nature portfolio

Peer Review File

Warmer Antarctic Summers in Recent Decades Linked to Earlier Stratospheric Final Warming Occurrences

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

15th Jun 23

Dear Dr Kim,

Your manuscript titled "Earlier Stratospheric Final Warming Has Caused Warmer Antarctic Summers in Recent Decades" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. Specifically, in order for publication in Communications Earth & Environment to be appropriate, we would need your manuscript to meet the following editorial thresholds:
- Present compelling evidence for a strong line between the timings of Stratospheric Final Warmings and surface climate in the past decades, based on up-to-date data (at least up to 2022).
- Provide a full justification on the methodology (e.g. cutoff year, group of ‘early’ and ‘late’ final warming dates), or modify the methodology

If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers’ comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Mengze Li, PhD
Editorial Board Member
Communications Earth & Environment

Heike Langenberg, PhD
Chief Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements (Download the link to your computer as a PDF.)

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This study proposes that pivotal changes in the Antarctic surface temperature trends since the 2000s can be largely attributed to the earlier occurrence of stratospheric final warming (SFW) onset events in the last two decades. The article presents valuable insights and findings; however, there are certain expressions that could be further enhanced through thoughtful modification.

L78 ‘surface circulation and surface temperature’. Given that the authors have previously discussed Antarctic sea ice and have conducted an analysis of sea ice concentration (SIC) in the results section, it would be more appropriate to refer to "sea ice" in this context.

L159 Why this resemblance reflects ‘the influence of the SFWOD advanced trend’? Could you please provide clarification on how it affects the surface circulation by changing surface weather pattern and elaborate on the logical relationships between them?

L164 This should be included in the method section.

L170 ‘the signature of SFWOD substantially explains the observed trend changes in the MSLP and SAT anomalies’ Is SFWOD the reason for surface circulation anomalies in each year? Could it be that they are only linked through the interannual variability?

L208 ‘This result is consistent with that of late SFW events’. What does ‘that’ refer to here? Could you provide further details on the relation between the significant signals in the troposphere/surface and the SH tropospheric zonal mean zonal wind?

In the discussion section, the authors discuss a lot with previous studies. It is recommended to emphasize the most important new findings and contributions in this study, answering how the earlier stratospheric final warming caused warmer Antarctic summers.

Reviewer #2 (Remarks to the Author):

Summary

The authors have presented a concise investigation of the relationship between the date of the Southern Hemisphere polar stratospheric vortex annual reversal (final warming) and the surface weather and sea ice conditions. They propose that warmer surface temperatures and positive mean sea level pressure anomalies are associated with a relatively early breakdown of the polar stratospheric vortex, while the opposite is true in years with a relatively late breakdown date. The authors performed regression analyses in addition to compositing years with late and early final warming dates to examine the relationship and physical drivers. They also briefly examined potential links to stratospheric ozone and its trend to the strength of the Southern Hemisphere polar stratospheric vortex.

I find the authors' claims to be novel, interesting, and well-supported enough for publication, though I feel there are several places in which the authors could improve their manuscript, therefore I recommend minor revisions before publication.

Suggested revisions

The change I feel is most important but simplest to make, is the title. The use of the phrase "has caused" is loaded with deeper meaning, and should be changed. A causal link has not been established by this work, but a relationship has been shown, as many potential competing and confounding factors have not been ruled out. I would suggest something like:
"Establishing a Link Between Southern Hemisphere Final Warming Date and Warmer Antarctic Summers"
"Stratospheric Final Warming Date in the Southern Hemisphere Linked to Warmer Antarctic Summers"

In terms of additional steps that should be taken, I question both the use of an older reanalysis product (ERA-I, for which access is discontinued I believe), and cutoff year of 2017, when further data exist using modern, better performing (e.g. Tetzner et al., 2019) reanalysis products (e.g. ERA-5, NASA MERRA-2, etc.). While it may not be feasible to re-perform the analysis on a completely different dataset, some justification ought to be given, or the analysis re-performed.

In addition to the dataset and time period selection, Figure 1 shows surface temperature averaged over 10˚W - 270˚W, as you state later that averaging does not include the Antarctic Peninsula, is the averaging taking place from 10˚W - 270˚E (90˚W) instead? Apart from this, it would also be helpful to add reasoning as to why this is not a zonal mean, it doesn't appear to be lack of surface stations, so the reader is left to wonder if it alters the results.

Another concern I have is the grouping of "early" and "late" final warming dates. It may be useful to not include those dates very close to the mean date, since there isn't a great deal of dynamical difference between a final warming on 6 December grouped with "early" and another on 7 December, grouped with "late".

The results presented show a reasonable statistical significance, though I wonder if it is somewhat overstated. As results from one grid box to the next are not statistically or physically independent, assessing their statistical significance with point-wise T Tests without correcting for this may contribute to an overestimation of field significance (Wilks, 2016). I suggest using a correction for this, called false discovery rate correction, which may reduce some visible statistical significance, but increase confidence.

There are also several places where a "trend change" is referred to. In a few places this is an appropriate description of a change in the trend direction, however, in the caption / title of figure 3, it is stated that the trend change is depicted. Is this a change over time of the trend (i.e. has units of K decade^-2, hPa decade^-2?)? If it is a difference of trends in the "early" years compared with "late" years, a more precise description would be "trend difference" over the groups, as stating "trend changes between SFWOD-delay and advance period" may make your reader think that you are presenting a rate of change rather than a difference of trends.
Other places this distinction should be made: line 130, line 194, line 235, line 528 (Fig 4 caption).

Alongside this correction, referring to the "periods" of late and early final warming years encourages me to think of them as continuous periods of time, rather than groups of years, which I believe is more precise. Changing this would help the reader understand that you aren't referring to pre- and post-1999 averages.

Closing remarks

I find this paper well written, though my reading was out of order, since I find it useful to know about the data and methods used prior to examination of the results (though I think this order is specified by the journal). The figures are quite well done, and provide good justification for the conclusion that a relationship exists linking the SAM, stratospheric final warming, and surface climate, that is a reasonable intuitive conclusion, but one I don't believe has been presented in this way before.

References
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1. Tetzner D, Thomas E, Allen C. A Validation of ERA5 Reanalysis Data in the Southern Antarctic

Peninsula—Ellsworth Land Region, and Its Implications for Ice Core Studies. Geosciences. 2019; 9(7):289. https://doi.org/10.3390/geosciences9070289.

2. Wilks, D. S., 2016: "The Stippling Shows Statistically Significant Grid Points": How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It. Bull. Amer. Meteor. Soc., 97, 2263–2273, https://doi.org/10.1175/BAMS-D-15-00267.1.

Reviewer #3 (Remarks to the Author):

Comments on "Earlier stratospheric final warming has caused 1 warmer Antarctic summers in recent decades" by Choi et al.

All of my comments for this paper are not well considered in this study when it is submitted to [another journal]. I copy those comments again. If those issues are not well addressed, I would repeat them again.

Summary
Choi et al. (2022) tried to establish the possible linkage between the stratospheric final warming date and the long-term trend of the Antarctic surface temperature using the ERA-Interim reanalysis and station observations. To verify the possible contribution of the SFW date on the surface temperature trend, the authors select the early SFWs and late SFWs, and explore the possible impact of the SFW date on the near surface via the stratosphere-troposphere coupling pathway. However, I found that the surface anomalies have appeared before the SFW date as the authors show in Figure 4. The surface anomalies during November and December before the SFW date are even larger and more significant than the surface anomalies in December and January after the SFW date. Further, this study does not include some of the most recent report in literature, and some of the results have been reported in other studies. Due to those shortcomings, I can not recommend to publish the paper in the Communication journal at the present time.

Major comments
1. Some of the results have been reported in a recent study that the SFW date in both Southern and Northern Hemispheres has a delayed trend in the late 20th century (https://doi.org/10.1007/s00382-021-05647-6). However, the authors did not review on this report. The split of the short period (1979–2018) in two subperiods further diminish the reliability of this study. This study also explores the possible linkage between the ozone recovery and the SFW advancement in the future scenarios.

2. This short pause in the cooling trend of the Antarctic surface is consistent with the global warming hiatus, and its linkage with the stratosphere and SFW is not persuasive. This pause is more related to the phase conversion of some decadal mode, eg. PDO, AMO, and others. At least, the authors should provide more evidence that the pause in cooling trend in other months is not identified. If the pause in the Antarctic cooling trend in other months/seasons is also identified especially when the stratosphere-troposphere cooling is weak, I can not attribute this pause to the SFW date advancement. It is a random coincidence.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):
This study proposes that pivotal changes in the Antarctic surface temperature trends since the 2000s can be largely attributed to the earlier occurrence of stratospheric final warming (SFW) onset events in the last two decades. The article presents valuable insights and findings; however, there are certain expressions that could be further enhanced through thoughtful modification.

L78 'surface circulation and surface temperature'. Given that the authors have previously discussed Antarctic sea ice and have conducted an analysis of sea ice concentration (SIC) in the results section, it would be more appropriate to refer to "sea ice" in this context.
>> Thank you for your comment. We refer to "sea ice" in the revised manuscript. (L80)

L159 Why this resemblance reflects 'the influence of the SFWOD advanced trend'? Could you please provide clarification on how it affects the surface circulation by changing surface weather pattern and elaborate on the logical relationships between them?
>> We appreciate for careful reading of the manuscript. Figure R1 displays trends in surface circulation and surface air temperature anomalies during SFW-delay and SFW-advance periods, respectively, as well as the trend differences between these two eras. The low-pressure anomalies over Antarctica deepened during the SFWOD-delay period weakened during the SFWOD-advance period (Figures R1A and R1B). The West and East Antarctic cooling trends and the Antarctic Peninsula warming trends found during the SFWOD-delay period were paused or slightly reversed during the SFWOD-advance period (Figures R1D and R1F). This difference is clearer in Figures R1C and R1F where the pause in trends is related to the positive trend difference in the mean sea level pressure anomaly over the Amundsen Sea and Antarctic continent and the positive trend difference in the surface air temperature anomaly over West and East Antarctica between the two periods. The spatial patterns of these trend differences resemble those of early SFW events (Figures 2A and 2C in the revised manuscript). This resemblance implicitly reflects the strengthening of prominent surface circulation and near-surface temperature patterns during the austral summer for the early SFW events since 1999. Congruence analyses are conducted to investigate the role of SFWOD as a physical driver (Figure 3 in the revised manuscript). The differences in the congruent trends between the SFWOD delay and advance periods were similar to the spatial patterns of the observed trend differences in terms of their amplitudes and horizontal distribution. This indicates that the long-term SFWOD variability is closely related to the observed trend differences resulting from strengthening surface weather patterns of early SFW events. We believe that the reviewer's question in part comes from our unclear explanation, so we attempt to express the sentence more clearly. (L162)

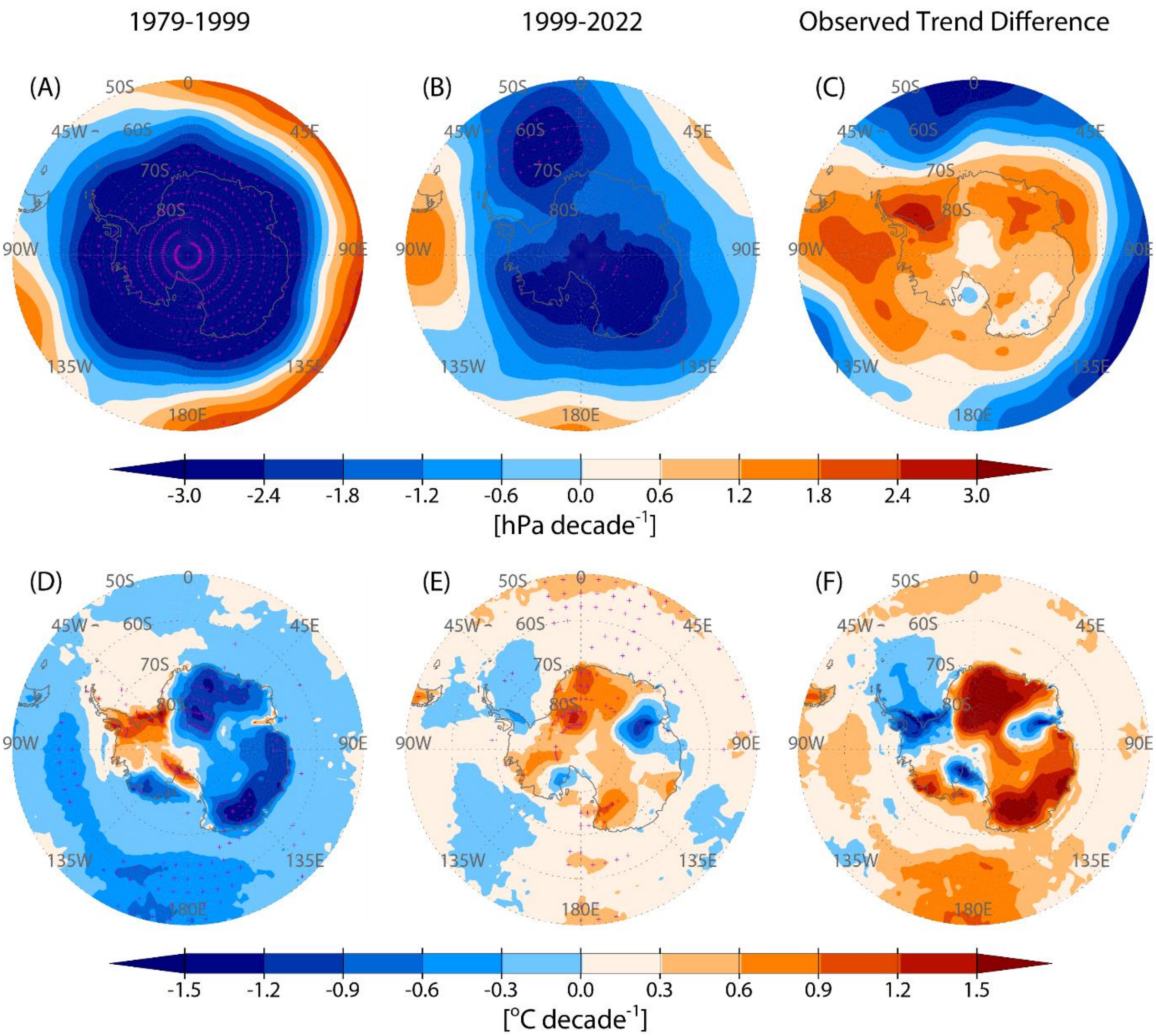

Figure R1. Trends of mean sea level pressure anomalies averaged over austral summer (December and January) during (A) SFWOD-delay (1979–1999) and (B) SFWOD-advance (1999–2022) periods from the ERA5. Pink crosses in (A) and (B) indicate significance at the 95% confidence level. (C) Trend differences between SFWOD-delay and SFWOD-advance period (post-1999 period minus pre-1999 period). (D, E, F) are equivalent to (A, B, C) for surface air temperature anomalies. (C, F) are identical to Figures 3A and 3C in the revised manuscript.

L164 This should be included in the method section.

>> Considering the reviewer's comments, we moved sentences in the method section. (L364)

L170 'the signature of SFWOD substantially explains the observed trend changes in the MSLP and SAT anomalies' Is SFWOD the reason for surface circulation anomalies in each year?

>> Yes it is, the variability in SFWOD is closely linked to surface circulation anomalies in each year (Please see Figure 2 in the revised manuscript).

Could it be that they are only linked through the interannual variability?

>> We are afraid that only the interannual variability may not explain the feature. Surface circulation anomalies are associated not only with interannual variability but also with long-term trend in the SFWOD as illustrated in Figure 3 in the revised manuscript.

L208 ‘This result is consistent with that of late SFW events’. What does ‘that’ refer to here? Could you provide further details on the relation between the significant signals in the troposphere/surface and the SH tropospheric zonal mean zonal wind?

>> ‘That’ in the sentence refers to results confirmed in a previous study that is mentioned later in the sentence. For late SFW events, tropospheric responses before the mean onset date were reported in Byrne et al. (2017), which used zonal mean zonal wind. We modified the sentence to ensure that the meaning is conveyed in the revised manuscript. (L206)

In the discussion section, the authors discuss a lot with previous studies. It is recommended to emphasize the most important new findings and contributions in this study, answering how the earlier stratospheric final warming caused warmer Antarctic summers.

>> Following the suggestion by the reviewer, we emphasized the main results and further discussed contributions of this study. (L335)

Reviewer #2 (Remarks to the Author):

Summary

The authors have presented a concise investigation of the relationship between the date of the Southern Hemisphere polar stratospheric vortex annual reversal (final warming) and the surface weather and sea ice conditions. They propose that warmer surface temperatures and positive mean sea level pressure anomalies are associated with a relatively early breakdown of the polar stratospheric vortex, while the opposite is true in years with a relatively late breakdown date. The authors performed regression analyses in addition to compositing years with late and early final warming dates to examine the relationship and physical drivers. They also briefly examined potential links to stratospheric ozone and its trend to the strength of the Southern Hemisphere polar stratospheric vortex.

I find the authors' claims to be novel, interesting, and well-supported enough for publication, though I feel there are several places in which the authors could improve their manuscript, therefore I recommend minor revisions before publication.

Suggested revisions

The change I feel is most important but simplest to make, is the title. The use of the phrase "has caused" is loaded with deeper meaning, and should be changed. A causal link has not been established by this work, but a relationship has been shown, as many potential competing and confounding factors have not been ruled out. I would suggest something like:

"Establishing a Link Between Southern Hemisphere Final Warming Date and Warmer Antarctic Summers"

"Stratospheric Final Warming Date in the Southern Hemisphere Linked to Warmer Antarctic Summers"

>> We appreciate your careful comments and helpful suggestions. Considering the reviewer's comments, we have revised the title to "Warmer Antarctic Summers in Recent Decades Linked to Earlier Stratospheric Final Warming Occurrences ". (Line 4)

In terms of additional steps that should be taken, I question both the use of an older reanalysis product (ERA-I, for which access is discontinued I believe), and cutoff year of 2017, when further data exist using modern, better performing (e.g. Tetzner et al., 2019) reanalysis products (e.g. ERA-5, NASA MERRA-2, etc.). While it may not be feasible to re-perform the analysis on a completely different dataset, some justification ought to be given, or the analysis re-performed.

>> This study was conducted as an extension of our previous research that was carried out using ERA-I covering the period from 1979 to 2017 (Kwon et al., 2020). At that time, ERA-5 data was not available to us, so we performed all analyses using ERA-I. Following the suggestion by the reviewer, we reproduced all main figures (Figures 1-6 and Supplementary Figures 1 and 2 in the revised manuscript) using ERA-5 data covering the period from January 1, 1979, to January 31, 2023. The period of monthly mean in situ surface air temperature data and sea-ice concentration data has also been extended. We have confirmed that the main conclusions in this study are not sensitive to different datasets and the inclusion of additional years.

Reference

H. Kwon, H. Choi, B. M. Kim, S. W. Kim, S. J. Kim, Recent weakening of the southern stratospheric polar vortex and its impact on the surface climate over Antarctica. *Environ. Res. Lett.* **15**, 094072 (2020).

In addition to the dataset and time period selection, Figure 1 shows surface temperature averaged over 10˚W - 270˚W, as you state later that averaging does not include the Antarctic Peninsula, is the averaging taking place from 10˚W - 270˚E (90˚W) instead?

>> Yes, it is. We revised 10°W-270°W to 10°W-270°E (90°W)

Apart from this, it would also be helpful to add reasoning as to why this is not a zonal mean, it doesn't appear to be lack of surface stations, so the reader is left to wonder if it alters the results.

>> Thank you for your comment. To identify the influence of opposite behavior between the Antarctic Peninsula (AP) region and the rest of Antarctica on results, we examined the time series of DJ-mean surface air temperature (SAT) anomalies averaged over the entire Antarctica and investigated the relation to SFW onset date (SFWOD) (Figure R1). Figure R1 is equivalent to Figure 1A in the revised manuscript for Antarctica, but now including the AP region. The SAT anomalies were averaged over 0°E-360°E and 70°S-90°S for the ERA5 reanalysis data and calculated from 20 stations located in the 0°E-360°E for the observations. The SAT anomalies based on reanalysis data (solid black line) and station observations (dashed-dotted black line) displayed a similar evolution, with a correlation coefficient of 0.76. On an interannual time scale, the two SAT anomalies from the reanalysis and observed data were related to SFWOD, with correlation coefficients of -0.27 and -0.36, respectively. The correlations with reanalysis-based SAT anomalies and observation-based SAT anomalies were not significant at the 95% confidence level, but significant at the 90% confidence level. On a decadal time scale, the SAT anomalies based on reanalysis and station observations show the cooling trends with -0.25 °C decade^{-1} and -0.17 °C decade^{-1} during the pre-1999 period, respectively. The cooling trends based on reanalysis and observed data, however, were only about half and one-third compared to the SAT anomalies trends calculated for the same period **excluding the AP region** (Figure 1A), respectively. Moreover, they were not significant even at both the 90% and 95% confidence levels. During the post-1999 period, the SAT anomalies based on reanalysis and station observations show insignificant trends with 0.29 °C decade^{-1} and -0.04 °C decade^{-1}, respectively. Therefore, averaging over the entire Antarctica, including AP region, significantly reduced the cooling trends during pre-1999 periods, making it ambiguous to claim a pause in the cooling trends since 1999. We added the Figure R1 as Figure S2 and specified it in the revised manuscript. (Line 117)

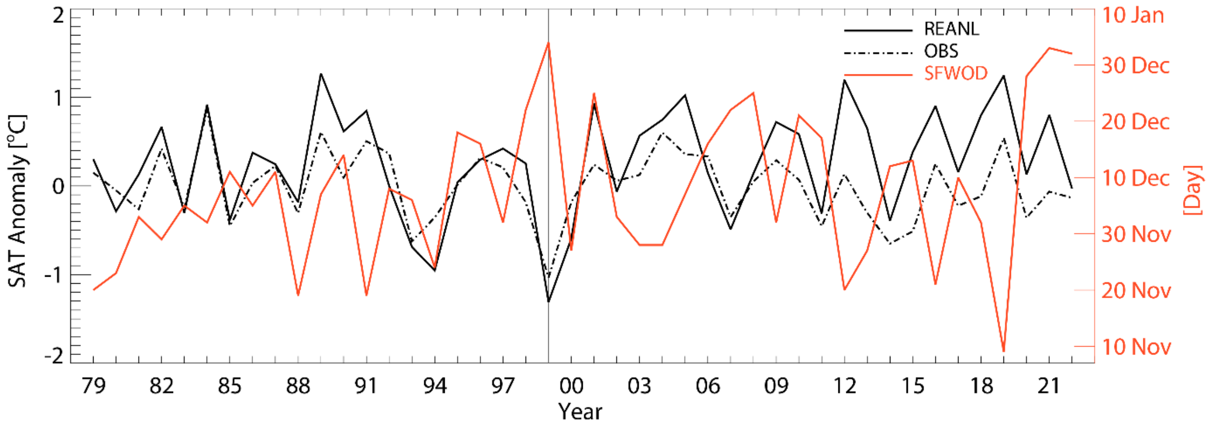

Figure R1. Time series of DJ-mean SAT anomaly averaged over Antarctica including the AP region (black) and SFWOD (orange). The black solid and dashed-dotted lines correspond to the results from the ERA5 reanalysis data and station observations, respectively. The vertical gray line represents the year 1999.

Another concern I have is the grouping of "early" and "late" final warming dates. It may be useful to not include those dates very close to the mean date, since there isn't a great deal of dynamical difference between a final warming on 6 December grouped with "early" and another on 7 December, grouped with "late".

>> We appreciate your comments. We examine the impact of the criteria dates used to distinguish “early” and “late” SFW events on the composite analysis of mean sea level pressure (MSLP) and SAT

anomalies. For the time period 1979–2022, the standard deviation of the onset date of SFW is about 13 days. We defined a moderate early- and late SFW event when the SFW onset falls below –0.5 standard deviations (December 1) and exceeds 0.5 standard deviations (December 14), respectively. There were a total of 13 moderate early-SFW events and 13 moderate late-SFW events. The mean sea level pressure and SAT anomalies in Figure R2 exhibit strengthened features compared to Figure 2 in the revised manuscript, though they show similar spatial patterns. We conducted the same analysis using 8 extreme early-SFW events and 9 extreme late-SFW events, which were classified based on –1.0 standard deviations (November 25) and 1.0 standard deviations (December 21), respectively (Figure R3). Strong surface responses are observed, but the spatial patterns are nearly identical to those in Figure 2 of the revised manuscript and Figure R2. This provides evidence that the main conclusions hold regardless of choice of specific thresholds for classifying cases. While demonstrating quantitative differences would also be valuable, our study places a greater emphasis on revealing the potential connection between SFW timing and surface responses. Therefore, we believe that our straightforward method for classifying "early" and "late" SFW events is suitable for conveying key results without serious deficiency. We discussed this point in the revised manuscript (line 357).

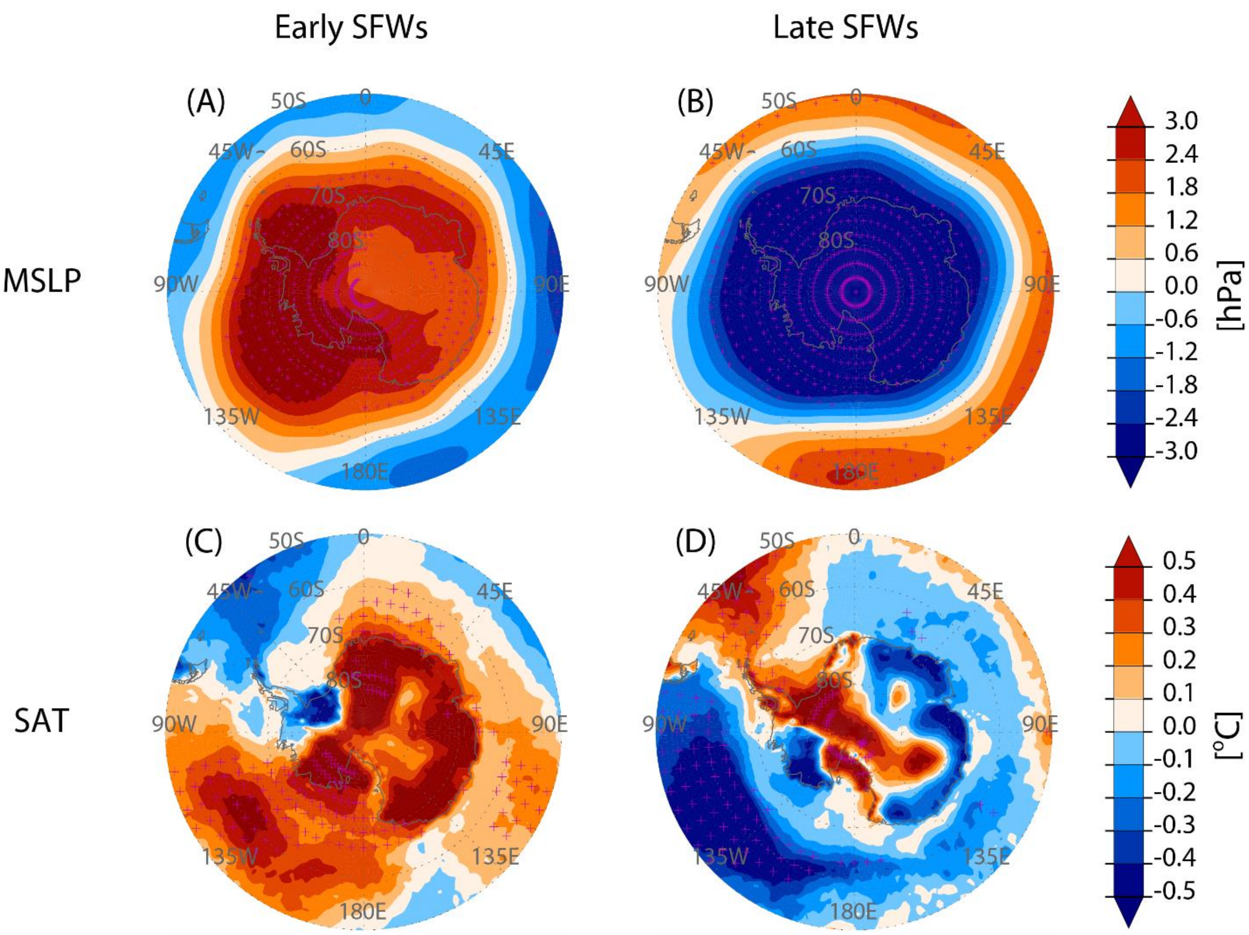

Figure R2. DJ-mean MSLP anomalies for (**A**) the moderate early-SFW and (**B**) moderate late-SFW events. (**C, D**) are equivalent to (**A, B**) for DJ-mean SAT anomalies. Pink crosses indicate significance at the 95% confidence level.

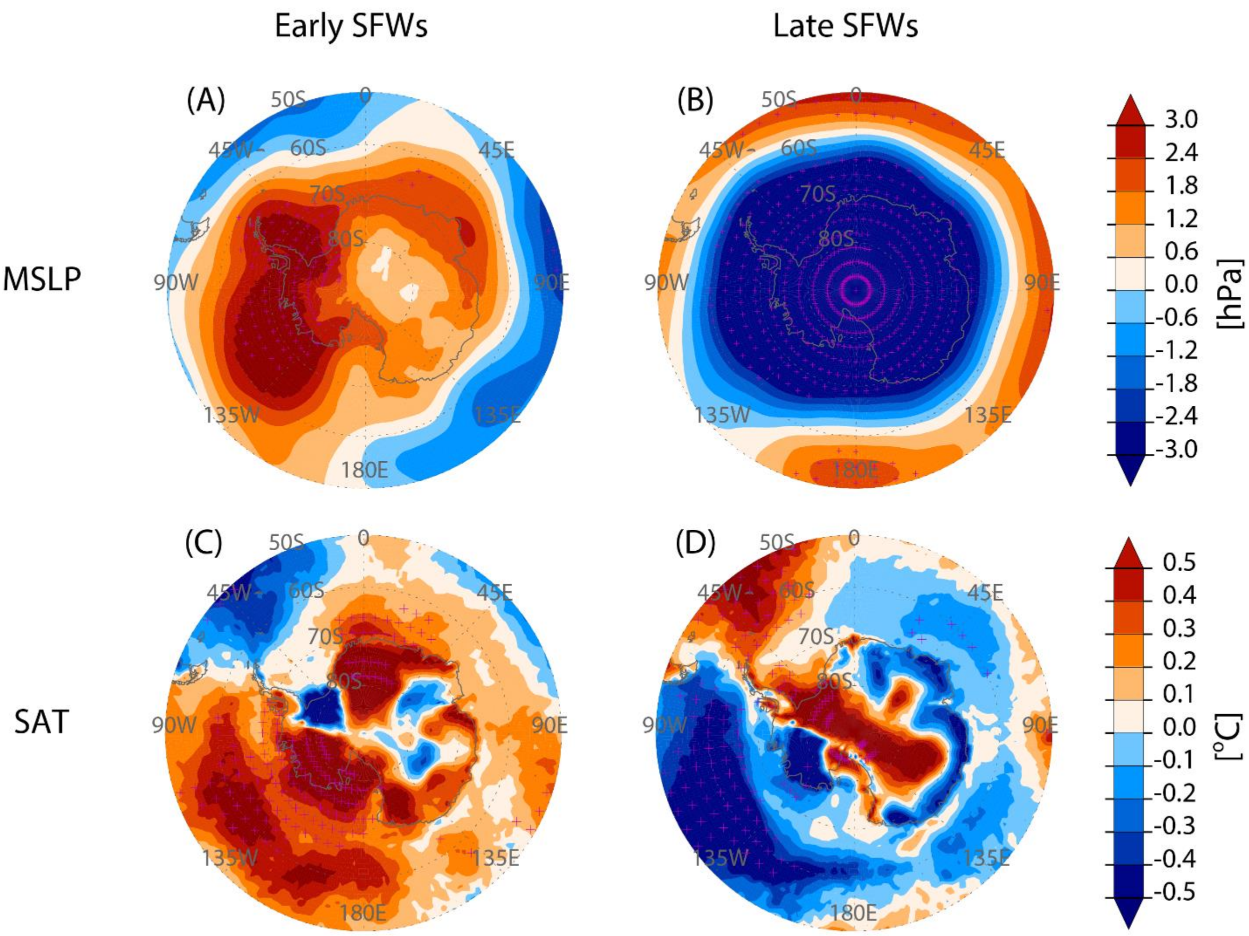

Figure R3. DJ-mean MSLP anomalies for (**A**) the extreme early-SFW and (**B**) extreme late-SFW events. (**C, D**) are equivalent to (**A, B**) for DJ-mean SAT anomalies. Pink crosses indicate significance at the 95% confidence level.

The results presented show a reasonable statistical significance, though I wonder if it is somewhat overstated. As results from one grid box to the next are not statistically or physically independent, assessing their statistical significance with point-wise T Tests without correcting for this may contribute to an overestimation of field significance (Wilks, 2016). I suggest using a correction for this, called false discovery rate correction, which may reduce some visible statistical significance, but increase confidence.

>> Thank you for your comment. The purpose of this paper is to qualitatively, rather than quantitatively, show and link the possible relationship between the onset date of SFW and surface responses. The Student's t-test has been widely used to determine statistical significance due to the simplicity of the method. Therefore, we believe that this method can be used in this study without significant error.

There are also several places where a "trend change" is referred to. In a few places this is an appropriate description of a change in the trend direction, however, in the caption / title of figure 3, it is stated that the trend change is depicted. Is this a change over time of the trend (i.e. has units of K decade^-2, hPa decade^-2?)? If it is a difference of trends in the "early" years compared with "late" years, a more precise description would be "trend difference" over the groups, as stating "trend changes between SFWOD-delay and advance period" may make your reader think that you are presenting a rate of change rather than a difference of trends.

Other places this distinction should be made: line 130, line 194, line 235, line 528 (Fig 4 caption).

>> We appreciate your close observation once again. The term "trend change" in captions and titles of

Figures 3–4 denotes differences in trends between the SFWOD-delay and advanced periods, expressed in units of hPa decade^{-1} and K decade^{-1}. Following the suggestion by the reviewer, we revised "trend change" to "trend difference".

Alongside this correction, referring to the "periods" of late and early final warming years encourages me to think of them as continuous periods of time, rather than groups of years, which I believe is more precise. Changing this would help the reader understand that you aren't referring to pre- and post-1999 averages.

>> We revised it. (Lines 199, 203, 244)

Closing remarks

I find this paper well written, though my reading was out of order, since I find it useful to know about the data and methods used prior to examination of the results (though I think this order is specified by the journal). The figures are quite well done, and provide good justification for the conclusion that a relationship exists linking the SAM, stratospheric final warming, and surface climate, that is a reasonable intuitive conclusion, but one I don't believe has been presented in this way before.

References

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1. Tetzner D, Thomas E, Allen C. A Validation of ERA5 Reanalysis Data in the Southern Antarctic Peninsula—Ellsworth Land Region, and Its Implications for Ice Core Studies. Geosciences. 2019; 9(7):289. https://doi.org/10.3390/geosciences9070289.

2. Wilks, D. S., 2016: "The Stippling Shows Statistically Significant Grid Points": How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It. Bull. Amer. Meteor. Soc., 97, 2263–2273, https://doi.org/10.1175/BAMS-D-15-00267.1.

Reviewer #3 (Remarks to the Author):

Comments on "Earlier stratospheric final warming has caused 1 warmer Antarctic summers in recent decades" by Choi et al.

All of my comments for this paper are not well considered in this study when it is submitted to [another journal]. I copy those comments again. If those issues are not well addressed, I would repeat them again.

Summary
Choi et al. (2022) tried to establish the possible linkage between the stratospheric final warming date and the long-term trend of the Antarctic surface temperature using the ERA-Interim reanalysis and station observations. To verify the possible contribution of the SFW date on the surface temperature trend, the authors select the early SFWs and late SFWs, and explore the possible impact of the SFW date on the near surface via the stratosphere-troposphere coupling pathway. However, I found that the surface anomalies have appeared before the SFW date as the authors show in Figure 4. The surface anomalies during November and December before the SFW date are even larger and more significant than the surface anomalies in December and January after the SFW date.
>> We appreciate your careful reading of the manuscript. As mentioned in our original manuscript, the preceding stratospheric polar vortex condition is associated with subsequent vortex breakdown events. Kwon et al. (2020) showed that extreme southern stratospheric polar vortex (SSPV) weakening events, which occurred often during the austral late winter and spring season (August–October), had impacts on the surface through stratosphere-troposphere coupling for approximately three months. We examined the linkage not only between extreme SSPV weakening events and SFW timing but also with surface responses before December shown in the original Figure 5. The analysis was performed using the ERA-interim data for the period from January 1, 1979, to January 31, 2018, as employed in Kwon et al. (2020). Figure R1 shows the composite of polar cap-height (PCH) anomalies based on the years with or without preceding extreme SSPV weakening events for early and late SFWs, respectively. Extreme SSPV weakening events were referenced from Kwon et al. (2020)'s Table 1, with an average onset date of September 22nd, which is about three months earlier than the average onset date of December 7th for the SFWs (original Table S2). There are two notable points. First, from the perspective of the SSPV weakening events, 11 cases out of the 15 cases of the SSPV weakening events (Figures R1A and R1C) are followed by early SFW events (Figure R1A), while 15 cases out of the 24 cases without SSPV weakening events (Figures R1B and R1D) are followed by late SFW events (Figure R1D). Second, regardless of the timing of SFW, before mid-November, positive anomalies are observed for years with the SSPV weakening events (Figures R1A and R1C), whereas negative anomalies are identified for years without SSPV weakening events (Figures R1B and R1D). However, after mid-November, positive anomalies are observed during early SFW events (Figures R1A and R1B) while negative PCH anomalies are observed during late SFW events (Figures R1C and R1D). In other words, surface responses before mid-November are mainly associated with extreme SSPV weakening events, whereas those afterward appear to be closely linked with SFWOD. Therefore, we believe it is appropriate to focus on the period after December for examining SFWOD-related responses. We have discussed this point in the revised manuscript. (Line 211).

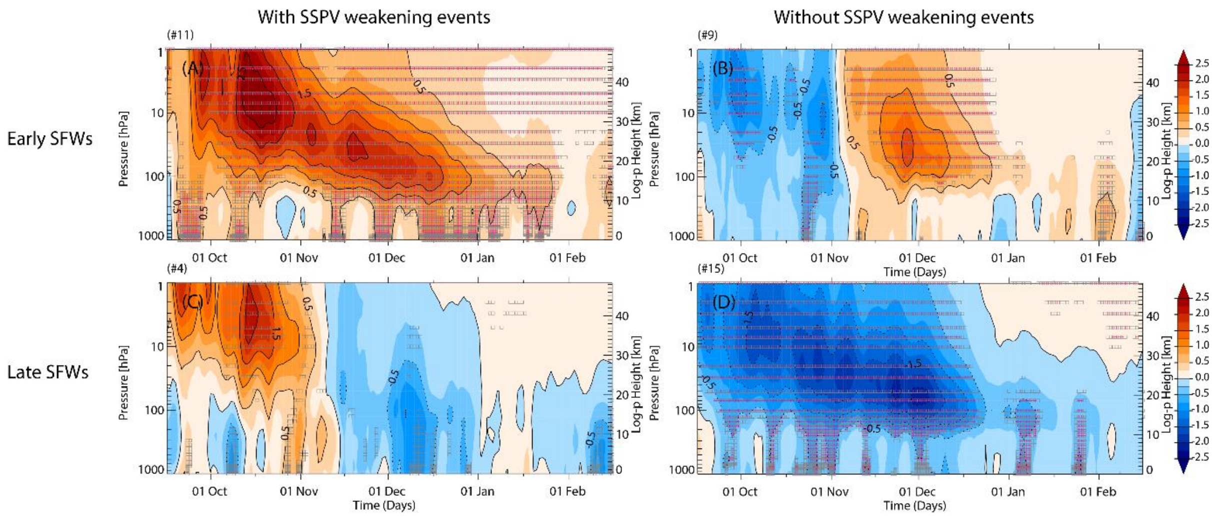

Figure R1. Composite of the ERA-Interim polar cap-height (PCH) anomalies based on the calendar day of the year (A) with and (B) without extreme southern stratospheric polar vortex (SSPV) weakening events for early SFW events. (C, D) are equivalent to (A, B) for late SSW events. The number of events used in the composite analysis is indicated in the top left corner of each panel. Pink crosses and gray squares indicate significance at the 95% and 90% confidence levels, respectively.

Further, this study does not include some of the most recent report in literature, and some of the results have been reported in other studies. Due to those shortcomings, I can not recommend to publish the paper in the Communication journal at the present time.

>> In light of the reviewer's feedback, we've carefully reviewed and updated our manuscript to incorporate recent literature reports and address overlapping findings (Line 70, 128, 218, 304, 323). We are confident that these revisions have significantly enhanced the quality of our manuscript.

Major comments

1. Some of the results have been reported in a recent study that the SFW date in both Southern and Northern Hemispheres has a delayed trend in the late 20th century (https://doi.org/10.1007/s00382-021-05647-6). However, the authors did not review on this report.

>> Thank you for your comment. While reviewing the manuscript, we noticed that Rao and Garfinkel (2021) was cited in the main text but not included in the reference section. We added their paper in the reference and further mentioned the Rao and Garfinkel (2021) regarding the trend of SFW dates in future scenarios (Line 70, 324).

The split of the short period (1979–2018) in two subperiods further diminish the reliability of this study.

>> The decadal variability in SFWOD and surface circulation over the past few decades, based on observational data, has been noted not only in our study but also in other previous studies (1–5). In Particular, Banerjee et al. (2020) confirmed the pause in circulation trends during austral summer not only using reanalysis data but also model simulations and showed that the pause did not occur solely due to internal or natural variability of the climate system. This can be one piece of evidence that the observed trend differences aren't merely coincidental. As described in the introduction of our manuscript, the anomalous behavior or the polar vortex is linked to tropospheric variability. Therefore, we believe that examining the relationship between the long-term variability of the polar vortex and tropospheric responses is meaningful, and this study will help enhance our understanding of climate change in the Southern Hemisphere during the summer season.

References

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1. R. X. Black, B. A. McDaniel, Interannual variability in the Southern Hemisphere circulation organized by stratospheric final warming events. *J. Atmos. Sci.* **64**, 2968-2974 (2007).
2. J. Turner, H. Lu, I. White, J. C. King, T. Phillips, J. S. Hosking, J. B. Thomas, J. M. Gareth, M. Robert, D. Pranab, Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. *Nature*, ***535*(7612)**, 411-415 (2016).
3. S. Hirano, M. Kohma, K. Sato, A three-dimensional analysis on the role of atmospheric waves in the climatology and interannual variability of stratospheric final warming in the Southern Hemisphere. *J. Geophys. Res.: Atmos.* **121**, 8429-8443 (2016).
4. A. Banerjee, J. C. Fyfe, L. M. Polvani, D. Waugh, K. L. Chang, A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature* **579**, 544-548 (2020).
5. A. H. Butler, D. I. Domeisen, The wave geometry of final stratospheric warming events. *Weather Clim. Dyn.* **2**, 453-474 (2021).

This study also explores the possible linkage between the ozone recovery and the SFW advancement in the future scenarios.
>> We believe that the reviewer is describing the content of a previously submitted manuscript to another journal. In the version of manuscript submitted to Communications Earth & Environment, we did not link the ozone recovery to the SFW advancement, but referred to existing literature reporting various factors that can affect the stratospheric polar vortex as well as an increase in greenhouse gases that can mitigate the impact of ozone by strengthening the polar vortex. Additionally, we removed the sentence mentioning the potential linkage between ozone recovery and the SFW advancement in the future (Line 318).

2. This short pause in the cooling trend of the Antarctic surface is consistent with the global warming hiatus, and its linkage with the stratosphere and SFW is not persuasive. This pause is more related to the phase conversion of some decadal mode, eg. PDO, AMO, and others. At least, the authors should provide more evidence that the pause in cooling trend in other months is not identified. If the pause in the Antarctic cooling trend in other months/seasons is also identified especially when the stratosphere-troposphere cooling is weak, I can not attribute this pause to the SFW date advancement. It is a random coincidence.
>> The variability in the Antarctic temperature is a result of multiple factors. Not only the stratospheric polar vortex but also natural variability, stratospheric ozone, and Southern Annular Mode all influence Antarctic temperature. Tropical Pacific forcings such as ENSO, IPO, and PDO also play an important role in the Antarctic surface temperature modulation. We made this point clear in the manuscript and included relevant references (Line 59)

We performed a brief examination of the relationship between the PDO and Antarctic surface temperature during the austral summer. The PDO index is taken from National Centers for Environmental Information (https://www.ncei.noaa.gov/access/monitoring/pdo/) The December-January (DJ)-mean PDO in Figure R2 shows that the significant negative trend with -0.71 decade^{-1} at the 90% confidence level during the pre-1999 period weakened to an insignificant negative trend with -0.2 decade^{-1} during post-1999 period. This weakening in the negative DJ-mean PDO trend is consistent with the pause of cooling in the summertime surface temperature, of the delayed trend in SFWOD, of the positive phase in SAM during summertime, and of the ozone decline trend during springtime. On an interannual time scale, however, the relationship between the DJ-mean surface temperature over west and east Antarctic regions based on reanalysis data and DJ-mean PDO is weak, with a correlation coefficient of -0.05. The congruence analysis is influenced not only by long-term variability but also interannual variability (Please see Methods in the revised manuscript). Therefore, the weak relationship on interannual timescale could lead to a small fraction of trends in surface circulation and surface temperature congruent with the DJ-mean PDO compared to that with the SFWOD as shown in Figure R3.

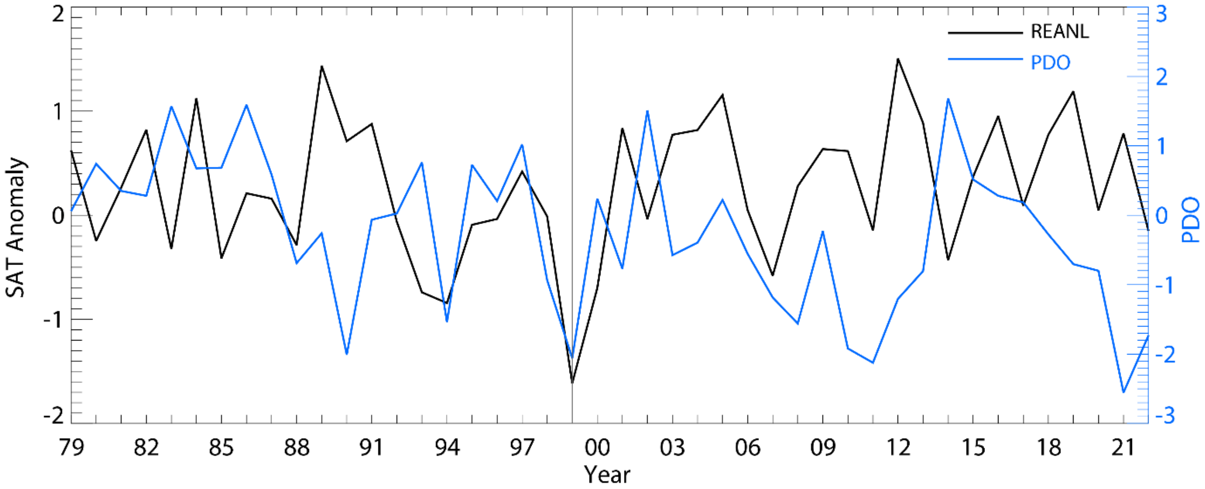

Figure R2. Time series of December-January (DJ)-mean surface air temperature anomaly averaged over Antarctica excluding the Antarctic Peninsula region (black) and DJ-mean PDO (blue). The vertical gray line represents the year 1999.

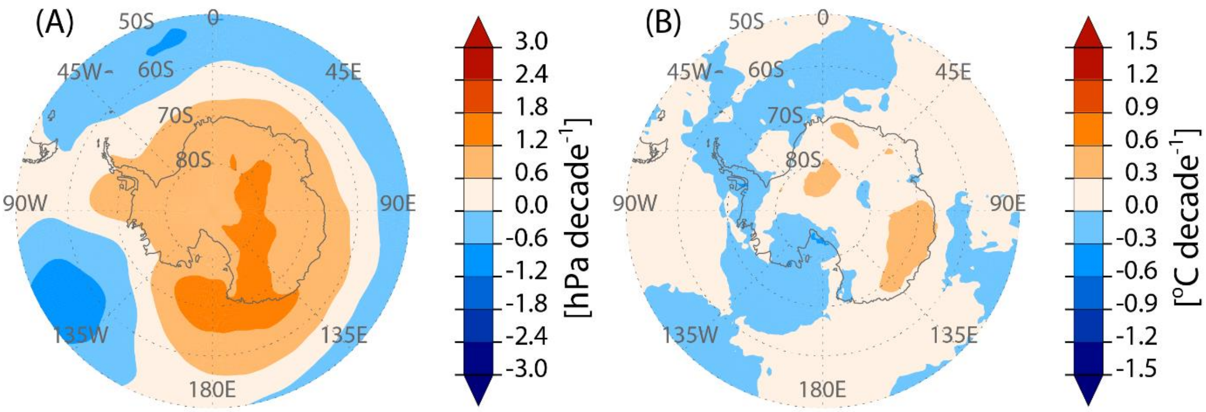

Figure R3. (A) Trend differences in the DJ-mean surface circulation congruent with the DJ-mean PDO between SFWOD-delay and advance period (post-1999 period minus pre-1999 period. (B) is equivalent to (A) for surface temperature. Note that (A) and (B) are equivalent to Figures 3B and 3D in the revised manuscript, respectively, for trends linearly congruent with DJ-mean PDO.

Following the reviewer's comment, we examined the time series of the Antarctic surface temperature during the opposite season (June-July-August, JJA) of summer (Figure R4). The pause in the Antarctic cooling trend does not occur in austral winter; The surface air temperature anomaly based on reanalysis (station data) shows an insignificant warming trend with 0.24 °C decade^{-1} (0.42 °C decade-1) at the 90% confidence level during the pre-1999 period. During the post-1999 period, a warming trend with 0.2°C decade^{-1} (0.07 °C decade^{-1}) is still observed, but it is slightly weaker than that during the pre-1999 period. This simple trend analysis indicates that the cessation of the Antarctic cooling occurs during summertime with strong stratosphere-troposphere coupling, but not in the wintertime. Therefore, we believe that the influence of SFW timing on the warming of Antarctic summers over the recent decades could not be ruled out, and more research is needed. Figure R2 is included in the revised manuscript as

Figure S1. (Line 109)

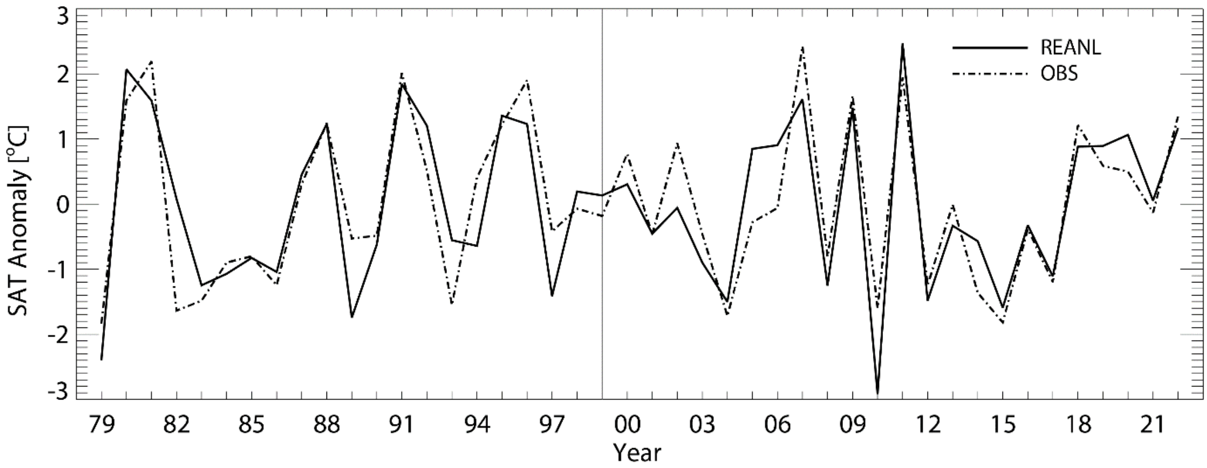

Figure S4. Time series of June-July-August (JJA)-mean surface air temperature anomaly averaged over Antarctica excluding the Antarctic Peninsula region. The black solid and dashed-dotted lines correspond to the results from the reanalysis data (ERA5) and station observations, respectively. The vertical gray line represents the year 1999.

6th Dec 23

Dear Dr Kim,

Your manuscript titled "Warmer Antarctic Summers in Recent Decades Linked to Earlier Stratospheric Final Warming Occurrences" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

Specific requests from us:

Line 101: We recommend adding student t-test after 95% confidence level for clarity, although it is stated in the Methods.
Lines 105-107: (1) why are there two trends (-0.43 and -0.53) for two confidence levels; (2) didn't state confidence level for post-1999 period; (3) post-1999 trend is unclear, you state two trends: 0.29 and -0.004.
Line 126: please state confidence level for post-1999 period.
Line 290: please state confidence level for pre-1999 period.

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Best regards,

Mengze Li, PhD
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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript has been carefully revised by the authors according to the suggestions. Updated data and results illuminate the connection between the date of the Southern Hemisphere polar stratospheric vortex annual reversal (final warming) and the Antarctic surface weather. The comprehensive analysis not only establishes robust relationships but also elucidates the underlying physical drivers with clarity. The findings presented in the manuscript are well-founded and novel, rendering them suitable for publication.

Reviewer #3 (Remarks to the Author):

The authors have answered all of my questions and well revised the manuscript. I can recommend to publish the paper as it is.