configurations of the MPI-ESM to represent NH SSWs was analyzed for example in Hall et al. (2022). They showed that the MPI model is one of the models, that has a decent frequency of split events, which is underestimated by most other models. At the same time the number of displacement events is on the higher end. The resulting total SSW frequency is only slightly overestimated in the MPI model in comparison to reanalysis data (6.12 events per decade in MPI-ESM1-2-HR vs 5.97 events per decade in ERA data). In comparison to other models, the MPI model has a higher number of SSWs (consistent also with Wu and Reichler, 2020). The FOCI1 model itself was evaluated thoroughly before it was used for scientific questions; this evaluation is published in Matthes et al. (2020). The SSW frequency is described in section 4.3. It is a bit lower than in reanalysis with 0.44 events per year in FOCI1 as compared to 0.52 events per year in a combined ERA/ERA-Interim dataset. This frequency is closer to the multi-model mean shown in Wu and Reichler (2020). A significant deviation from the observations was found in the seasonal distribution. Matthes et al. (2020) showed that FOCI1 overestimated early events, especially in November. This seems to be an issue in ECHAM (Charlton et al., 2007; Wu and Reichler, 2020). The exact simulation of the seasonal distribution of SSWs is a common problem in climate models (Charlton et al., 2007). We mention the ability of FOCI1 to represent SSWs in the data section and include some more information on this now in Lines: 211-212.

FOCI1 was already used in studies on the SH stratosphere (Ivanciu et al., 2022a, 2022b, 2021) showing a good representation of stratospheric responses to ozone and GHG changes within the 21st century along with their surface responses and the capability to represent ridging South Atlantic Anticyclones, that contribute to an important amount of precipitation over southern Africa. Our present study shows that FOCI1 has a great potential to replicate the observed imprint of the 2019 minor SSW event at the surface. Xu et al. (2025) used FOCI1 along with CMIP models to study the effect of a freshwater release in the Southern Ocean and investigated the stratospheric response. In this study, FOCI1 compares well to the other participating models. We therefore argue that the model is well suited to study SH stratospheric processes and don't consider a correction to be necessary (lines: 204-212).

3. The results from the 1.5, 2, 3, 4K are very different. The downward propagation of the SSW signals is different for the those warming scenarios. The near surface impact of the SSWs is strongest for the 2K experiment. However, the composite near surface anomalies in the high warming scenario is weak. The changes of the near surface composite SSW signals are nonlinear with the global warming value. The explanation is that the interaction between ozone and CO₂ might explain the nonlinear changes. However, the model seems not to have a chemistry ozone in the stratosphere. Please clarify.

Yes, we think that this non-linearity can be explained to some extent by the counteracting effects of GHG increase and Ozone recovery. Stratospheric ozone is prescribed, which means that there is an ozone recovery in the model which depends on the CMIP6 ozone concentrations during the time of the respective warming level. This is explained in the methods section (lines 130-139), in which we now include the different CO₂ levels as well as a reference to new Supplementary Figure S2 (previously S7), which depicts the polar cap stratospheric ozone in the different time slice simulations. We also include the GHG mixing ratios prescribed in the time slice experiments in the new Table 2 now.

The change in the 4K experiment, on the other hand, shows a drastic decrease in stratosphere-troposphere coupling under high temperature increases, which is an interesting result on its own. But detailing this nonlinearity is beyond the scope of this study (already long paper).

4. The composite pattern for 4K scenario is nearly opposite to that for other cases. Can you give some explanations? Although the composite significance level is weak, the composite value is very large over both South Africa and Australia. The nonlinear impact between ozone and CO₂ is also not enough to explain the reversal of the composite near surface change.

This is correct. However, these signals are insignificant. We argue that the coupling strength between the stratosphere and troposphere diminishes at very high warming levels (4K). The number of nSSWs increases and also the dSSWs do not show a significant surface signature anymore. This might be due to the lower number of events but also due to the later onset of events (Fig. 7). Late events also have a weaker surface impact on the NH (Monnin et al., 2022).

Other Comments:

1. L18: 1,5 years => 1.5 years.

revised

2. L23: 60 degrees latitudes => 60 degrees N.

We actually used degrees latitude on purpose. We extended our description on how SSWs are defined but would like to keep this formulation since we apply this definition in both hemispheres.

3. L25: The minor SSW in September 2019 in the Southern Hemisphere is earliest reported in Rao et al. 2020, doi: doi:10.1029/2020JD032723. Then followed by Lim et al. 2021 and Chen et al. 2025, doi: 10.1038/s41612-025-01234-2.

We cited Safieddine et al. (2020) here, who published as early as Rao et al. (2020). We are happy to include the Rao paper here, too. The DOI you provided for the Chen et al. paper leads to Feng et al. (2025). Is that the one you were aiming for? We include also include Feng et al. (2025) now (lines 37, 85).

4. L33: How did you determine the global warming level? Do you use the near surface temperature change to determine this level?

Yes, we include that information in the methods section. We include the information on the near surface temperatures now: "[...] different global warming states: present-day, 1.5 K, 2 K, 3 K and 4 K global warming levels with respect to pre-industrial 2m air temperatures."

5. L58: This enhancement is forced or internally generated? The 2002 major SSW happened under global warming? If so, why no SSWs happened after 2002 in the Southern Hemisphere?

We refer to the Ozone Assessment from 2022 here, where it is stated that *"Since the last Assessment, springtime Antarctic ozone exhibited significant year-to-year dynamically driven variations. The polar cap total ozone ranged from anomalously low in 2018 and 2020 to record high in 2019 [...]"* We

missed on adding information on the Chapter before but refined that reference now. Although there has not been another major warming in the SH, a strong minor warming with significant impacts on the stratospheric and tropospheric conditions was observed in 2019 (Lim et al., 2021; Roy et al., 2022) and weaker minor warmings events were also observed in 2024 (Zi et al., 2025). Our study highlights the possibility of additional minor warmings in the coming decades.

6. L65-66: A recent paper by Feng et al. 2025 also discusses the hot-dry extremes in Australia and its linkage with the wildfires.

Thanks for pointing this out. We agree that adding this reference strengthens the conclusion here.

7. L103: Daily mean values? Do you mean that you use a 365-day annual cycle as the SST and SIC boundary or anything else?

Yes, that is correct. We use a 365-day annual cycle based on the 2018 SSTs for the present-day experiment. For the transient simulations we prescribe transient SSTs and SIC in daily temporal resolution.

8. L112, 123: How did you determine that the global warming is just 1.5, 2, 3, 4K? What is the mean level of CO₂ and ozone. What is the year that reaches the 1.5, 2, 3, and 4K in the SSP585 scenario? The description of the experiment is very long and misleading. Can you simplify the description of the experiment setup. Just tell us the CO₂ level that can guarantee a 1.5, 2, 3, and 4K.

Sorry for the confusion, we changed the description and hopefully improved readability. In lines 134-138 we explain how the warming levels are determined followed by the information on the CO₂ mixing ratios: "The corresponding global mixing ratios of CO₂ are: 460.62 ppm (1.5 K), 542.21 ppm (2K), 751.62 ppm (3K) and 985.39 ppm (4K). Table 2 summarizes the GHG mixing ratios prescribed in the time slice experiments." We also refer to new Supplementary Fig. S2 (previously S7) for the polar cap ozone levels.

9. L125: Do you add the warming amplitude directly? If you add the trend, how many years of spinup is run? The warming amplitude can be directly added. If you added the trend, the SST and SIC forcing changes year by year. Can you clarify?

Sorry for the confusion. We actually added the amplitude on top of the existing day-to-day SST variability. The word trend was not correct. Thank you for pointing that out. It now reads: "... the change in SSTs from 2018 to the 1.5, 2, 3 and 4 K warming level ..."

10. Table 1: Add the CO₂ level in the table to reach the 1.5, 2, 3, and 4 K warming amplitude.

We mention the CO₂ level in the text now and would rather not overwhelm Table 1 with another column. See previous answers.

11. L138: The simulation of the SFWs and SSWs in the northern hemisphere and southern hemisphere has been reported in Rao and Garfinkel. I suggest to add some discussion on the simulation skill of SSWs in your model and CMIP6 models. (Rao and Garfinkel, 2021a, b: 10.1007/s00382-021-05647-6; doi: 1088/1748-9326/abd4fe)

Rao and Garfinkel (2021) only discuss NH SSWs, while Rao and Garfinkel (2021b) only consider final warmings.

12. L152: data is => data are

revised

13. L169: What is “our definition”? Is the WMO definition yours?

The term “our definition” was meant as “the one we use”. We describe the definition in the methods section and refer to that in the previous sentence. It is based on Rao et al. (2022) for minor warmings, and the WMO criterion, as described in Charlton and Polvani (2007), for major warmings. We revised the sentence and don’t use the term “our definition” anymore.

14. Figure 4 and 5: The nSSW also show negative SAM pattern in the near surface. The negative SAM also propagates downward into the near surface. Please check it again.

The warming in the stratosphere is also for nSSWs connected with an anomaly in the SAM. The downward propagation is still happening, but it is weaker. It is also not as well connected to the surface. To distinguish between nSSWs and dSSWs – thresholds were defined according to Karpechko et al. (2017). We show the method works very well as surface signals for nSSWs are not perfectly resembling the annular mode nor are they statistically significant.

15. References should include Feng et al. 2025 Rao et al. 2020

Our results are based on OND mean values. These are best comparable to the Lim studies, while Rao et al. and Feng et al. considered different response periods. However, we include those references in the introduction now. See earlier responses.

16. L192: The frequency is much higher than in ERA5. Can you give some discussion on the uncertainty of this study.

As discussed in the manuscript (original lines: 170-172), the observed frequency falls within the spread between single ensemble members (ranging between 0 and 7 warmings between 1980-2019). That does not mean, of course, that the modeled frequency is resembling the truth. The larger variability in our model could lead to an overestimation of the SSW frequency. Nevertheless, FOCI is among well-performing models in this aspect, and the focus of our study is rather on **relative** changes in SSW frequency compared to the model's present day. We discuss this now in the manuscript. See our answer to your major comment 2.

17. Figure 6: nSSW shows opposite sign to the dSSW. The results are unstable for those experiments. Why show the composite in Oct-Dec. Usually just show the composite relative to the SSW onset.

The response to nSSWs is not significant. There are only 5 nSSWs included in that composite and the lack of the stratospheric forcing makes those years less stable as you put it. But that is expected. It is true that we could have composited everything with respect to the onset days. This was a choice we made early in the analysis process to compare our results with the studies from Lim et al.

18. L210: The negative SAM is missing. However, the positive SAM is evidently shown. What happens?

We don’t see a positive SAM response for nSSWs. Largely, we don’t see any statistically significant response for nSSWs at the surface. This is due to the definition of nSSWs.

19. L213, 218: The frequency is too high in my understanding.

It is possible that our model overestimates the frequency – however, it is still very well performing in this aspect, and the focus of our study is rather on **relative** changes in SSW frequency compared to the model's present day. We do not attempt to predict future SSW frequency. This study wants to highlight that the changing background conditions at intermediate warming (CO₂) levels do still allow for the occurrence of SSWs in the SH in the coming decades. We discuss this issue now in the paper. See also your major comment 2.

20. Figure 8: For 1.5, 2, 3 K experiments, the composite is downward propagation SSW pattern. For 4 K experiment, the composite is nondownward propagation SSW pattern. Looks so weird.

Yes, we find that the connection between the stratosphere and the troposphere decreases drastically at 4 K warming. The 4 K composites includes 9 dSSW and 5 nSSW events.

21. Figure 9: Show the same question as in Figure 6. The composite for 4K is illusive.

See answer on Figure 6

22. L250: Values are not small.

They are not small per se but they are insignificant.

23. L261-262, 268-269: Does you model include those processes?

Yes, we prescribe GHGs as well as ozone changes. Both influence the radiative balance in the model.

24. L278: CMIP5/6 diverges on the SSW frequency changes. Please see Rao and Garfinkel 2021a, 2021b

Looking into Rao and Garfinkel (2021a,b), we find that CMIP5 and 6 models agree on the delay of final warmings, especially in the SH; and we find that there is a discrepancy between CMIP5 and 6 models concerning the increase /decrease in SSW frequency in the NH. The NH polar vortex, however, behaves different compared to the SH polar vortex. A conclusion on SSWs in the SH can't be drawn from these papers.

25. L287: Both Jucker and this study give an overestimate of the SSW frequency in models.

We include that issue in the manuscript now, especially in lines 206-212. Nevertheless, our model is performing well in this aspect, and the focus of our study is rather on relative changes in SSW frequency compared to the model's present day

Reviewer 2

Review for the submitted paper "Southern Hemisphere Sudden Stratospheric Warmings Continue to Be Relevant Under Global Warming» by Bischof et al

This paper investigates the role of Major and Minor Sudden Stratospheric Warmings (SSWs) in the Southern Hemisphere (SH) stratosphere on the surface climate during historical, present-day and future global warming levels.

For this an atmospheric general circulation model is used and set-up with prescribed forcing for Greenhouse gases, ozone, solar, land use, sea surface temperature and sea ice conditions. The paper includes interesting new aspects with respect to SSWs in the SH during a future warmer climate. However, the manuscript includes some significant shortcomings as further described below. If these can be adequately addressed the manuscript may be publishable.

General comments:

1. The introduction needs to be substantially revised to include the state of knowledge of Sudden Stratospheric Warmings in the Southern Hemisphere (see AMS JAS special issue in 2005, PREFACE in: Journal of the Atmospheric Sciences Volume 62 Issue 3 (2005); Baldwin et al 2021 SSW Reviews of Geophys, and other key papers listed below). The authors/manuscript need to give credits to original references for SSWs in general and for Southern Hemispheric once. Both major and minor SSWs need to be introduced. More minor SSWs occurred in the SH which are not mentioned in the introduction nor in the rest of the paper. This needs to be also taken up in the results, discussion and conclusions of the paper. See further details below.

Major SSWs are frequently observed in the Northern Hemisphere stratosphere since their discovery in 1952 (Scherhag, 1952) with major events occurring every 2-3 years (i.e., Labitzke and van Loon 1999; Labitzke and Naujokat 2000

http://www.atmosp.physics.utoronto.ca/SPARC/News15/15_Labitzke.html; Baldwin et al 2021). In contrast, only one major SSW was observed in the SH since regular monitoring of the stratosphere began with the International Geophysical Year in 1957 (Naujokat and Roscoe 2005; Simmons et al 2005; AMS JAS special issue on the major SSW in 2002 in the SH). However, minor SSWs which are defined with a rapid warming of the polar stratosphere within a couple of days reversal can occur several times per winter in the NH stratosphere and occasionally in the SH mid-winter as well.

Minor and Major SSWs in the SH (list may not be complete; AMS JAS special issue 2005 and add ons):

-September 1956 (Godson 1963; Naujokat and Roscoe 2005), → (Naujokat and Roscoe, 2005)

-July 1957 (Labitzke and van Loon 1965),

-July/August 1963 (Quiroz 1966; Julian 1967),

-August 1964 (Phillpot 1969),

-September 1967 (Phillpot 1969),

-July 1974 (Barnett 1974; Al-Ajmi et al. 1985), → (Barnett, 1975)

-August/September 1988 (Kanzawa and Kawaguchi, 1990; Hirota et al. 1990),

(-1991? and Sept 1992? (i.e., Poberaj et al 2011 JAS; Newman and Nash 2005 JAS) - minor SSWs?)
(Newman and Nash, 2005)

-September 2002 major SSW (AMS JAS special issue in 2005)

-September 2019 minor SSW (Liu et al 2022).

Thank you very much for this comment and the literature research. We realize that we should have given more emphasize to the description of SSWs in general. We include more background information on major and minor warmings now, including the most important and original papers by Scherhag, Labitzke and others. We also include the minor events that were observed. There were two minor warmings observed in 1988, that we missed upon (Schoeberl et al., 1989; Hirota et al., 1990; Kanzawa and Kawaguchi, 1990). In the study of Roy et al. (2022) a summary on the early research on stratospheric warmings in the SH is given. However, the 1988 events are the only stratospheric warming events that were observed prior to 2002. We added these now to the introduction as well and highlight the study of Roy et al. (2022) for more details on early work. More recently, in 2024, 2 minor warming events, although much weaker than the one in 2019, were observed (Zi et al., 2025). This information is now added to our manuscript as well.

2. The manuscript stays rather descriptive and misses physical and synoptical explanations, f.e., why the different changes for the surface response during different warming levels? How are the surface changes connected to synoptic patterns in the SH? What about the timing of ozone recovery versus the GHG increase impacts in relation to stratospheric temperature and wind and surface climate responses?

A detailed description of individual events is (far) beyond the scope of this study. We discuss composite (average) responses to SSWs as also done in other publications to describe a general surface response that is likely to occur in SSW years on the SH. We comment on this issue in the methods section now (lines 167-169). However, the physical mechanism for the impact of SSWs on the surface is essentially due to a shift in the southern hemispheric jet (line 61). We extend upon the description of the mechanism a bit and cite Zheng et al. (2014) for a more thorough description of the tropospheric response to the SAM. (lines: 61 and following)

3. The authors seem to imply that the readers know their mentioned references already (f.e., Rao et al 2022 among others) and therefore understand their results presented here, for example on surface responses (Figures 5-6, 8-9). This could be improved i) by providing the basic facts and ii) by adding more clarifying panels to the figures as described below.

Thank you for this comment – we expanded on the description of the cited results and answer your comments on the figure captions below. We clarified which data is shown and added time periods when applicable. We don't want to add the number of years or events to each panel, but refer the reader to Table 1 (which includes all the information) in the figure captions now and refer to Table 1 more often in the text (e.g., lines: 155, 178, 197, ...).

4. For the model validation of SH major and minor SSWs more ERA5 data/graphics need to be added to i) validate the model and ii) for a better understanding; see detailed comments below.

We include additional figures in the supplement (new Supplementary Figure S1) now and refer more closely to already published studies that prove the capability of the model to represent stratospheric dynamics (lines 207-212). We give more detailed answers for the specific comments below.

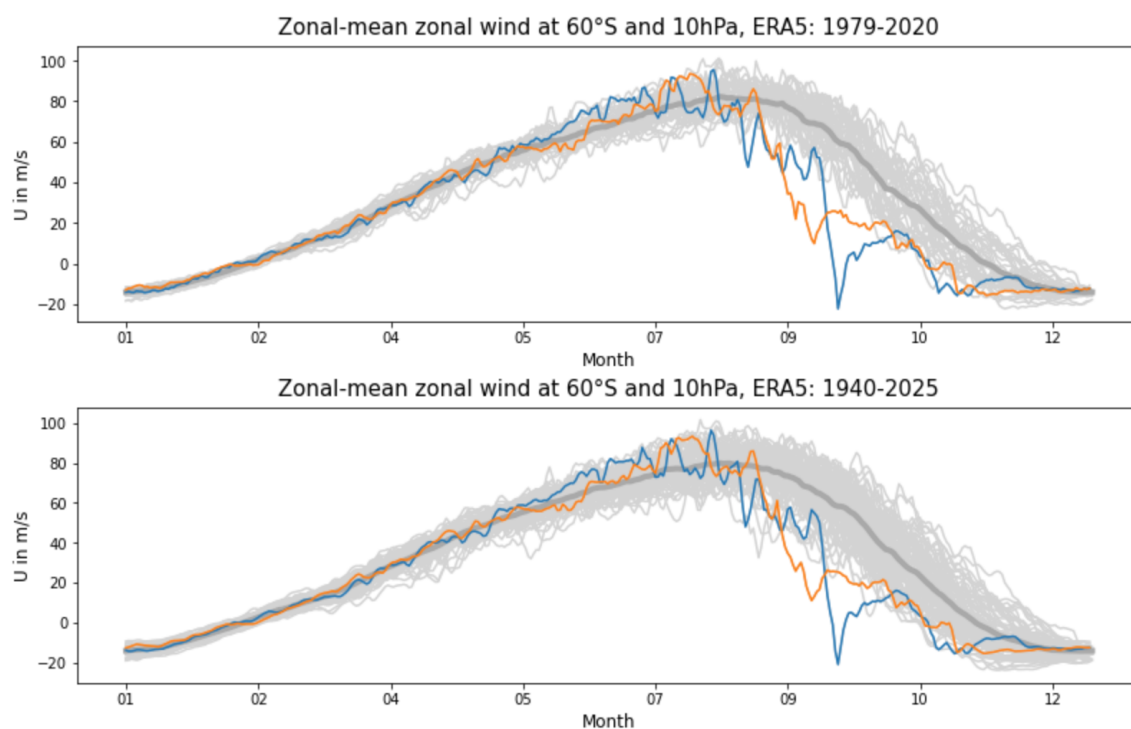
5. A discussion of the results is missing and would be very helpful for the readers including, f.e, model validation, model biases, physical reasons for the stratospheric and surface response changes during the different global warming-ozone recovery levels, synoptic details, SH dynamics of SSWs, and the relevance of SH SSWs given that their occurrences is so rare.

We revised the discussion and added a section on the effect of ozone recovery. We refer the referee to the updated manuscript, starting in line 301, and to the answers to the specific comments below.

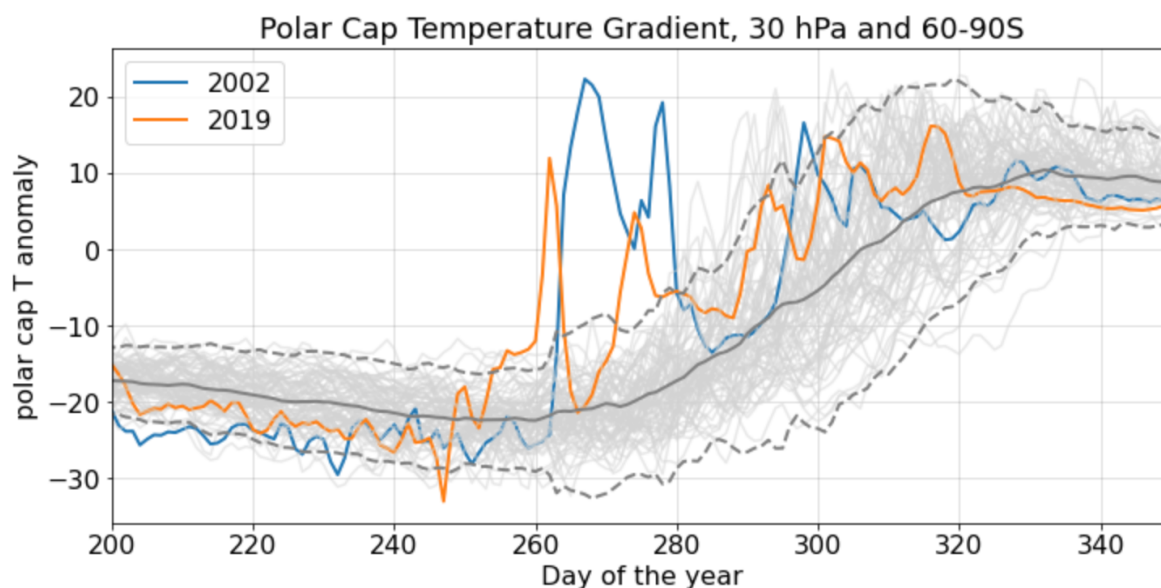
Specific comments:

-Introduction: Add minor SSW definition(s). The occurrence and frequency of minor SSWs in the SH need to be corrected and earlier events shall be added.

As mentioned in our answer to your general comment, we revised the introduction accordingly. Some more analysis on stratospheric warmings follows here. Even after thorough literature research, additional minor SSW events, seem to only have occurred in 1988 (see response to major point one). Since the ERA5 data is available for 1940 to 2025 now, we use this extended period to quickly check on which events we find based on different definitions. We include an additional figure here to show that there were no other years within that period that met the criterion we chose in our study.



Since the original definition of minor warmings is based on the temperature gradient between 90° and 60° latitude, we include a figure of the polar cap temperature gradient at 30 hPa below. Colored are all years in which the gradient turns positive before October (to exclude early Final Warmings). The only warmings that show up are the 2002 and the 2019 warming. They are clearly exceptional.



-Method: How can the model surface climate response be used in the results if the SST and sea ice fields are forced? Pls comment and discuss the limitations.

The prescribed SSTs and sea ice fields ensure that the response we see is solely due to the atmospheric forcing. Potential impacts of the lower boundary (ocean and land) are the same every year – variability between the years is therefore only due to atmospheric variability. Since we don't look into ocean-atmosphere coupling, this method is very valuable, enabling a large sample size for different warming levels with reduced impacts of ocean and sea ice variability.

-Table 1: -Which period is used for ERA5? ERA5 data exists from the 1940s. -When were the “X”K levels reached and how does this relate to the ozone recovery and GHG levels? Pls add the details and discuss this point.

We revised the section of the methods in which we describe the experimental setup to clarify (starting in line 133). We now also include the respective CO₂ mixing ratios and refer to new Supplementary Fig. S2 (previously S7) for the SH polar cap ozone levels. We use ERA5 data only from 1980 to 2019 to compare to the period that was simulated in our historical simulations. We point to that in the header of table 1.

-Lines 135-136: Below a criterion is introduced which is different than here, pls clarify.

We revised the description of the method for clarification (lines 151-161).

-Lines 138-140: Here a minor SSW criterion for the SH is mentioned following Rao et al (2022). How does this 20 m/s threshold-criteria compare with the original minor SSW criteria (WMO criteria, AMS JAS SH major SSW 2002 special issue) with a sudden warming in the polar stratosphere used in earlier papers for the SH? This needs explanations and careful revision.

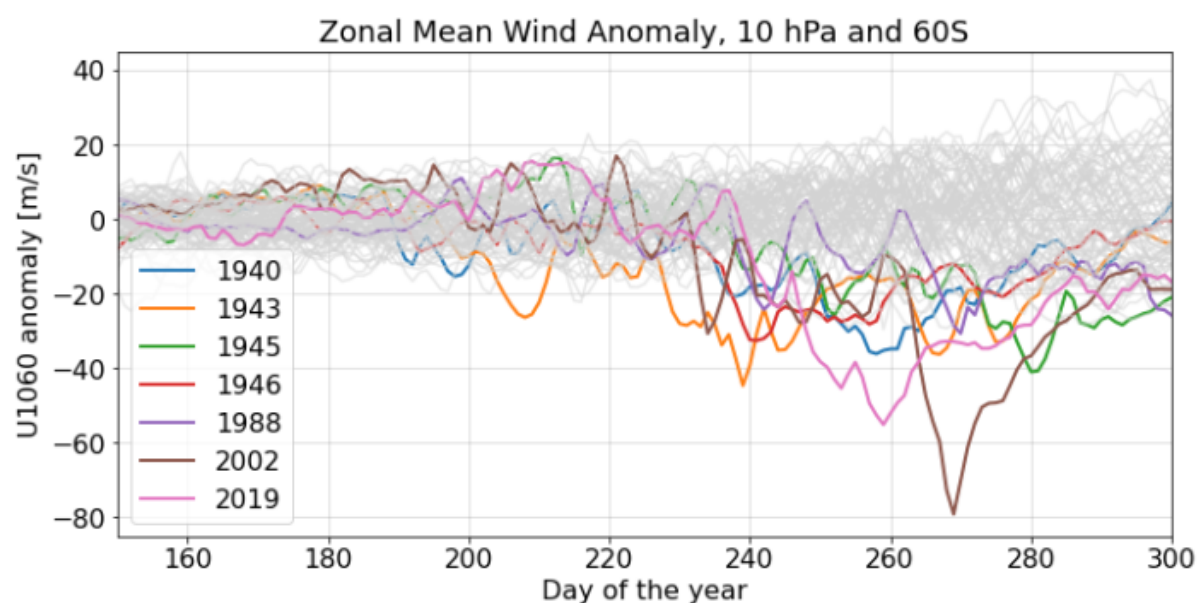
See our response to specific comment 1: both criteria result in the detection of the same events in ERA5 data. We include these figures in the supplement now (new Supplementary Figure S1) and refer to them in the lines: 94 and 162-164.

-Figure 1: Which period is shown for ERA5? Pls add number of winters in both panels. Add panels to show the polar warming as well either with T_{90S} or T_{90S-60S} at 10, 30, or 50 hPa. Add more years for ERA5 (before 1980) to show the other minor SSWs in the SH (see list above) as well.

The number of years (and winters) is included in Table 1. We also mention that in the caption now and in the header of Table 1.

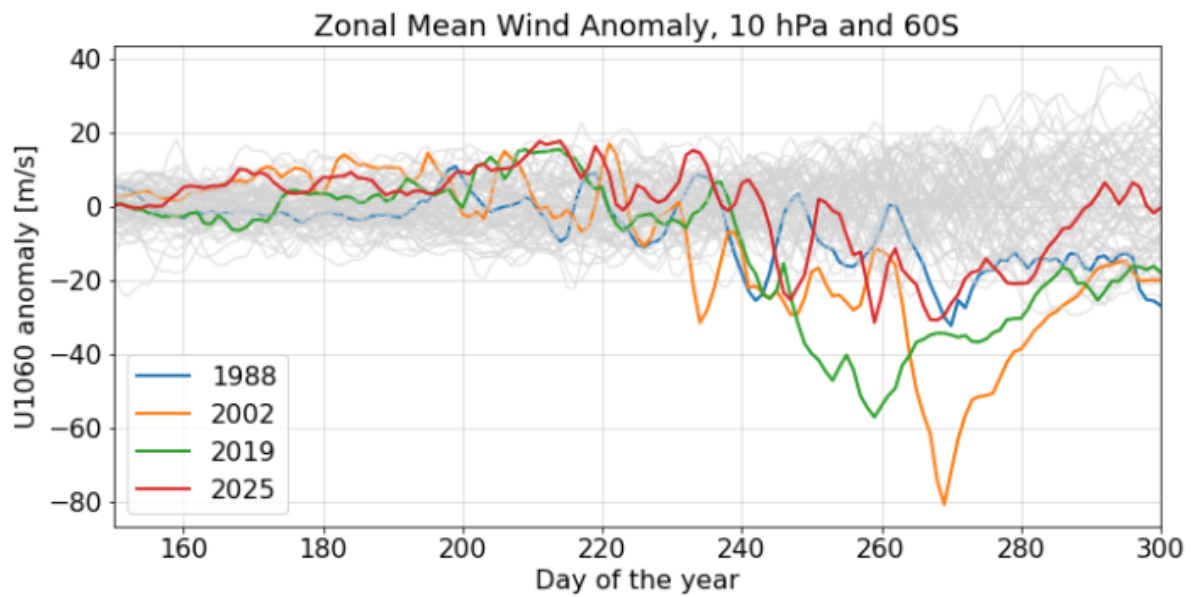
We include the polar cap temperature gradient and an extended period for the ERA5 data in the supplementary material now (new Supplementary Figure S1). We think this is sufficient to show that the definition that we used captures the important stratospheric warmings. To dig a bit deeper into the other events we include some additional figures here.

Using a criterion that is not based on the absolute wind but zonal mean wind anomalies (calculated over the whole period – 1940 to 2025) of -30 m/s results in the following event detection:

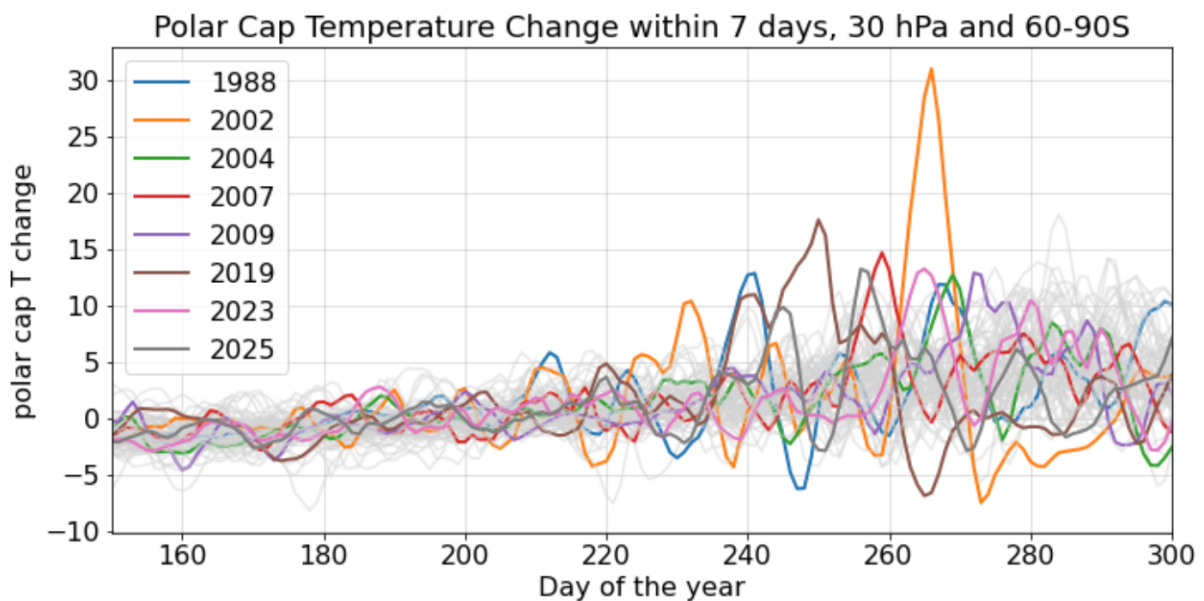


Although it is interesting to see the additional events in the 1940s, ERA5 data is not well constrained during that period and prove of the actual occurrence of these minor warmings is lacking. However, year 1988 pops out additionally. We include that event now in the introduction although it was definitely weaker than the 2002 and 2019 events.

Starting in 1950 (slightly changing the climatology) reveals that in 2025, the zonal mean zonal wind was also very weak, with an anomaly of comparable magnitude as in 1988.



Since the original definition of minor warmings is based on the polar cap temperatures, we include the polar cap (60 – 90°S) temperature at 30 hPa here additionally. The following figure is based on ERA5 data from 1950 – 2025. It shows the cumulative polar cap temperature change for a running 7-day period, following (Butler et al., 2015). We colored all years that exceeded a threshold of 12 K. The 12 K were chosen to capture the 1988 warming. When using this threshold, a few more weak warmings are detected. These occur predominantly after the year 2002. The published warmings in 2024 were not detected.



In our study, we focus on events that have a potential impact on the surface. This impact was shown for the 2002 event as well as for the 2019 event. Weaker events were not reported to impact the surface significantly. We therefore stick to the definition that is based on the Rao et al. 2022 paper.

-Figure 2: Add 2002 and 2019 as well to show the detailed evolution in comparison. What is shown model or ERA5 data? How many cases?

As stated in the caption, the figure shows the data from the historical ensemble. We include the word “model” now to make it clearer that model data is shown. Table 1 indicates the number of events, which is 17 in this

case. Since we don't investigate single event dynamics, we didn't include ERA5 data here. We think it is sufficient to refer to previous papers for the comparison to observations or reanalysis since this has been done in detail before.

-Line177: Here the 20 m/s (at 60S, 10hPa) "Rao2022" criterion is used for both major and minor SSWs. Why is it different here compared to the one above?

The criterion is not different. Major events are detected when the zonal mean wind at 10hPa and 60S changes from westerly to easterly. However, to composite all events together in one figure we decided to use the 20 m/s criterion for the central day. This makes comparison across events easier. We added a sentence on that decision in the methods section (line 168).

-Figure 3: What is shown: model or ERA5? If the first, show ERA5 data and climatology as contours as well. What is different to Fig. 6a right?

It is as for Figure 2 specified in the figure caption that the historical ensemble is used – hence the model data. We refer to our answer to your comments on Figure 2 here too.

In Figure 6a the present-day model experiment is shown whereas in Figure 3 the historical model experiment is shown. The historical model experiment is used for comparison against ERA5 data, whereas the present-day time slice is used to show that it compares well to the historical setup (therefore the time slice setup can be used in the global warming framework) and to introduce the concept of dSSWs vs nSSWs. At the same time, it is one of the different warming level experiments and the starting point for the upcoming analysis for increased warming levels.

-Figure 4: Which period and data are shown? How many cases? For the nSSWs composite, why is there a similar downward propagating pattern with negative anomalies in the troposphere between days 50-120?

Periods and data are summarized in Table 1. The caption that specifies the experiment considered in this figure was updated. nSSWs are defined following the criteria from Karpechko et al. 2017, given in lines following line 174. All three criteria have to be fulfilled to be classified as a dSSW. All other events are classified as a nSSW. Although the stratospheric SAM is significantly negative in the beginning and some downward propagation is visible for nSSWs in Figure 4, the connection to the surface is missing. The negative anomaly that occurs in the troposphere after day 50 is not significant (no hatching).

-Lines 183-187: Connection to the synoptic situation? Why?

As mentioned above, we do not consider single events, and therefore do not describe synoptic situations here. The high pressure anomaly is a result of the stratospheric anomaly that is propagating downward and impacting the surface with a certain lag in time as shown in Fig. 2a. The surface SLP anomaly is associated with an equatorward shift of the tropospheric jet (as described in the introduction), which is typical for a negative SAM anomaly. This leads to a shift in mean weather patterns and therefore also temperature and precipitation as shown in the following figures.

-Figure 5: Which period, how many cases?

See above

-Figure 6: Which period, how many cases? Add ERA5 data for 2002 and 2019 as well. Why the difference in the anomaly patterns for the three composites? What is different for the nSSW composite compared for the other two once in terms of synoptic evolution?

In lines 242-250, we describe the behavior of the different SSW categories. In the case of nSSWs, no effect of the stratospheric anomaly reaches the surface. Hence, there is no significant surface response for nSSWs. dSSWs, those SSWs that lead to significant surface responses, show the largest surface responses. When considering a composite of dSSWs together with nSSWs, the response of dSSWs dominates the signal.

-Table 2 & Fig 7: Add ERA5 in Table 2 as well. Why 0.44 in the 2K case; what is different here? Fig. 7: Are all SSWs (which criteria?) shown? Why the different evolution of SSWs onsets? Relate to > ozone recovery, GHG level, synoptics... > and discuss. This is interesting. Add the number of SSWs in the figure.

We didn't add ERA5 data in Table 2 since it is based on a record of only 40 years to be comparable to the period of our historical experiment. Based on that period it would be 0.25 dSSWs and 0.25 nSSWs per decade. This is lower than in our model simulations – shown also in Table 1. However, the main scope of the manuscript (and of Table 2) is to estimate how the occurrence of SSWs might change in the future. A comparison to ERA5 data in Table 2 is therefore not intended.

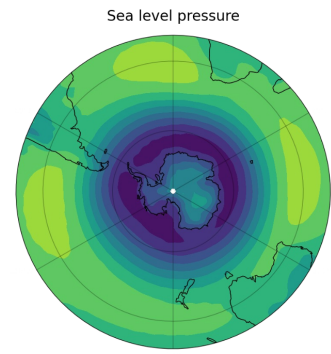
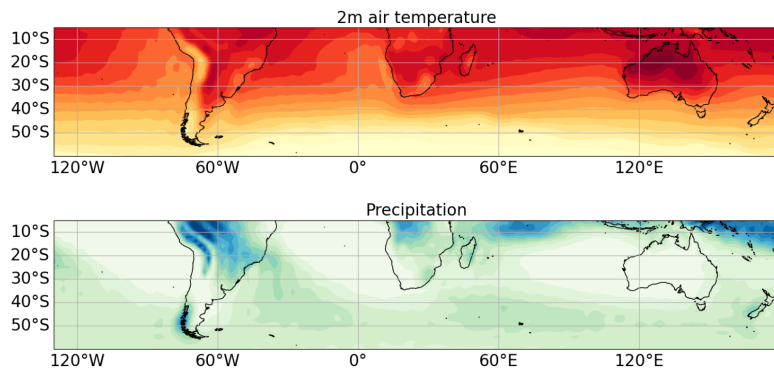
For Figure 7, we included the information on the criterion in the caption now (sorry for missing out on that earlier). We also include the timing for the 2002 and 2019 events based on ERA5 data in the caption now.

It is indeed interesting that the 2K warming case does not really seem to fit perfectly. It has a larger number of nSSWs, while still showing a strong surface response. This might be due to the different timing of the events – that is why we included the boxplot with the SSW onset days. The majority of nSSWs in the 2K warmer climate occurs late in the year (Supplementary Fig. S4). It is not clear to us why there is this enhanced occurrence of nSSWs. While the ozone recovery is impacting the state of the vortex, the difference to the 1.5 K warming event is not very large (Figure 10). We discuss the behavior of the 2K experiment at the end of the results section (section 3.4, lines 326-331) and include it also in the conclusion now (lines 364-369).

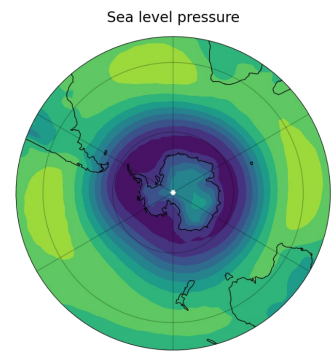
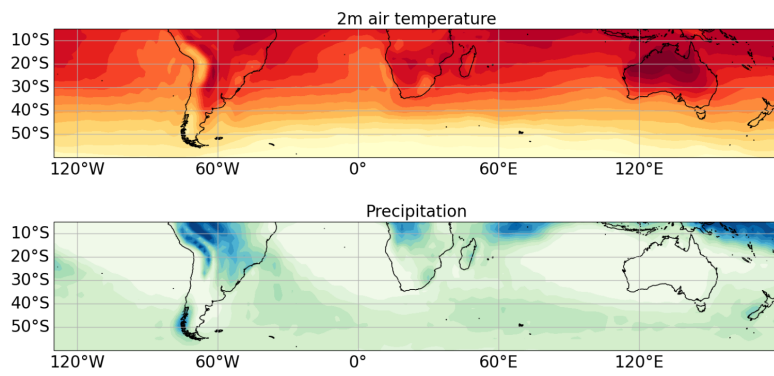
-Fig. 9: Interesting to see this. Are the surface impacts in the SH depending on ENSO? Add to the discussion. Add climatology as contours (also for the other figures or add climatologies in the supplement).

Climatology figures for the OND season are now included in the supplement (Supplementary Fig. 3). We include the figures here as well for convenience.

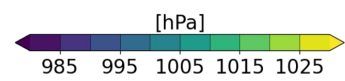
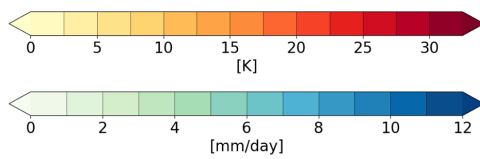
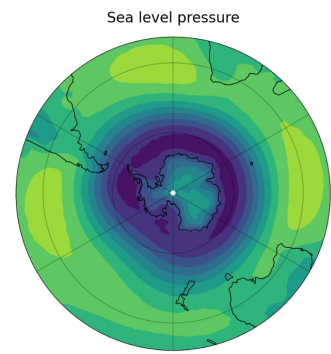
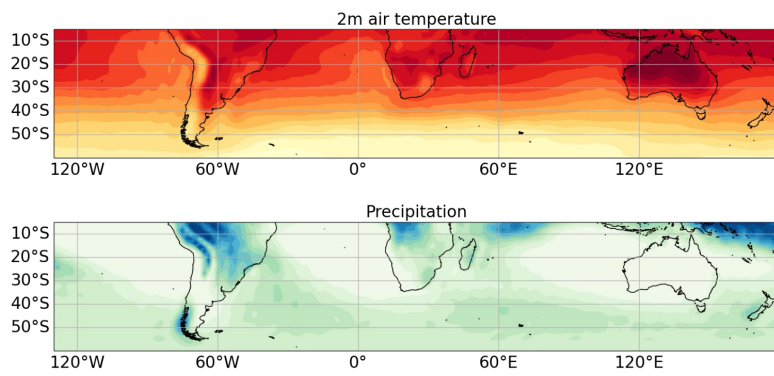
Historical

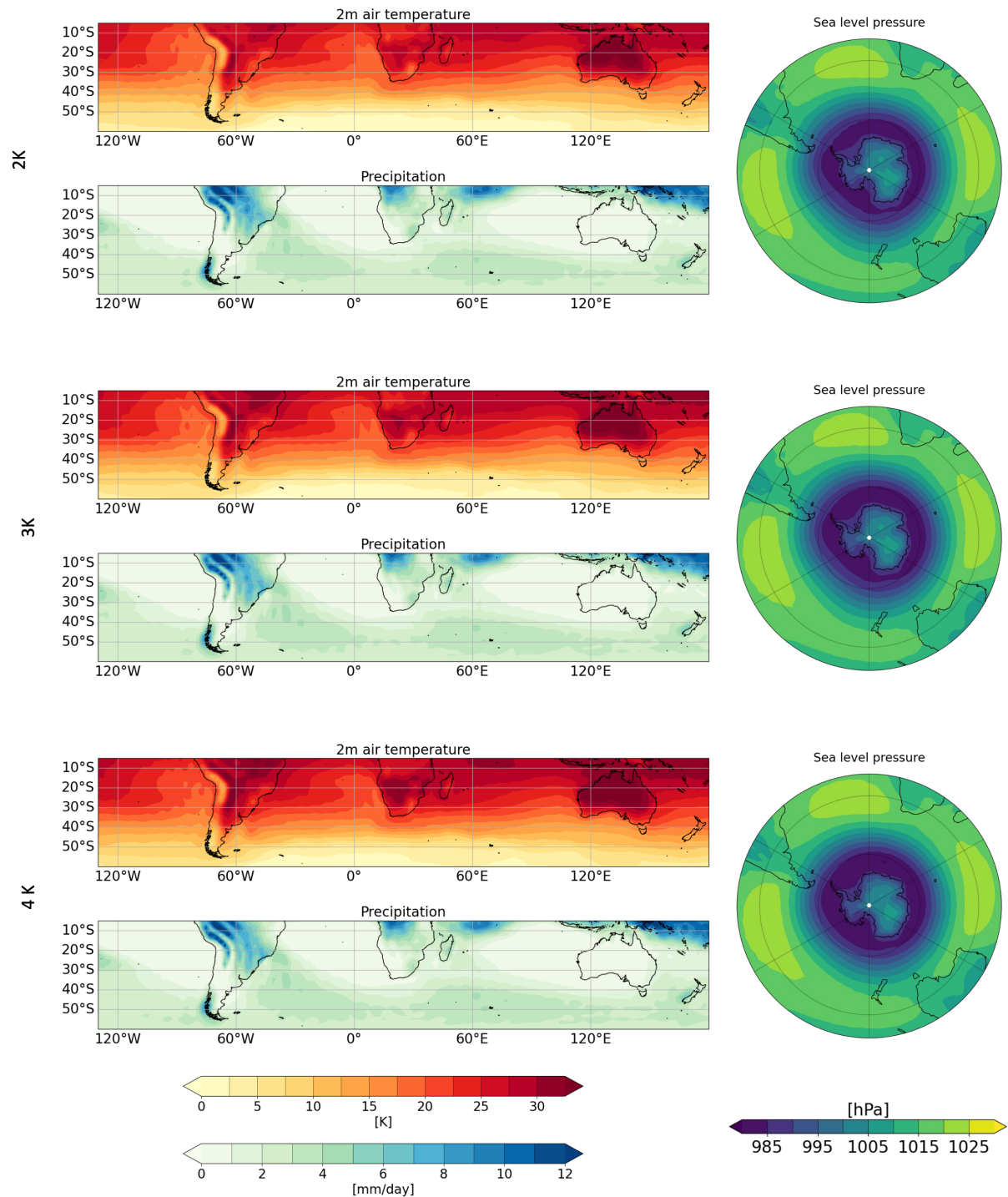


Present-Day



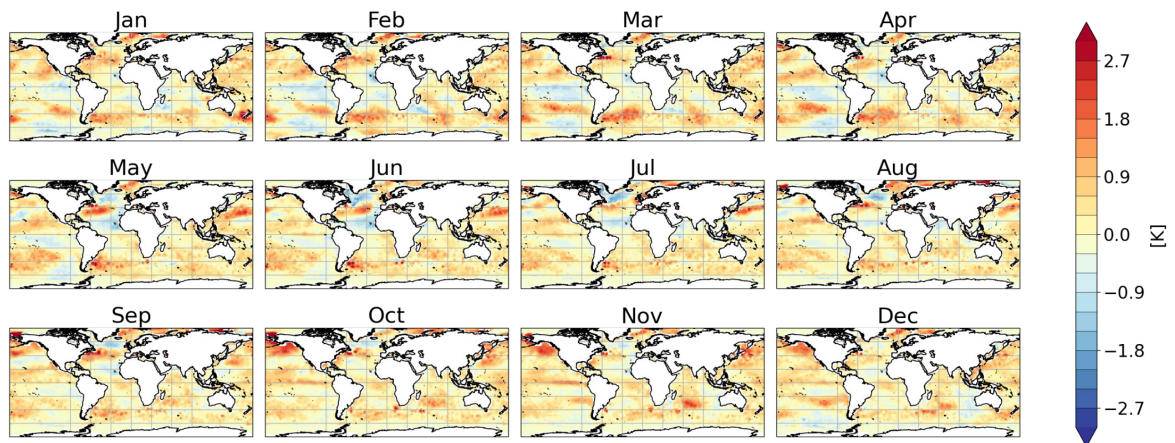
1.5 K



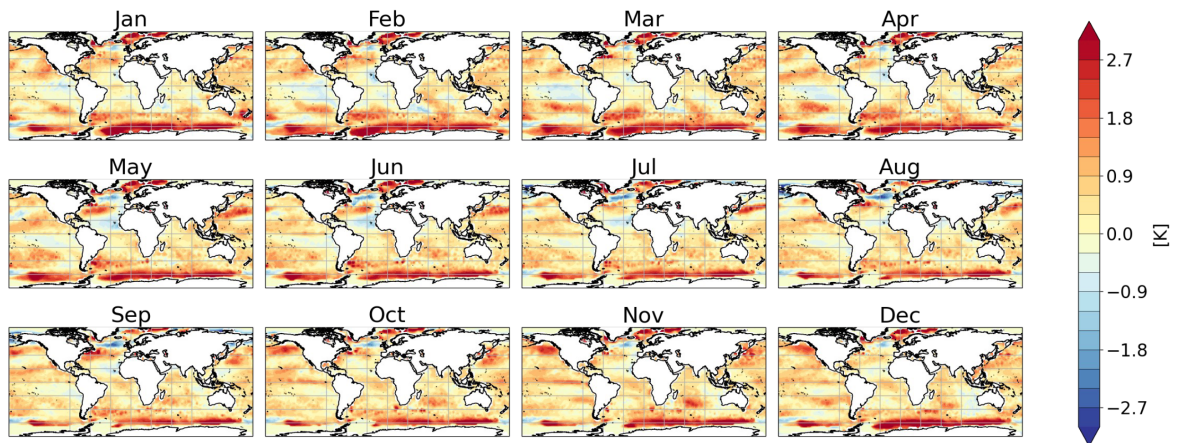


ENSO does not play a role since there is no interannual variability in the SST forcing and anomalies are calculated based on the whole time periods of the respective experiments. The 2018 SST field that was used as a base forcing, was not characterized by anomalous ENSO conditions (see figure below). The warming pattern itself, is not dominated by ENSO either (see figure below). There is a strong warming of the Southern Ocean, but that is consistent across the different warming thresholds. We attach the SST anomaly fields (anomalies with respect to 1980-2019) here for reference.

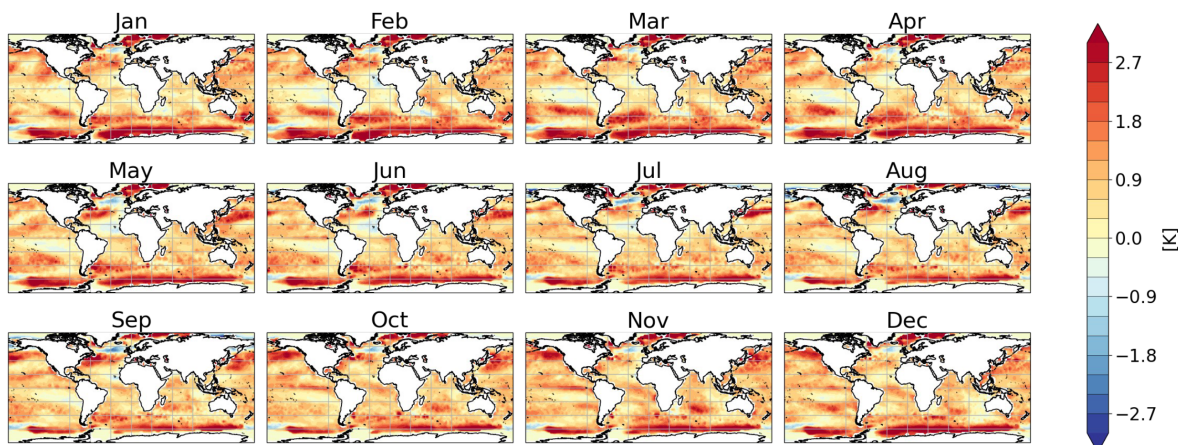
2018



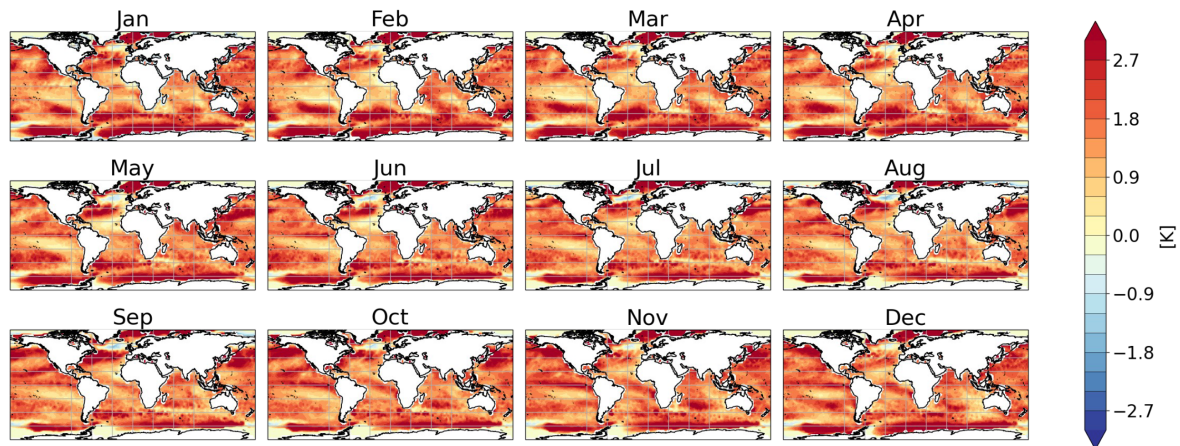
1.5 K GW



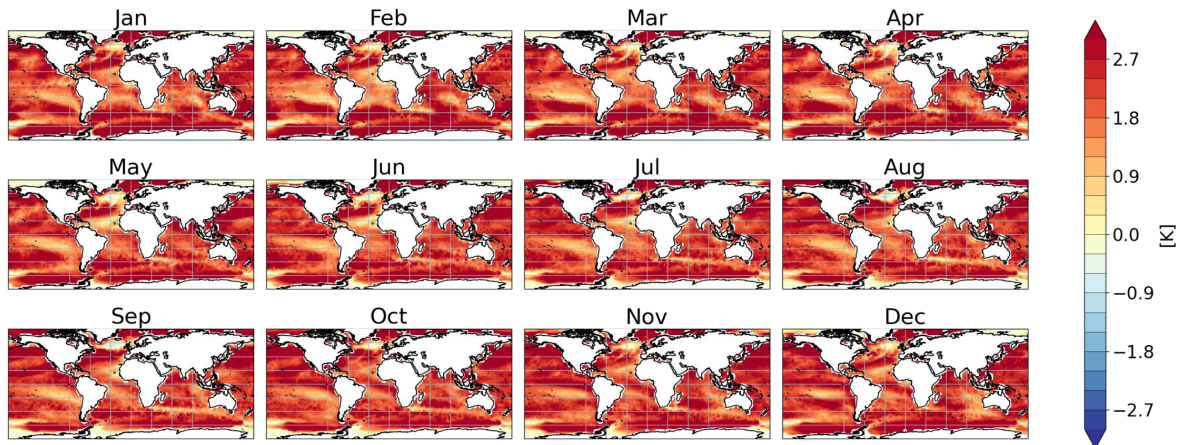
2 K GW



3 K GW



4 K GW



-Line 220; “find a higher frequency of nSSWs”. Why?

See answer above. We include a sentence here now stating: “This non-linearity might be due the interplay between ozone recovery and GHG increase, which will be discussed later.”

-Line 240: “impact by SH SSW is South Africa” Why and how? Also occurring in reanalyses /observations?

Sorry, that we missed upon including a reference to the observed response here. South African climate variability has indeed been described – however mostly for the response to tropospheric SAM anomalies. As well as for the Australian response the reason for the changes in South African summer conditions is due to changes in the position of the jet stream. We now include: “A similar behavior in temperature and precipitation was found by Lim et al. (2021) following the 2019 minor SSW event. Gillett et al. (2006), who regressed the SAM index onto station measurements of 2 m air temperature and precipitation, also found a significant precipitation deficit in South Africa for negative SAM conditions, while not detecting a significant temperature response in that region.”

Add Discussion: -ozone recovery-GHG level timings, any QBO and ENSO impacts?

We separated the last paragraph of the results to highlight the discussion on the GHG and ozone recovery impacts on the mean vortex states and added more to the discussion. We included the non-linear behavior in that new paragraph too. The QBO is internally generated. We didn't check for differences in the QBO across the different warming levels. This might actually have an influence on the strength of the polar vortex during spring and the timing of final warming (Anstey et al., 2022). However, the polar cap temperature means seem to be dominated by GHG and ozone forcing. An analysis of the QBO is out of scope for this publication. We commented on ENSO above. ENSO is included in the methods and discussion now. The QBO is mentioned as a possible contributor in the discussion as well.

Conclusion:

-I would add a validation of the model here as well.

We include that in the methods part and simply state the model captures the observed surface to SSWs. We reordered paragraphs in the conclusion section to address this earlier.

-Decrease of SSWs in 4K global warming levels. Why and when does it happen? > any link to the ozone recovery timing?

This is discussed now in more detail in section 3.4.

-Lines 284-286: No significant surface response for the 4K global warming level versus the 3K one. Why are they different? > any link to the ozone recovery timing?

The missing surface response hints to a decrease in STC under high global warming levels. Further analysis, maybe different experiments, would be needed to better understand the underlying reasons for that. We include a statement on that issue in lines 323-325.

-Lines 310-311: Show the ozone recovery and GHG levels timings together with the modelled changes of the SSWs responses to discuss and conclude this aspect.

We refer the reader to Figure 10 and Supplementary Figure S2 on this aspect.

Refs:

-Line 314: Pls clarify if Garden 2022 is a Bachelor or a PhD thesis. See also reference in line 349.

Thanks for pointing that out. This information is corrected in the bibliography now.

Anstey, J.A., Simpson, I.R., Richter, J.H., Naoe, H., Taguchi, M., Serva, F., Gray, L.J., Butchart, N., Hamilton, K., Osprey, S., Bellprat, O., Braesicke, P., Bushell, A.C., Cagnazzo, C., Chen, C., Chun, H., Garcia, R.R., Holt, L., Kawatani, Y., Kerzenmacher, T., Kim, Y., Lott, F., McLandress, C., Scinocca, J., Stockdale, T.N., Versick,

- S., Watanabe, S., Yoshida, K., Yukimoto, S., 2022. Teleconnections of the Quasi-Biennial Oscillation in a multi-model ensemble of QBO-resolving models. *Q. J. R. Meteorol. Soc.* 148, 1568–1592. <https://doi.org/10.1002/qj.4048>
- Barnett, J.J., 1975. Large sudden warming in the Southern Hemisphere. *Nature* 255, 84–87.
- Butler, A.H., Seidel, D.J., Hardiman, S.C., Butchart, N., Birner, T., Match, A., 2015. Defining Sudden Stratospheric Warmings. *Bull. Am. Meteorol. Soc.* 96, 1913–1928. <https://doi.org/10.1175/BAMS-D-13-00173.1>
- Charlton, A.J., Polvani, L.M., 2007. A New Look at Stratospheric Sudden Warmings. Part I: Climatology and Modeling Benchmarks. *J. Clim.* 20, 449–469. <https://doi.org/10.1175/JCLI3996.1>
- Charlton, A.J., Polvani, L.M., Perlwitz, J., Sassi, F., Manzini, E., Shibata, K., Pawson, S., Nielsen, J.E., Rind, D., 2007. A new look at stratospheric sudden warmings. Part II: Evaluation of numerical model simulations. *J. Clim.* 20, 470–488. <https://doi.org/10.1175/JCLI3994.1>
- Feng, K., Rao, J., Garfinkel, C.I., Butler, A.H., Jie, W., Wu, T., Hitchcock, P., Lim, E.-P., Dowdy, A.J., Seviour, W., 2025. Can stratospheric nudging improve surface predictability? Insights from the 2019 Southern Hemisphere sudden stratospheric warming. *Npj Clim. Atmos. Sci.* 8, 353. <https://doi.org/10.1038/s41612-025-01234-2>
- Gillett, N.P., Kell, T.D., Jones, P.D., 2006. Regional climate impacts of the Southern Annular Mode. *Geophys. Res. Lett.* 33, L23704. <https://doi.org/10.1029/2006GL027721>
- Hall, R.J., Mitchell, D.M., Seviour, W.J.M., Wright, C.J., 2022. How Well Are Sudden Stratospheric Warming Surface Impacts Captured in CMIP6 Climate Models? *J. Geophys. Res. Atmos.* 127, 1–16. <https://doi.org/10.1029/2021JD035725>
- Hirota, I., Kuroi, K., Shiotani, M., 1990. Midwinter warmings in the southern hemisphere stratosphere in 1988. *Q. J. R. Meteorol. Soc.* 116, 929–941. <https://doi.org/10.1002/qj.49711649407>
- Ivanciu, I., Matthes, K., Biastoch, A., Wahl, S., Harlaß, J., 2022a. Twenty-first-century Southern Hemisphere impacts of ozone recovery and climate change from the stratosphere to the ocean. *Weather Clim. Dyn.* 3, 139–171. <https://doi.org/10.5194/wcd-3-139-2022>
- Ivanciu, I., Matthes, K., Wahl, S., Harlaß, J., Biastoch, A., 2021. Effects of prescribed CMIP6 ozone on simulating the Southern Hemisphere atmospheric circulation response to ozone depletion. *Atmos. Chem. Phys.* 21, 5777–5806. <https://doi.org/10.5194/acp-21-5777-2021>
- Ivanciu, I., Ndarana, T., Matthes, K., Wahl, S., 2022b. On the Ridging of the South Atlantic Anticyclone Over South Africa: The Impact of Rossby Wave Breaking and of Climate Change. *Geophys. Res. Lett.* 49. <https://doi.org/10.1029/2022GL099607>
- Kanzawa, H., Kawaguchi, S., 1990. Large stratospheric sudden warming in Antarctic late winter and shallow ozone hole in 1988. *Geophys. Res. Lett.* 17, 77–80. <https://doi.org/10.1029/GL017i001p00077>
- Karpechko, A.Yu., Hitchcock, P., Peters, D.H.W.W., Schneidereit, A., 2017. Predictability of downward propagation of major sudden stratospheric warmings. *Q. J. R. Meteorol. Soc.* 143, 1459–1470. <https://doi.org/10.1002/qj.3017>
- Kwon, H., Choi, H., Kim, B.-M., Kim, S.-W., Kim, S.-J., 2020. Recent weakening of the southern stratospheric polar vortex and its impact on the surface climate over Antarctica. *Environ. Res. Lett.* 15, 094072. <https://doi.org/10.1088/1748-9326/ab9d3d>
- Lim, E.-P., Hendon, H.H., Butler, A.H., Garreaud, R.D., Polichtchouk, I., Shepherd, T.G., Scaife, A., Comer, R., Coy, L., Newman, P.A., Thompson, D.W.J., Nakamura, H., 2020. The 2019 Antarctic sudden stratospheric warming. *SPARC Newsl.* 10-undefined.
- Lim, E.-P., Hendon, H.H., Butler, A.H., Thompson, D.W.J., Lawrence, Z.D., Scaife, A.A., Shepherd, T.G., Polichtchouk, I., Nakamura, H., Kobayashi, C., Comer, R., Coy, L., Dowdy, A., Garreaud, R.D., Newman, P.A., Wang, G., 2021. The 2019 southern hemisphere stratospheric polar vortex weakening and its impacts. *Bull. Am. Meteorol. Soc.* 102, E1150–E1171. <https://doi.org/10.1175/BAMS-D-20-0112.1>
- Matthes, K., Biastoch, A., Wahl, S., Harlaß, J., Martin, T., Brücher, T., Drews, A., Ehlert, D., Getzlaff, K., Krüger, F., Rath, W., Scheinert, M., Schwarzkopf, F.U., Bayr, T., Schmidt, H., Park, W., 2020. The Flexible Ocean and Climate Infrastructure version 1 (FOCI1): mean state and variability. *Geosci. Model Dev.* 13, 2533–2568. <https://doi.org/10.5194/gmd-13-2533-2020>
- Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T., Esch, M., Fast, I., Fiedler, S., Fläschner, D., Gayler, V., Giorgetta, M., Goll, D.S., Haak, H., Hagemann, S., Hedemann, C., Hohenegger, C., Ilyina, T., Jahns, T., Jimenéz-de-la-Cuesta, D., Jungclaus, J., Kleinen, T., Kloster, S., Kracher, D., Kinne, S., Kleberg, D., Lasslop, G., Kornblueh, L., Marotzke, J., Matei, D., Meraner, K., Mikolajewicz, U., Modali, K., Möbis, B., Müller, W.A., Nabel, J.E.M.S., Nam, C.C.W., Notz, D., Nyawira, S., Paulsen, H., Peters, K., Pincus, R., Pohlmann, H., Pongratz, J., Popp, M., Raddatz, T.J., Rast, S., Redler, R., Reick, C.H., Rohrschneider, T., Schemann, V., Schmidt, H., Schnur, R., Schulzweida, U., Six, K.D., Stein, L., Stemmler, I., Stevens, B., Von Storch, J., Tian, F., Voigt, A., Vrese, P., Wieners, K.,

- Wilkenskjeld, S., Winkler, A., Roeckner, E., 2019. Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO₂. *J. Adv. Model. Earth Syst.* 11, 998–1038. <https://doi.org/10.1029/2018MS001400>
- Monnin, E., Kretschmer, M., Polichtchouk, I., 2022. The role of the timing of sudden stratospheric warmings for precipitation and temperature anomalies in Europe. *Int. J. Climatol.* 42, 3448–3462. <https://doi.org/10.1002/joc.7426>
- Naujokat, B., Roscoe, H.K., 2005. Evidence against an Antarctic Stratospheric Vortex Split during the Periods of Pre-IGY Temperature Measurements. *J. Atmos. Sci.* 62, 885–889. <https://doi.org/10.1175/JAS-3317.1>
- Newman, P.A., Nash, E.R., 2005. The Unusual Southern Hemisphere Stratosphere Winter of 2002. *J. Atmos. Sci.* 62, 614–628. <https://doi.org/10.1175/JAS-3323.1>
- Rao, J., Garfinkel, C.I., 2021a. CMIP5/6 models project little change in the statistical characteristics of sudden stratospheric warmings in the 21st century. *Environ. Res. Lett.* 16, 034024. <https://doi.org/10.1088/1748-9326/abd4fe>
- Rao, J., Garfinkel, C.I., 2021b. Projected changes of stratospheric final warmings in the Northern and Southern Hemispheres by CMIP5/6 models. *Clim. Dyn.* 56, 3353–3371. <https://doi.org/10.1007/s00382-021-05647-6>
- Rao, J., Garfinkel, C.I., Wu, T., Lu, Y., Chu, M., 2022. Mean State of the Northern Hemisphere Stratospheric Polar Vortex in Three Generations of CMIP Models. *J. Clim.* 35, 4603–4625. <https://doi.org/10.1175/JCLI-D-21-0694.1>
- Roy, R., Kuttippurath, J., Lefèvre, F., Raj, S., Kumar, P., 2022. The sudden stratospheric warming and chemical ozone loss in the Antarctic winter 2019: comparison with the winters of 1988 and 2002. *Theor. Appl. Climatol.* 149, 119–130. <https://doi.org/10.1007/s00704-022-04031-6>
- Safieddine, S., Bouillon, M., Paracho, A.C., Jumelet, J., Tencé, F., Pazmino, A., Goutail, F., Wespes, C., Bekki, S., Boynard, A., Hadji-Lazaro, J., Coheur, P.F., Hurtmans, D., Clerbaux, C., 2020. Antarctic Ozone Enhancement During the 2019 Sudden Stratospheric Warming Event. *Geophys. Res. Lett.* 47, 1–10. <https://doi.org/10.1029/2020GL087810>
- Schoeberl, M.R., Stolarski, R.S., Krueger, A.J., 1989. The 1988 Antarctic ozone depletion: Comparison with previous year depletions. *Geophys. Res. Lett.* 16, 377–380. <https://doi.org/10.1029/GL016i005p00377>
- Wu, Z., Reichler, T., 2020. Variations in the Frequency of Stratospheric Sudden Warmings in CMIP5 and CMIP6 and Possible Causes. *J. Clim.* 33, 10305–10320. <https://doi.org/10.1175/JCLI-D-20-0104.1>
- Xu, X., Martin, T., Beadling, R.L., Liu, J., Bischof, S., Hattermann, T., Huo, W., Li, Q., Marshall, J.C., Muilwijk, M., Pauling, A.G., Purich, A., Smith, I.J., Swart, N.C., Thomas, M., 2025. Robustness and Mechanisms of the Atmospheric Response Over the Southern Ocean to Idealized Freshwater Input Around Antarctica. *Geophys. Res. Lett.* 52, e2024GL113734. <https://doi.org/10.1029/2024GL113734>
- Zheng, F., Li, J., Liu, T., 2014. Some advances in studies of the climatic impacts of the Southern Hemisphere annular mode. *J. Meteorol. Res.* 28, 820–835. <https://doi.org/10.1007/s13351-014-4079-2>
- Zi, Y., Long, Z., Sheng, J., Lu, G., Perrie, W., Xiao, Z., 2025. The Sudden Stratospheric Warming Events in the Antarctic in 2024. *Geophys. Res. Lett.* 52. <https://doi.org/10.1029/2025gl115257>