

Peer Review File

Stratospheric Final Warmings fall into two categories with different evolution over the course of the year



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

24th Jun 21

Dear Dr Hauchecorne,

Your manuscript titled "Final Stratospheric Warmings and the memory of the stratosphere" has now been seen by three 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 present new and important insights into final stratospheric warmings, and to discuss your findings more comprehensively in the context of the literature, as well as address all the criticisms raised, we would be happy to look at a substantially revised manuscript.

However, 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 referees' comments (which should be in a separate document to any cover letter) 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 me 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,

Heike Langenberg, PhD

Chief Editor
Communications Earth and Environment

On Twitter: @CommsEarth

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please include line and page numbers, and 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:

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review of the Nature Communications Earth & Environment article „Final Stratospheric Warming and the memory of the stratosphere” by Alain Hauchecorne, Chantal Claud, Philippe Keckhut, Alexis Mariaccia.

The authors investigate the final stratospheric warming (FSW) in the Arctic spring using 71 years of ERA5 data. They divide the FSW into dynamically driven FSW and radiatively driven FSW using the date of the final wind reversal in the stratosphere and the maximum temperature anomaly around this date. Afterwards they compare stratospheric characteristics of these two classes covering one year but with a focus on winter. The major finding of this study is that the state of the stratosphere in mid-winter is correlated with the state of the stratosphere in spring and that in turn is correlated with the state of the stratosphere in summer at least until July.

These results are novel and will be of interest to others in the community since it has the potential to improve the sub seasonal to seasonal forecast not only in spring but also in summer. Overall this work is convincing but needs minor further evidence and some clarification and corrections (see below).

Comments:

The sentence “In early spring the stratospheric zonal reverse from winter westerly circulation to summer easterly circulation” in the introduction sounds strange and should be rephrased.

“Major SSW events are preceded by one or several minor SSWs characterized by peaks of warming in the middle and upper polar stratosphere but without zonal wind inversion.” For this statement a reference is missing. Major SSW are not always preceded by minor SSWs but often.

In Final stratospheric warming: in the last two points a “before” is missing in “from 7 days to 7 days

after the inversion day". Thus, it should be "from 7 days before to 7 days after the inversion day"
"Figure 2 shows the amplitude of geopotential wave 1 and 2 during the FSW": Figure 2 shows only the amplitude of wave 1 and not wave 2. Please correct that also in the subsequent sentence.

Figure 1: The font size could be larger. The headline in the left plot is misleading as the date of the final warming is shown but also the temperature anomaly. It would be helpful to write the correlation coefficient into the right plot. Additionally, it would be helpful to depict which dots belong to the dynamical FSW and which to the radiative FSW, either by different colors of the dots or by including rectangles showing the defined thresholds respectively. In the figure caption please correct "corelation" to "correlation".

Figure 2: The first letter of the x-axis label should also be a capital letter as for the y-axis.

"... radiative composite with temperature anomaly < 5K (40 members)": Is the result even clearer when using 0K (zero) as a threshold? When using 5K the days of the radiative FSW overlap with those of the dynamical FSW.

Figure 3: I suggest to include the overall composite as a grey line. This way, quite inaccurate statements like "relatively strong vortex in February" could be better quantified.

"We can said that there is a memory of the stratosphere ..." please correct to "We can say that there is a memory of the stratosphere ..."

Figure 4: Why is the first plot larger as the other two? In the first plot the letters F and half of the M are not visible. Please correct that. You wrote in the figure caption "For correlation between two months of the same variable, the diagonal is left blank ...". However, this is true only for the left plot. This should be corrected for the middle and right plot.

Please delete the incomplete sentence: "between February and March, and March and May June."

Why are daily data at 12UT used and not daily mean data?

Where were the levels 70 and 100hPa used in this study?

Please correct: "... we use the data set ERA5.1 for the period 200-2006 to correct ..." to "... we use the data set ERA5.1 for the period 2000-2006 to correct ..."

Reviewer #2 (Remarks to the Author):

Comments on "Final Stratospheric Warmings and the memory of the stratosphere" by Hauchecorne et al. (2021)

Summary

Hauchecorne et al. (2021) used the ERA5 reanalysis to study the lead/lag relationship between the stratospheric circulation, which is probably a basis for the subseasonal to seasonal weather forecast. However, I have a worry about the originality and novelty of the paper that some result in the paper might be found in previous publications. The authors did not well review on the previous studies concerned the SFW, and changed to use an alternate term for early and late SFW (radiative and dynamical SFW in this paper). As far as I know, most of pervious studies used stratospheric final warming (SFW) to name the seasonal transition from westerly to easterly in the stratosphere, although Butler et al. 2019 also used the terminology stratospheric final warming. Due to the problematic issues, I would not suggest to publish the paper at this time. A substantial revision is required.

Major comments

1. The abstract begins from the SSW, which might be shortened and replaced by the SFW. This paper mainly focuses on the seasonal transition of the stratosphere, and all the composites and analyses

are around the final warming. The abstract might be improved by considering the SFW first.

2. The SFW-SSW relationship was studied in Hu et al. 2014, and they found that a midwinter SSWs might be associated with a late and radiative SFW. Whereas, a SSW-absent midwinter might be followed by an early dynamic SSW. The authors might consider the previous study in the introduction.

3. Compared with the data from 1979-2020, the data before 1979 is not very trustworthy. After 1979 satellite observations were available and the data are trustworthy. If the authors only use the post-1979 data, I am not sure if the results will change.

4. Final warming definition is also problematic. Final warming should correspond to a polar warming in the stratosphere, so the negative temperature anomalies are unbelievable at all. The authors did not show the page number and line number in the manuscript, it is not easy to point out the place. I leave the work for the authors themselves.

Minor comments

5. P1: "owe their existence to the equator-to-pole gradient of the Coriolis force". I do not believe this is true. Please correct.

6. P1: "PWs are generated by temperature contrasts between the continents and the oceans and the flow over the orography". Should be thermal contrast.

7. P1: "There is a growing interest in the study of dynamical coupling between the stratosphere and the troposphere during SSW events due to the potential to improve sub-seasonal to seasonal weather predictions" Please refer to Rao et al. (2018, 2019), Taguchi et al. 2018, Karpechko et al. 2018. The first two references in the citation do not discuss the S2S prediction of warming events.

8. P2: "...causing the polar vortex to end..." Change "end" to collapse. Please refer to Rao and Garfinkel 2021.

9. P2: "The objectives of this paper is to characterize FSW events according to their nature and their date of occurrence, and to explore the seasonal memory of the stratosphere in relation with mid-winter SSW and FSW events" Please mention that Hu et al 2014 have studied this.

10. P2: Final warming event identification is not easy to read. Please refer to Rao and Garfinkel 2021 for more details.

11. P2: "between -3.8K (in 1999) and +24.7K (in 2016)" -3.8 K is cooling rather than warming. Please check the results.

12. P2: "During the period 1995-2010 the FSW dates were later and the temperature anomalies were smaller but the reverse was true after 2010." Please refer to Rao and Garfinkel Figure 2 (red line). The authors seemed to fail to read the most recent results for SFW.

13. P3: 20 members => 20 samples; 40 members => 40 samples

14. P3: "It means that the nature of the FSW is related to the evolution of the polar vortex during the preceding winter, a February SSW favouring a late radiative FSW and a March SSW favouring an

early dynamical FSW.” This was reported in Hu et al. 2014

15. P4: Figure 4: the three paper is not of the same size. Please correct. The bottom left – top right diagonal line should be 1 in Figure 4a, 4b. Figure 4b is right but Figure 4a is wrong. Please correct the coding and update the figure.

16. P5: first line: Delete “between February and March, and March and May- June.”

17. P5: The first conclusion is not a new finding in this study. The discussion on the stratosphere-troposphere coupling is really lacking in this paper.

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Rao, J., R. Ren, H. Chen, Y. Yu, and Y. Zhou, 2018: The Stratospheric Sudden Warming Event in February 2018 and its Prediction by a Climate System Model. *Journal of Geophysical Research: Atmospheres*, 123, 13332–13345.

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Hu, J. G., R. C. Ren, and H. M. Xu, 2014: Occurrence of Winter Stratospheric Sudden Warming Events and the Seasonal Timing of Spring Stratospheric Final Warming. *Journal of the Atmospheric Sciences*, 71, 2319-2334.

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Karpechko, A. Y., A. Charlton-Perez, M. Balmaseda, N. Tyrrell, and F. Vitart, 2018: Predicting Sudden Stratospheric Warming 2018 and its Climate Impacts with a Multi-Model Ensemble. *Geophysical Research Letters*, 45, 13538–13546.

Rao, J., and C. I. Garfinkel, 2021: Projected changes of stratospheric final warmings in the Northern and Southern Hemispheres by CMIP5/6 models. *Climate Dynamics*, 56, 3353-3371.

Reviewer #3 (Remarks to the Author):

In this manuscript, the authors distinguish between dynamically and radiatively forced Final Stratospheric Warmings (FSWs) on the basis of stratospheric temperature anomalies, with larger (smaller) anomalies identified as dynamically (radiatively) forced FSWs. However, this distinction is not correct. As shown in previous works not cited by the authors (Waugh et al., JGR 1999; Waugh and Rong, JMSJ 2002; Black et al., JAS 2006; Black and McDaniel, JAS 2007), all FSWs are dynamically forced. This is because the weakening stratospheric westerlies during the Spring season permit

vertical propagation of planetary waves from the troposphere into the stratosphere before they are trapped by stratospheric easterlies during the Summer. Also, arbitrarily identifying FSWs on the basis of temperature anomalies is not correct. It is possible for strong dynamical forcing late in the season to produce a large stratospheric warming but only a small temperature anomaly relative to the climatologically warmer temperatures late in the season. Thus, such an event would be misclassified by the authors as a radiatively forced event.

It would be far more interesting and original to classify the FSWs according to the relative contribution of radiative warming versus dynamical warming (through vertical wave activity flux convergence). Surely all FSWs have a radiative component to them, especially those late in the season, but what distinguishes those FSWs that are primarily radiatively forced versus those that are mostly dynamically forced? Is it the time of the season or are there other complexities? These questions have not been answered by the authors (nor others) but deserve attention.

Lesser concerns are listed below.

1. The term "inversion" used throughout has a well-known thermodynamic meaning and should be replaced by the more typically used "reversal".
2. Geopotential wave 2 is not shown in Figure 2, as stated in the text.
3. The statement in the paragraph below Figure 2 that "a February SSW favoring a late radiative FSW and a March SSW favouring an early dynamical FSW" is not supported by any figures.
4. At the end of that paragraph, the second principal component is discussed, but what about the first principal component?

REVIEWER COMMENTS:

We thank the three reviewers for their very constructive comments that allowed us to improve our article considerably. The detailed response to these comments is provided below.

Reviewer #1 (Remarks to the Author):

Review of the Nature Communications Earth & Environment article „Final Stratospheric Warming and the memory of the stratosphere” by Alain Hauchecorne, Chantal Claud, Philippe Keckhut, Alexis Mariaccia.
The authors investigate the final stratospheric warming (FSW) in the Arctic spring using 71 years of ERA5 data. They divide the FSW into dynamically driven FSW and radiatively driven FSW using the date of the final wind reversal in the stratosphere and the maximum temperature anomaly around this date. Afterwards they compare stratospheric characteristics of these two classes covering one year but with a focus on winter. The major finding of this study is that the state of the stratosphere in mid-winter is correlated with the state of the stratosphere in spring and that in turn is correlated with the state of the stratosphere in summer at least until July. These results are novel and will be of interest to others in the community since it has the potential to improve the sub seasonal to seasonal forecast not only in spring but also in summer. Overall this work is convincing but needs minor further evidence and some clarification and corrections (see below).

Comments:

The sentence “In early spring the stratospheric zonal reverse from winter westerly circulation to summer easterly circulation” in the introduction sounds strange and should be rephrased.

The sentence has been rephrased “In early spring the stratospheric zonal wind reverses from wintertime westerly circulation to summertime easterly circulation”.

“Major SSW events are preceded by one or several minor SSWs characterized by peaks of warming in the middle and upper polar stratosphere but without zonal wind inversion.” For this statement a reference is missing. Major SSW are not always preceded by minor SSWs but often.

Replaced by “Major SSW events are often preceded by one or several minor SSWs”. A reference is added.

In Final stratospheric warming: in the last two points a “before” is missing in “from 7 days to 7 days after the inversion day”. Thus, is should be “from 7 days before to 7 days after the inversion day”

OK, “before” added.

“Figure 2 shows the amplitude of geopotential wave 1 and 2 during the FSW”: Figure 2 shows only the amplitude of wave 1 and not wave 2. Please correct that also in the subsequent sentence.

OK, corrected.

Figure 1: The font size could be larger. The headline in the left plot is misleading as the date of the final warming is shown but also the temperature anomaly. It would be helpful to write the correlation coefficient into the right plot. Additionally, it would be helpful to depict which dots belong to the dynamical FSW and which to the radiative FSW, either by different colors of the dots or by including rectangles showing the defined thresholds respectively. In the figure caption please correct “corelation” to “correlation”.

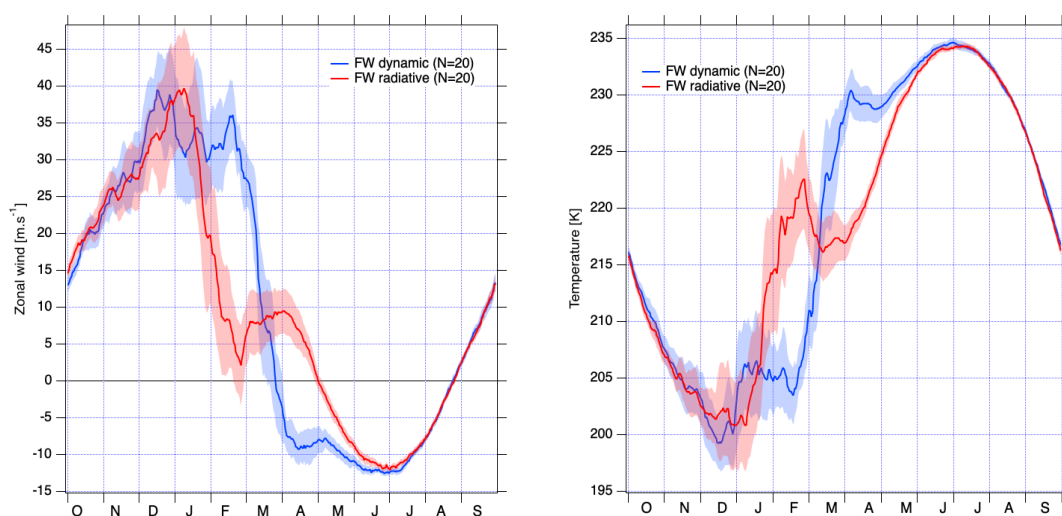
The suggested modifications have been made, including the addition of the correlation coefficient in the right panel.

Figure 2: The first letter of the x-axis label should also be a capital letter as for the y-axis.

“... radiative composite with temperature anomaly < 5K (40 members)”: Is the result even clearer when using 0K (zero) as a threshold? When using 5K the days of the radiative FSW overlap with those of the dynamical FSW.

We agree that there is slight overlap between the ireversal day with temperature anomaly > 10 K and < 5 K. The 5K was been fixed to increase the statistics. If we use the more the 0 K limit for radiative FSWs, the main results are not changed and the separation between the two composites is even stronger. In particular, the wind deceleration in January-February is stronger. We decide to follow the reviewer’s suggestion to fix the temperature anomaly to < 0 K for the radiative composite in the revised version of the paper.

With temperature anomaly < for the radiative composite:



With temperature anomaly < 5 K for the radiative composite:

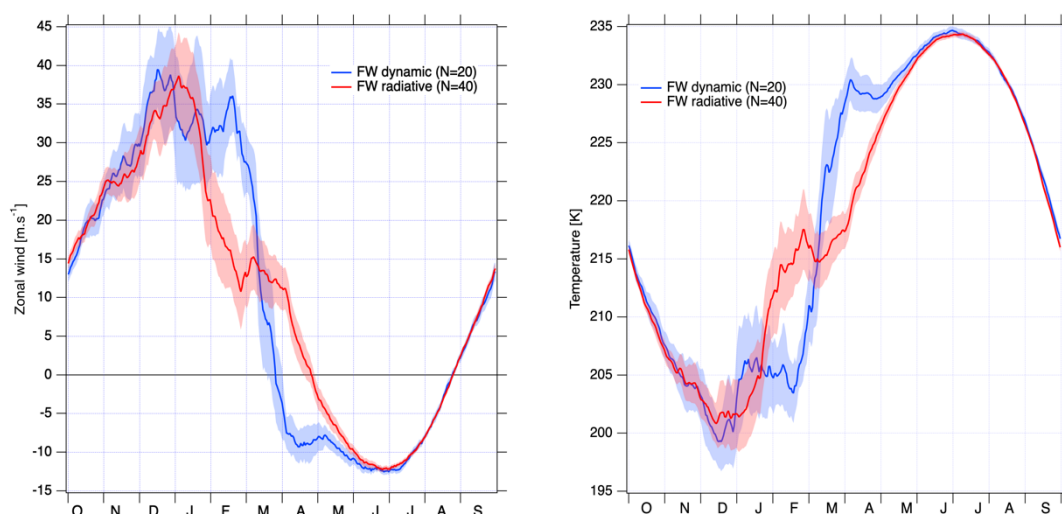


Figure 3: I suggest to include the overall composite as a grey line. This way, quite inaccurate statements like “relatively strong vortex in February” could be better quantified.

Done.

“We can said that there is a memory of the stratosphere ...” please correct to “We can say that there is a memory of the stratosphere ...”

Corrected.

Figure 4: Why is the first plot larger as the other two? In the first plot the letters F and half of the M are not visible. Please correct that. You wrote in the figure caption “For correlation between two months of the same variable, the diagonal is left blank ...”. However, this is true only for the left plot. This should be corrected for the middle and right plot.

Please delete the incomplete sentence: “between February and March, and March and May June.”

Done.

Why are daily data at 12UT used and not daily mean data?

To our knowledge, ERA5 data are available at specific hours but not as daily mean. To reduce the amount of data to process, we decided to choose 1 value per day at 12 UT. We are looking at planetary waves and SSWs, evolving with time constants of several days at least. We consider that the 12 UT value is not very far from the daily mean.

Where were the levels 70 and 100hPa used in this study?

The levels 70 and 100 hPa are not used. We corrected the text.

Please correct: "... we use the data set ERA5.1 for the period 200-2006 to correct ..." to "... we use the data set ERA5.1 for the period 2000-2006 to correct ..."

Corrected.

Reviewer #2 (Remarks to the Author):

Comments on "Final Stratospheric Warmings and the memory of the stratosphere" by Hauchecorne et al. (2021)

Summary

Hauchecorne et al et al. (2021) used the ERA5 reanalysis to study the lead/lag relationship between the stratospheric circulation, which is probably a basis for the subseasonal to seasonal weather forecast. However, I have a worry about the originality and novelty of the paper that some result in the paper might be found in previous publications. The authors did not well review on the previous studies concerned the SFW, and changed to use an alternate term for early and late SFW (radiative and dynamical SFW in this paper). As far as I know, most of previous studies used stratospheric final warming (SFW) to name the seasonal transition from westerly to easterly in the stratosphere, although Butler et al. 2019 also used the terminology stratospheric final warming. Due to the problematic issues, I would not suggest to publish the paper at this time. A substantial revision is required.

We thank the reviewer for providing a list of previous publications on the prediction of SSWs by climate models and on SFWs and their relation with tropospheric and surface weather. References to these publications have been added in the introduction. We recognize that the discussion of previous studies on SFWs was missing in the first version of the paper. The two acronyms FSW or SFW were used in the previous publications. However, SFW seems to be more widely used than FSW and we agree to follow the recommendation of the reviewer. The separation between early and late SFWs and the relation with planetary wave activity was already discussed in previous papers. The first originality of our paper is in the clear identification of this separation into two categories based on physical processes, the early dynamical SFWs forced by the amplification of planetary waves as for mid-winter SSWs and the late SFWs mainly driven by radiative processes. The second originality is to show that the two composites formed with dynamical and radiative SFWs follow a very different evolution in 60°N zonal wind and polar temperature from the month of January, which indicates that that the probability of having a type of heating can be estimated 2 months in advance, with a potential improvement in the seasonal weather forecast.

Major comments

1. The abstract begins from the SSW, which might be shortened and replaced by the SFW. This paper mainly focuses on the seasonal transition of the stratosphere, and all the composites and analyses are around the final warming. The abstract might be improved by considered the SFW first.

The abstract has been reorganized with SFW first and less emphasis on SSW.

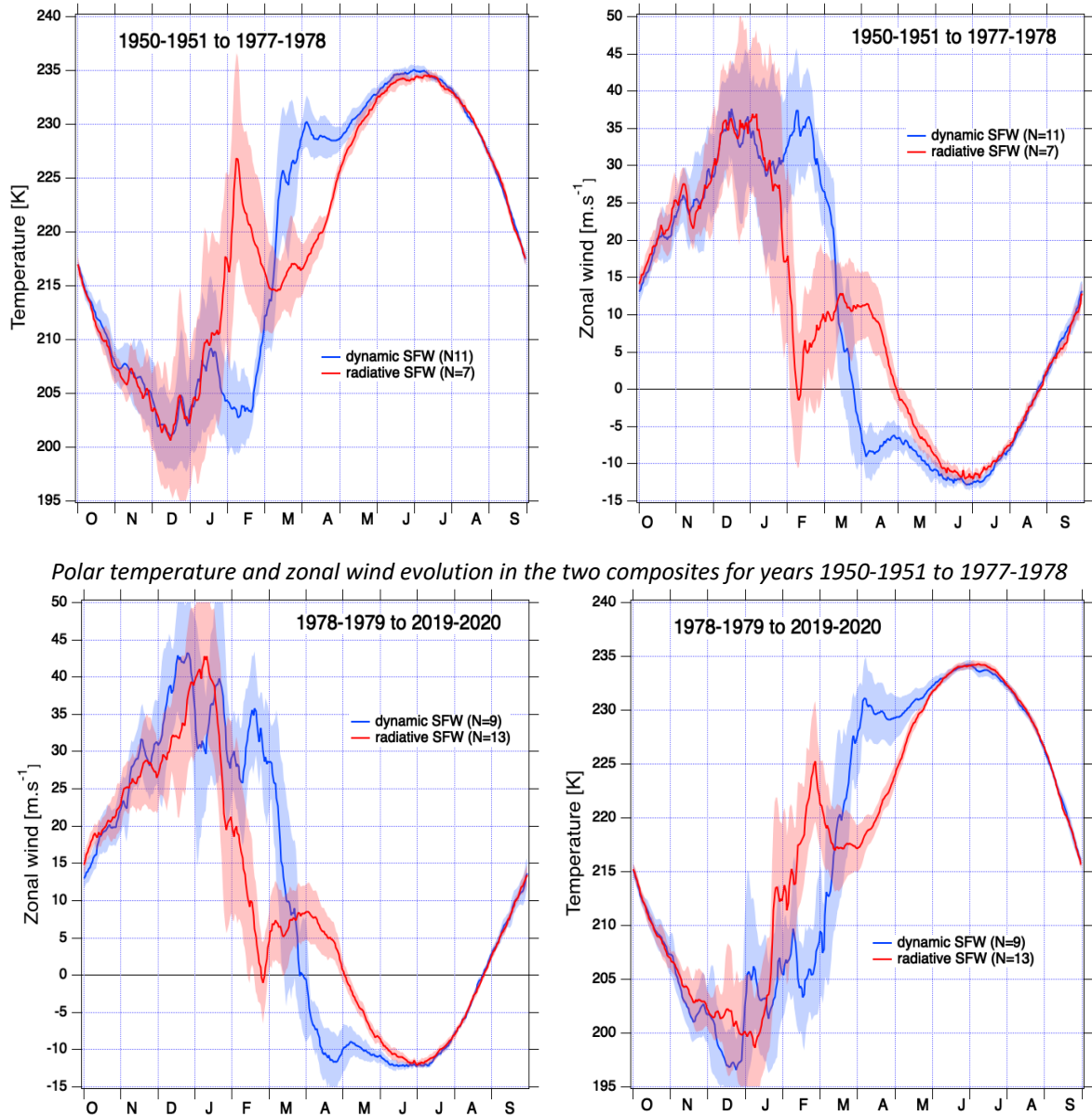
2. The SFW-SSW relationship was studied in Hu et al. 2014, and they found that a midwinter SSWs might be associated with a late and radiative SFW. Whereas, a SSW-absent midwinter might be followed by a early dynamic SSW. The authors might consider the previous study in the introduction.

Previous works on SFW are now mentioned in the introduction, including the Hu et al. (2014) work.

3. Compared with the data from 1979-2020, the data before 1979 is not very trustworthy. After 1979

satellite observations were available and the data are trustworthy. If the authors only use the post-1979 data, I am not sure if the results will change.

We agree that post-1979 data are better due to satellite observations. Before 1979 the main source of stratospheric data was from radiosondes. However, the state of the polar stratosphere up to 10hPa is rather well represented in ERA5 during the period 1950-1978 thanks due the dense network of radiosonde in the Northern Hemisphere. To test the impact of the lack of satellite observations before 1979, we performed a separate analysis using the years 1950-1978 and 1979-2020. The evolution of the polar temperature and the zonal wind in the two composites is very similar for both periods (see figures below). We note a higher frequency radiative SFWs during the first period (11 in 28 years, 37%) than in the second one (9 in 42 years, 21%) but 4 dynamical SFWs have been observed during the last decade (2011, 2014, 2015 and 2016).



Polar temperature and zonal wind evolution in the two composites for years 1978-1979 to 2019-2021

4. Final warming definition is also problematic. Final warming should correspond to a polar warming in the stratosphere, so the negative temperature anomalies are unbelievable at all. The authors did

not show the page number and line number in the manuscript, it is not easy to point out the place. I leave the work for the authors themselves.

The date of the final warming is defined by the final wind reversal, not by an increase in polar temperature. The temperature anomaly is the difference between the actual temperature and the 71-years climatology for the same day of the year. In the case of late radiative warming, the polar temperature is not increased by the wave activity and the temperature may be lower than the climatology that includes the years with more wave activity. This explanation is now added in the text.

Minor comments

5. P1: "owe their existence to the equator-to-pole gradient of the Coriolis force". I do not believe this is true. Please correct.

This sentence has been suppressed.

6. P1: "PWs are generated by temperature contrasts between the continents and the oceans and the flow over the orography". Should be thermal contrast.

Corrected.

7. P1: "There is a growing interest in the study of dynamical coupling between the stratosphere and the troposphere during SSW events due to the potential to improve sub-seasonal to seasonal weather predictions" Please refer to Rao et al. (2018, 2019), Taguchi et al. 2018, Karpechko et al. 2018. The first two references in the citation do not discuss the S2S prediction of warming events.

These references have been added in the introduction.

8. P2: "...causing the polar vortex to end..." Change "end" to collapse. Please refer to Rao and Garfinkel 2021.

Corrected, reference to Rao and Garfinkel (2021) added.

9. P2: "The objectives of this paper is to characterize FSW events according to their nature and their date of occurrence, and to explore the seasonal memory of the stratosphere in relation with mid-winter SSW and FSW events" Please mention that Hu et al 2014 have studied this.

Similar studies by Hu et al. (2014) are now mentioned in the second last paragraph of the introduction.

10. P2: Final warming event identification is not easy to read. Please refer to Rao and Garfinkel 2021 for more details.

Reference to Rao and Garfinkel (2021) added.

11. P2: "between -3.8K (in 1999) and +24.7K (in 2016)" -3.8 K is cooling rather than warming. Please check the results.

The results are correct. See our answer to comment #4 to explain a negative temperature anomaly at the time of the final warming.

12. P2: "During the period 1995-2010 the FSW dates were later and the temperature anomalies were smaller but the reverse was true after 2010." Please refer to Rao and Garfinkel Figure 2 (red line). The authors seemed to fail to read the most recent results for SFW.

We thank the reviewers for mentioning this very interesting recent publication. We refer now to this publication in relation with possible changes of the timing and intensity of SFWs.

13. P3: 20 members => 20 samples; 40 members => 40 samples

Corrected.

14. P3: "It means that the nature of the FSW is related to the evolution of the polar vortex during the preceding winter, a February SSW favouring a late radiative FSW and a March SSW favouring an early dynamical FSW." This was reported in Hu et al. 2014

We refer now to Hu et al. (2014) results in agreement with our own.

15. P4: Figure 4: the three paper is not of the same size. Please correct. The bottom left – top right diagonal line should be 1 in Figure 4a, 4b. Figure 4b is right but Figure 4a is wrong. Please correct the coding and update the figure.

The figures have been updated and put at the same size.

16. P5: first line: Delete "between February and March, and March and May- June."

Deleted.

17. P5: The first conclusion is not a new finding in this study. The discussion on the stratosphere-troposphere coupling is really lacking in this paper.

We recognize that our first conclusion is not totally new and that similar results have been previously published. However, we think that the originality of our paper is to build two composites (early dynamical and late radiative FSWs) and to show that the evolution of the stratospheric polar vortex in the two composites is very different starting in January. This separation may help to improve the seasonal weather forecast but the discussion on the stratosphere-troposphere coupling is behind the scope of our paper and will be the subject of future studies.

Suggested references:

Butler, A. H., A. Charlton-Perez, D. I. V. Domeisen, I. R. Simpson, and J. Sjöberg, 2019: Predictability of Northern Hemisphere Final Stratospheric Warmings and Their Surface Impacts. *Geophysical Research Letters*, 46, 10578-10588.

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Rao, J., and C. I. Garfinkel, 2021: Projected changes of stratospheric final warmings in the Northern and Southern Hemispheres by CMIP5/6 models. *Climate Dynamics*, 56, 3353-3371.

Suggested references added in the paper

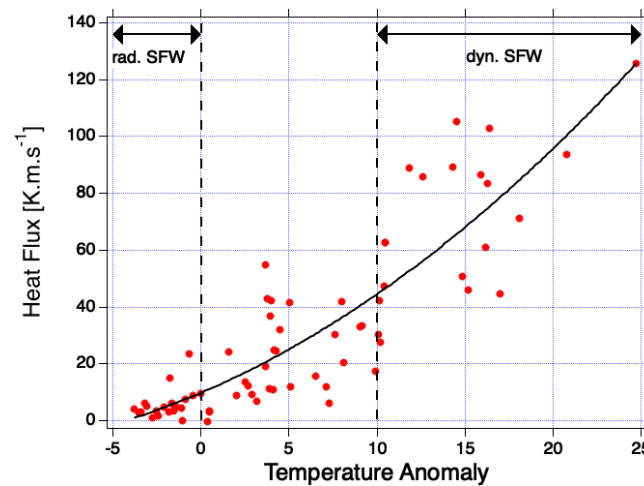
Reviewer #3 (Remarks to the Author):

In this manuscript, the authors distinguish between dynamically and radiatively forced Final Stratospheric Warmings (FSWs) on the basis of stratospheric temperature anomalies, with larger (smaller) anomalies identified as dynamically (radiatively) forced FSWs. However, this distinction is not correct. As shown in previous works not cited by the authors (Vaugh et al., JGR 1999; Waugh and Rong, JMSJ 2002; Black et al., JAS 2006; Black and McDaniel, JAS 2007), all FSWs are dynamically forced. This is because the weakening stratospheric westerlies during the Spring season permit vertical propagation of planetary waves from the troposphere into the stratosphere before they are trapped by stratospheric easterlies during the Summer. Also, arbitrarily identifying FSWs on the basis of temperature anomalies is not correct. It is possible for strong dynamical forcing late in the season to produce a large stratospheric warming but only a small temperature anomaly relative to the climatologically warmer temperatures late in the season. Thus, such an event would be misclassified by the authors as a radiatively forced event.

It would be far more interesting and original to classify the FSWs according to the relative contribution of radiative warming versus dynamical warming (through vertical wave activity flux convergence). Surely all FSWs have a radiative component to them, especially those late in the season, but what distinguishes those FSWs that are primarily radiatively forced versus those that are mostly dynamically forced? Is it the time of the season or are there other complexities? These questions have not been answered by the authors (nor others) but deserve attention.

Lesser concerns are listed below.

We agree to said that all FSWs (renamed SFWs in the paper following the Reviewer #2 recommendation) are both dynamically and radiatively forced but it is clear that the contribution of the two processes may be very different. In the case of early SFWs the reversal of the zonal wind is in general very rapid, with a strong peak in temperature and an amplification of the planetary wave activity. In the case of late SFWs the reversal of the wind is in general much smoother and the polar temperature stays colder than the climatology. With the stronger criterion (temperature anomaly < 0) for radiative SFWs, the difference in the evolution of polar temperature and zonal wind between the two composites is even larger (see updated Figure 3). As shown in Figure 2, the temperature anomaly is highly correlated with the amplitude of geopotential wave 1, indicating that a positive temperature is a good proxy of a strong dynamic forcing (In Figure 3 the amplitude of the geopotential was taken by mistake at 45°N in the first version. It is now at 60°N). The temperature anomaly is also highly correlated with the mean vertical heat flux during the two weeks before the reversal day (see Figure below, also added in the new version). All SFWs classified as radiative using the temperature anomaly correspond to a low heat flux ($< 24 \text{ ms}^{-1}$). On the contrary all dynamical SFWs correspond to a strong flux ($> 40 \text{ Kms}^{-1}$). We conclude that the polar temperature anomaly is a good proxy to classify SFWs according to the dominant forcing (radiative or dynamic). The use of vertical heat flux instead of temperature anomaly to build SFW composites would not change substantially our results.



1. The term "inversion" used throughout has a well-known thermodynamic meaning and should be replaced by the more typically used "reversal".

The term "inversion" is replaced by "reversal".

2. Geopotential wave 2 is not shown in Figure 2, as stated in the text.

The reference to wave 2 is removed in the text.

3. The statement in the paragraph below Figure 2 that "a February SSW favoring a late radiative FSW and a March SSW favouring an early dynamical FSW" is not supported by any figures.

This statement is illustrated by Figure 3. For the radiative composite, we observe a peak in temperature and a strong deceleration of the zonal wind in February while in the dynamical composite the temperature peak and the zonal wind deceleration occur in March – early April. This is in fact just a reformulation of the former sentence and we decided to remove it to lighten the text.

4. At the end of that paragraph, the second principal component is discussed, but what about the first principal component?

We decided to remove the paragraph on principal component analysis in the new version of the paper. This is a very interesting study that help us to better classify the years according to the evolution of the polar vortex but it deserves much more attention than just a small paragraph and it will be the subject for a future paper.

5th Nov 21

Dear Dr Hauchecorne,

Your manuscript titled "Stratospheric Final Warmings and the memory of the stratosphere" has now been seen by our reviewers, whose comments appear below. In light of their advice I am 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 address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Heike Langenberg, PhD

Chief Editor
Communications Earth and Environment

On Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Review Round 2 of the Nature Communications Earth & Environment articles „ Stratospheric Final Warming and the memory of the stratosphere” by Alain Hauchecorne, Chantal Claud, Philippe Keckhut, Alexis Mariaccia.

The authors investigate the final stratospheric warming (FSW) in the Arctic spring using 71 years of ERA5 data. They divide the FSW into dynamically driven FSW and radiatively driven FSW using the date of the final wind reversal in the stratosphere and the maximum temperature anomaly around this date. Afterwards they compare stratospheric characteristics of these two classes covering one year but with a focus on winter. The major finding of this study is that the state of the stratosphere in mid-winter is correlated with the state of the stratosphere in spring and that in turn is correlated with the state of the stratosphere in summer at least until July.

These results are novel and will be of interest to others in the community since it has the potential to improve the sub seasonal to seasonal forecast not only in spring but also in summer. My comments were implemented to my satisfaction. Overall this work is convincing but needs a minor clarification and some corrections (see below).

Comments:

In Final stratospheric warming: in the second point a “before” is missing in “from 7 days to 7 days after the inversion day”. Thus, it should be “from 7 days before to 7 days after the wind reversal”

In Final stratospheric warming: in the last point I suggest to change “... before the reversal day” to “... before the wind reversal day”.

Line 89/90: please delete “of” in: “... timing of and intensity of SFWs ...” to “... timing and intensity of SFWs ...”

Line 100: please add the Figure number (2) in the brackets.

Line 100 – 102: At this point in the text it is not clear how you classify radiative and dynamical SFWs. The description of your classification comes later in line 117 to 119. You should at least give a short comment about how you define the two classes at this point.

Figure 1, figure caption: please correct “(in blue, left scale)” to “(in blue, right scale)”.

Figure 2, figure caption: please correct “anomany” to “anomaly”.

Line 126: Please describe shortly the already published results.

Line 160 and 170: Please correct: “an SSW” to “a SSW”.

Reviewer #2 (Remarks to the Author):

The authors well replied to my comments and made substantial revision for the paper. I have no further questions. I recommend to publish the paper in the present form.

Reviewer #3 (Remarks to the Author):

This revised manuscript is now acceptable for publication following the correction of one minor typographical error: the units of low heat flux between lines 100 and 105 should be Kms^{*-1} .

Reviewer #1

In Final stratospheric warming: in the second point a “before” is missing in “from 7 days to 7 days after the inversion day”. Thus, it should be “from 7 days before to 7 days after the wind reversal”
Corrected

In Final stratospheric warming: in the last point I suggest to change “... before the reversal day” to “... before the wind reversal day”.
Modified

Line 89/90: please delete “of” in: “... timing of and intensity of SFWs ...” to “... timing and intensity of SFWs ...”
Corrected

Line 100: please add the Figure number (2) in the brackets.
Corrected

Line 100 – 102: At this point in the text it is not clear how you classify radiative and dynamical SFWs. The description of your classification comes later in line 117 to 119. You should at least give a short comment about how you define the two classes at this point.

The definition of the two classes has been moved before these lines and has been rephrased. New text:

“To better understand the difference between SFWs associated with high and low temperature anomalies, two composites were constructed, the dynamic composite including all years with an anomaly > 10 K (20 samples) and a radiative composite including all years with an anomaly < 0 K (20 samples). Using this classification, all SFWs belonging to the radiative composite correspond to a low heat flux ($< 24 \text{ Kms}^{-1}$). On the contrary all SFWs belonging to the dynamical composite correspond to a strong heat flux ($> 40 \text{ Kms}^{-1}$).”

Figure 1, figure caption: please correct “(in blue, left scale)” to “(in blue, right scale)”.
Corrected

Figure 2, figure caption: please correct “anomany” to “anomaly”.
Corrected

Line 126: Please describe shortly the already published results.

We added the sentence “showing that early SFWs tend to be preceded by non-SSW winters, while late spring SFWs are mostly preceded by SSW events in midwinter”.

Line 160 and 170: Please correct: “an SSW” to “a SSW”.
Corrected

Reviewer #3

This revised manuscript is now acceptable for publication following the correction of one minor typographical error: the units of low heat flux between lines 100 and 105 should be Kms^{-1} .
Corrected