Answers to reviewer 1: (in green in the "tracking" version)

We would like to thank reviewer 1 for the time taken to suggest new references and for the advices. We have generally taken these suggestions into account and modified the text. You will find below our answers to the major and minor comments.

Major comments

Lack of a sufficient review on the most recent publications.

The impact of ENSO, solar cycle, and QBO on the polar vortex in both hemispheres has been widely and exhaustively studied in literature. However, this manuscript fails to provide a sufficient review on the most recent publications. The impact of the canonical ENSO on the SH polar vortex is insignificant in both observations and modeling studies (Rao and Ren 2020 https://doi.org/10.1007/s00382-019-05111-6, Hurwitz et al. 2011 https://journals.ametsoc.org/view/journals/atsc/68/4/2011jas3606.1.xml).

The impact of QBO on the stratosphere is also reported in the latest literature (Rao et al. 2020 https://doi.org/10.1175/JCLI-D-19-0663.1; Butchart et al. 2019 https://doi.org/10.5194/gmd-11-1009-2018).

As the solar cycle's impact on the SH stratospheric polar vortex, it is also discussed most recently in Figure 3 of Rao et al. 2020JGR (https://doi.org/10.1029/2020JD03272). I suggest the authors to explore more of recent publications to see what has been done and what has not.

Thanks for the many advices on literature. We have added some of the references suggested in the introduction for the general presentation of the use of these factors in the literature:

Page 3 lines 23-28: "Domeisen et al. (2019) (https://doi.org/10.1029/2018RG000596) have indicated that the El Niño events are associated with a warming and weakening of the polar vortex in the polar stratosphere in both hemispheres, and Li et al. (2016) have shown that early breakup of the southern polar vortex occurs during El Niño events. In contrast, Rao and Ren., (2020) did not find a significant impact of the canonical ENSO index on the Southern Hemisphere polar vortex in both observations and modeling studies. With indices of Niño-3 and Niño-4 regions, Hurwitz et al., (2011) (https://doi.org/10.1175/2011JAS3606.1) have shown that during "warm pool event" (positive SST in Niño-4 regions) the heat flux is higher and the Antarctic vortex breaks up earlier."

Regarding the impact of ENSO, we would first like to remind that our study is focused on the intensity and position of the polar vortex edge, parameters that are generally not considered in other studies, which makes comparisons sometimes difficult. Following both reviewers remarks on the use of ENSO index, we have revised our analysis in section 4.2.3 and have excluded years with MEI.v2 values between the - 0.5 and + 0.5 as recommended by NOAA [4] (https://psl.noaa.gov/enso/mei/). With the revised calculation of the ENSO MEI.v2 index, we found, by removing the neutral years, that the polar vortex breaks up early during the warm ENSO years phase. See the new Figure 6 below with the combined SC and ENSO indices, plus the composite analysis with ENSO only.

Please see that references like « [4] » are defined at the end of the documents, in the « data availability » section.

We did not include a sensitivity study based on the use of Niño 3 and Niño 4 index as in Hurwitz et al., (2011) but we think it is a good idea for future work.

At the end of section 2.2 we have changed the sentence as follows:

Page 5 lines 20-22: "Then mean ENSO over the period is sorted to distinguish La Niña, characterized by negative values below -0.5 MEI.v2 (cold ENSO), and El Niño by positive values higher than +0.5 MEI.v2 (warm ENSO). Then 10 wENSO and 14 cENSO years are considered in this study."

The new Figure 6 with the combined SC and ENSO indices is as follows:

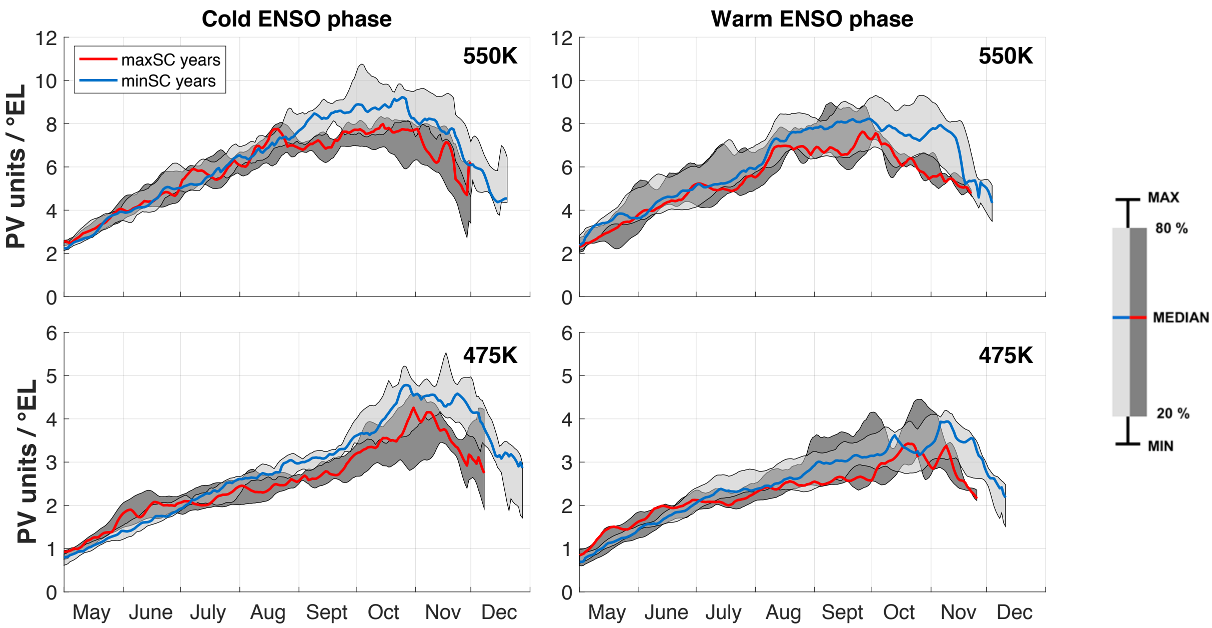
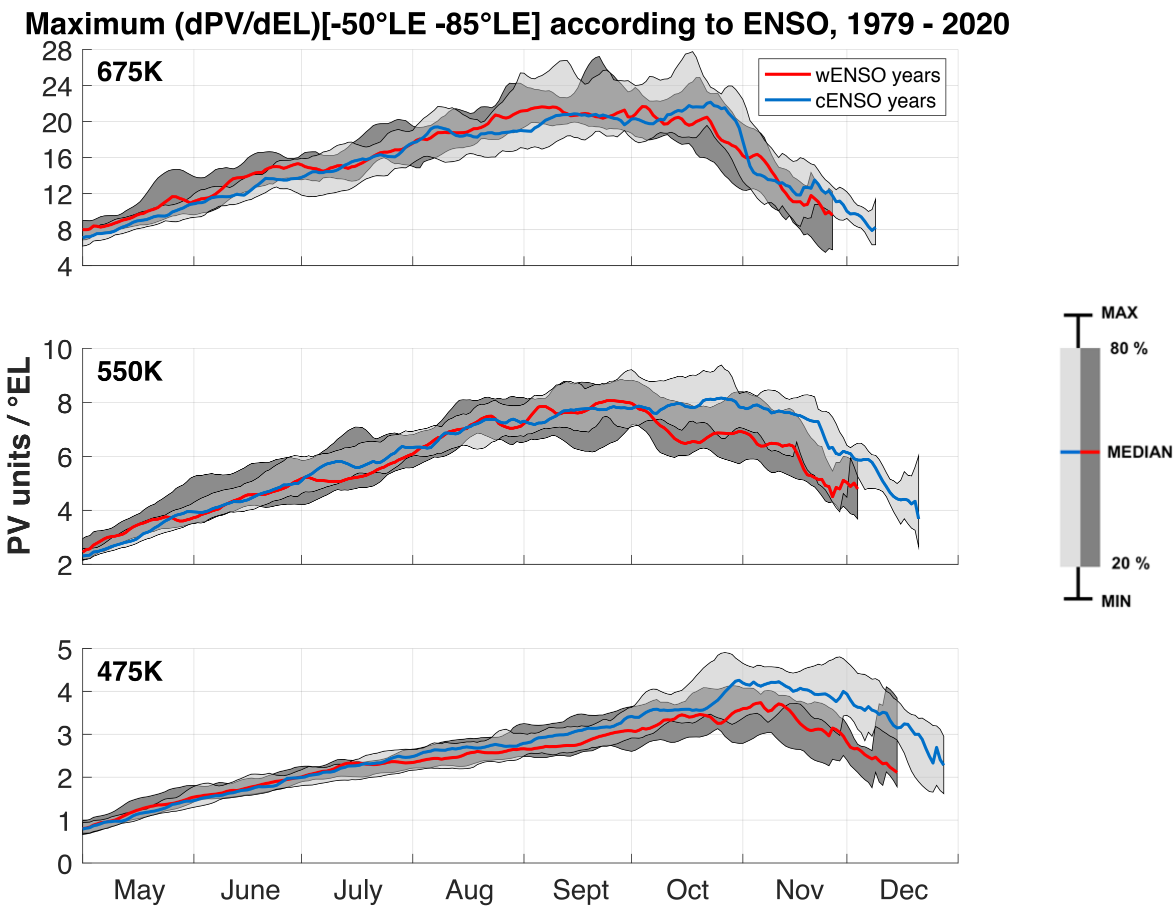


Figure 6: Composites of vortex edge intensity seasonal evolution according to SC and ENSO for the 1979 – 2020 period, from top to bottom: 550 K and 475 K. Left (right) panels represents cENSO (wENSO) phases (see section 2.2). Red (blue) curves represent median values for maxSC (minSC) years. Dark (light) grey-filled areas indicate values between 20 and 80 percentiles for maxSC (minSC) years.

The following figure (not shown in the article), displays the composite analysis with ENSO only. This figure is requested and described in the minor comment section 4.2.2, 4.2.3.



<u>Figure:</u> ENSO composites of vortex edge intensity's annual seasonal evolution for the 1979 – 2020 period, from top to bottom: 675 K, 550 K and 475 K. Red (blue) curves represent median values for wENSO (cENSO) years. Dark (light) grey-filled areas indicate values between 20 and 80 percentiles for wENSO (cENSO) years.

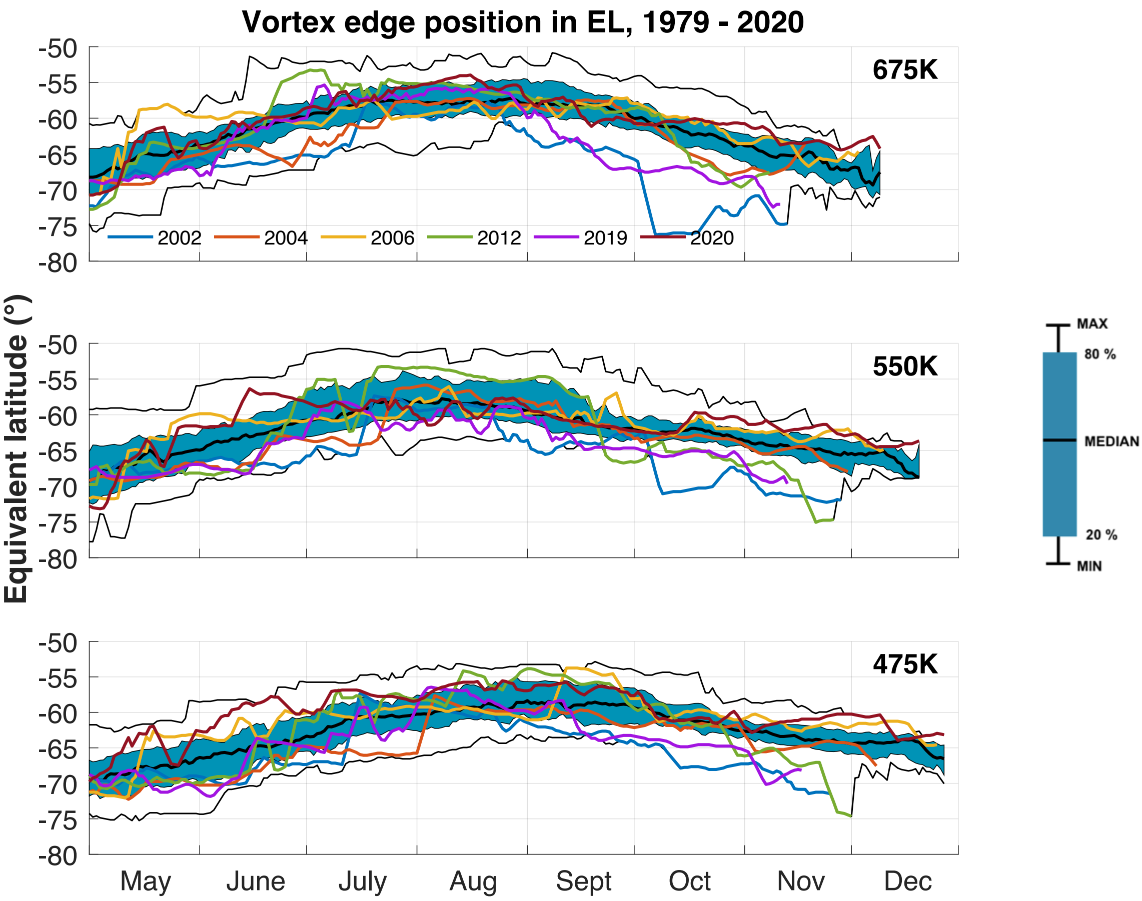
Discussion on the 2002 SSW but lack of the 2019 SSW

Ample evidence has reported the similarity of the 2002 and 2019 SSWs in the SH. The paper discusses the main characteristics of the polar vortex edge in 2002 but fails to mention the 2019 SSW. Related studies are also ignored in the paper. The main characteristics of the SH polar vortex during the 2019 SSW have also been reported in Rao et al. 2020JGR (https://doi.org/10.1029/2020JD032723), Shen et al. 2020GRL (https://doi.org/10.1029/2020GL089343). The background of this study is still lacking and the references can be further improved.

The 2019 sudden stratospheric warming has indeed been mentioned in the original version of the article (see page 16, lines 1-2) but we agree that this event deserves more attention in the article. See below new information and references added at various locations in the manuscript about the 2019 SSW.

Page 9, lines 4-7: "The 2019 winter impacts the minimum curve during the last 2 weeks of September at 675 K and is located between the minimum curve and the 20th percentile from September until the beginning of November for each level. During this year, a minor SSW occurred at the end of August, which displaced and weakened the polar vortex. The stratospheric polar vortex abruptly weakened and warmed on August 25th (Lim et al., 2021) (https://doi.org/10.1175/BAMS-D-20-0112.1). MERRA2 analyses showed a rapid 50 K increase of polar temperature at 10 hPa between September 5 and September 11 (Yamasaki et al., 2020) (https://doi.org/10.5194/acp-20-5111-2020). Minimum values of winds at 10 hPa and 60°S were found on September 18 (Rao et al., 2020) (https://doi.org/10.1029/2020JD032723). This event induced the smallest Antarctic ozone hole on record. Although it appeared earlier in August, the ozone hole reached an area of 15 million km^2 by September 1, but decreased to an area of 8 million km^2 by September 17 (Lim et al., 2021) (https://doi.org/10.1175/BAMS-D-20-0112.1)."

This figure (not shown in the article), supports the paragraph above, and shows the 2019 winter in purple, plotted among other winters, superimposed on the curves of Figure 2 of the article:



Page 20 line 5-7: "At all levels, particularly at 675 K and 475 K, there is a decrease in the edge position of the 2019 polar vortex, due to the minor SSW mentioned in section 4.1. Contrary to the 2002 SSW, the 2019 SSW occurred during a period of solar minimum"

Start date of the SH polar vortex and the final warming date

In my understanding, the start date of the stratospheric polar vortex in both hemispheres are mainly forced radiatively due to the annual cycle, and it should be very stable. I checked the start date of the polar vortex in the NH using the zonal mean zonal wind at 60N and 10hPa as the threshold. I found that the start date of the NH polar vortex is very stable. In contrast, the *final warming date in both hemispheres differs from year to year due to the dynamics associated with planetary wave activities. However, this study shows that both the start date and end date of the SH polar vortex have a large interannual variability. What forces such a strong variation of the start date of the stratospheric polar vortex. The authors also failed to mention the most recent studies on the final warming date in the SH (Rao and Garfinkel 2021CD, https://doi.org/10.1007/s00382-021-05647-6). They also discussed the possible impact of the ozone depletion and recovery on the polar vortex final warming date.*

In our study, a larger inter-annual variability is observed for the breakup dates than for the onset dates at the various levels and threshold values. We have calculated the standard deviation over the period after averaging the curves of the different thresholds and removing the long-term trend by a 3-degree polynomial. The standard deviation for the onset dates are equal to 8.2, 4.8 and 3.7 days at 475 K, 550 K and 675 K, compared to 10.6, 10.2 and 10.4 days, respectively.

For the onset dates, the variability is indeed more important for the 475 K level.
At this level, the wind is slower and less stable. It results in a slowly vortex formation with an important inter-annual variability of onset dates.

We did not add the reference to Rao and Garfinkel 2021CD (https://doi.org/10.1007/s00382-021-05647-6), because in this study the break up date is determined at 10 hPa level which is too high for the comparison with our results.

Minor comments

P1L18: This sentence should be supported by some citations. Please insert.

We have added the Randel and Newman, (1998) (https://doi.org/10.1007/978-1-935704-10-2_9) reference as follows:

Page 1 lines 18-19: "It appears due to the seasonal cooling associated with the decrease of solar radiation above the pole (Randel and Newman, 1998)."

L24: The most recent report by Rao and Garfinkel 2021CD checked the interannual variation of the final warming date from CMIP5/6 models and JRA55 reanalysis. Explore if you missed more recent reports.

The sentence is just very generic. We have added some references as well as the suggested one, as follows:

Page 1 lines 24-25, page 2 line 1: "Over Antarctica, the polar vortex is generally present from April until December with a large variability in the breakup dates resulting from the year-to-year variability of dynamical processes in the stratosphere (Waugh and Randel 1999 (https://doi.org/10.1175/1520-0469(1999)056<1594:COAAAP>2.0.CO;2); Rao and Garfinkel 2021)."

P2L1: The reference put too much on the ozone depletion, but review on other aspects of the stratospheric polar vortex is insufficient.

This part of the introduction was changed as follows in order to reduce the reference to ozone depletion and insert new statement about the importance of the southern polar vortex.

We removed the sentence "PSCs are found to be much more abundant in the Antarctic polar vortex as compared to the Arctic polar vortex due to the increased stability of the southern polar vortex. As a result of the asymmetry in polar vortices intensity, the southern vortex experiences much colder temperatures in winter, which results in stronger ozone depletion over a large area (the so-called ozone hole)." on page 2 lines 11-15 of the original document

We added a paragraph about the stratospheric vortex impact on the surface as follows:

Page 2 lines 21-27: "The polar vortex also has an impact on the climate surface in both hemispheres. Indeed, studies have shown an effect of the stratospheric polar vortex displacements on cold spells in the northern hemisphere, in North America (Tripathi et al., 2015) (https://doi.org/10.1002/qj.2432). In the southern hemisphere, others have shown that a weak vortices can have an influence on the surface climate in Australia. Lim et al. (2019) (https://doi.org/10.1038/s41561-019-0456-x) have highlighted that selected years of lower vortex intensity results in higher temperatures and less precipitation over eastern Australia. The dramatic weakening of the Antarctic vortex in 2019 had a large impact on meteorological conditions over the country that resulted in the strong Australian fires of the turn of the year 2019/2020.

L13: The ozone depletion events are also existing in the NH. The AUG organized one special issue for the NH ozone loss event in the 2019/2020 winter:

https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1944-8007.ARCTICSPV. Choose several references and discuss the ozone depletion in the NH (e.g., Garfinkel 2020, 2021; Feng et al. 2021). The authors really should read more to enrich the introduction of the paper. This version is really not satisfactory.

Our paragraph does not exclude the fact that there is no ozone loss in the Arctic. In fact, the authors are well aware of ozone depletion in the Arctic and have contributed to the evaluation of Arctic ozone depletion with several articles. We have however added more references and inserted a new sentence as follows:

Page 2 lines 4-6: "Ozone loss occurs in both hemispheres. This loss is variable in the northern hemisphere as many studies have shown (Solomon et al., 1999 (https://doi.org/10.1029/1999RG900008); Goutail et al., 2005 (https://doi.org/10.5194/acp-5-665-2005); Pommereau et al., 2018 (https://doi.org/10.1016/j.crte.2018.07.009); WMO 2018 (http://ozone.unep.org/science/assessment/sap); Grooß and Müller, 2020 (https://doi.org/10.1029/2020JD033339))."

L17-19: The future recovery of the ozone and its possible impact on the vortex in both hemispheres are also discussed in Rao and Garfinkel 2021CD.

We have inserted the following references in the sentence:

Page 2 lines 20-21: "Many studies document this phenomenon (e.g. WMO 2018 and references therein)."

L28: What is wind module? Please specify.

The following equation defines de wind module W:

$$W = \sqrt{U^2 + V^2}$$

Where U is the meridional wind and V is the zonal wind.

After correction and suggestions made by the reviewer 2, "wind module" has been replaced by "wind mean speed" throughout the text.

P3L2-3: The impact of QBO, ENSO, and solar cycle on the polar vortex in both hemispheres have been widely studied in literature. Please be more exhaustive when you mention the most recent studies. Please see my major comments.

Done by adding citations and suggestions in the text as described in our answer to the reviewer's first major comment.

L9-10: This conclusion is also reported by Rao et al. 2020JGR when they checked the possible impact of the QBO phase on the 2019 SSW in SH.

In this paragraph, we refer to studies that consider several winters. We thus added the following sentence and reference:

Page 3 line 19-20: "Camp and Tung (2007) (https://doi.org/10.1029/2006GL028521) supports this finding that the state of the northern hemisphere polar stratosphere is less perturbed during solar cycle minimum and westerly QBO phases."

L12-19: This part should be moved to the method section. Or I suggest to remove or shorten.

We understand this part is not clear. Here is the mentioned paragraph:

"Several methods have been suggested in order to determine the onset and breakup dates of the polar vortex. They are based on a minimum area computed from equivalent latitudes (Manney et al. 1994 (https://doi.org/10.1029/94GL02368); Zhou et al. 2000 (https://doi.org/10.1029/1999GL011018)) or wind speed thresholds at the edge of the vortex (e.g. Nash et al. 1996 (https://doi.org/10.1029/96JD00066)). Manney et al. (1994) and Zhou et al. (2000) consider that the vortex breaks down and disappears when its size falls below 1% of the Earth's surface, or when its edge position is larger than 78.5°EL. More recently, Millan et al. (2020) (https://doi.org/10.5194/acp-2020-1181) compared the polar vortex evolution with different reanalyses, including ERA-Interim. Results showed that all reanalyses where in agreement with the reanalysis ensemble mean (REM), which shows that we can be confident with the ERA-Interim reanalyses for our study."

Here is the new paragraph:

Page 3 lines 28-30: "Several methods have been suggested in order to determine the onset and breakup dates of the polar vortices. They are based on a minimum vortex area computed from equivalent latitudes (Manney et al. 1994; Zhou et al. 2000) or wind speed thresholds at the edge of the vortex (e.g. Nash et al. 1996). The latter is used in WMO (2018) to calculate the dates at which the Arctic and Antarctic polar vortex breaks each spring."

And we have moved the underlined part above, to the section 2.1:

Page 4 line 15-18: "Recently, Millan et al. (2020) compared the polar vortex evolution with different reanalyses, including ERA-Interim. Results showed that all reanalyses where in agreement with the reanalysis ensemble mean (REM), which shows that we can be confident with the ERA-Interim reanalyses for our study."

L24: You might emphasize the novelty of this study, because the possible impact of QBO, ENSO, and solar cycle have been widely reported.

We have added this sentence at the end of the paragraph.

Page 4, lines 1-2: "This is the first study of the variability of the Antarctic stratospheric polar vortex edge and persistence over a long period (42 years)."

P4L7-12: This sentence is toooo.... long. Can you split this sentence and clearly describe the model MIMOSA. Please tell readers what MIMOSA consist of and how it can predict the PV. Is it a forecast model?

MIMOSA can be used as a forecast model.

The sentence mentioned is: "The MIMOSA model is a three-dimensional high-resolution PV advection model (Hauchecorne et al., 2002) (https://doi.org/10.1029/2001JD000491) which has been used to analyze, among other studies, the permeability of the southern polar vortex to volcanic aerosols from Cerro Hudson and Mount Pinatubo eruptions in 1991 (Godin et al., 2001) (https://doi.org/10.1029/2000JD900459), to predict the 10 extension in the lower mid-latitude stratosphere of polar and subtropical air masses (Heese et al., 2001) (https://doi.org/10.1029/2000JD900818), or to evaluate average total ozone evolution within the Antarctic vortex with PV fields simulated by the model, used to determine the vortex position in Pazmino et al. (2018) (https://doi.org/10.5194/acp-18-7557-2018). »

The Reviewer 2 suggest to reword or remove the end of the sentence but we propose to modify the entire section 2.1 paragraph on pages 4 as follows:

"PV fields are calculated from ECMWF ERA-Interim reanalysis [1] (Dee et al., 2011) (https://doi.org/10.1002/qj.828). As these reanalyses end in August 2019, we used the operational data from ECMWF from September 2019 until December 2020. Recently, Millan et al. (2020) compared the polar vortex evolution with different reanalyses, including ERA-Interim. Results showed that all reanalyses where in agreement with the reanalysis ensemble mean (REM), which shows that we can be confident with the ERA-Interim reanalyses for our study. ERA-Interim temperature, geopotential and wind data with a resolution of 1.125° latitude x 1.125° longitude are inputs to the MIMOSA model, which is a three-dimensional high-resolution PV advection model (Hauchecorne et al., 2002). From MIMOSA high resolution PV fields, it is possible to follow the evolution of polar air masses and filamentation processes of the polar vortex. Sampled every 6 hours, ERA-Interim reanalyses are interpolated on selected isentropic surfaces. The model computes PV and EL fields on isentropic surfaces with a resolution of 0.3° latitude x 0.3° longitude, using a polar projection centered on the South from 90°S to 10°N. The advection method is applied to this orthographic grid. After some time, the MIMOSA grid is distorted by the horizontal gradients of the wind fields. A re-interpolation of the PV fields on the original grid every 6 hours is then performed. Finally, in order to take into account diabatic processes, a relaxation of the MIMOSA advected PV (APV) towards the ECMWF PV is made every 12 hours with a 10 day time constant. This model has been used to analyze, among other studies, the permeability of the southern polar vortex to volcanic aerosols from Cerro Hudson and Mount Pinatubo eruptions in 1991 (Godin et al., 2001), and to predict the extension in the lower mid-latitude stratosphere of polar and subtropical air masses (Heese et al., 2001). In Pazmino et al. (2018), PV fields simulated by the model are used to evaluate average total ozone evolution within the Antarctic vortex. For this study, PV fields are computed at 675 K, 550 K and 475 K isentropic levels."

L18: Rao et al. 2019 JGR also used this index to select the solar max and min years. Please refer to Table 3 in Rao et al. 2019 JGR (https://doi.org/10.1029/2019JD030826)

We did not cite any reference here because a lot of other studies use this index.

Section 2.2: L20: 23th => 21st

The sentence has been rewritten differently as reviewer 2 suggested:

Page 5, line 8: "Data were obtained for solar cycles 21 to 24 (1976 to 2020)."

Section 2.2 : L25: If you read Rao et al. 2019 JGR (supplementary material), please mention that they also consider the intensity change for each solar cycle.

We do not find the « supplementary material » section here https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JD030826 but a « support information »

On page 5 lines 8-11, we added: "Years characterized by minimum and maximum solar intensity were selected from the difference of maximum and minimum intensity of each cycle (a methodology also considered in Rao et al., 2019). The minimum (maximum) intensity threshold was defined as the lower (upper) third of this difference, so that the minimum and maximum thresholds are different for each cycle.

L27-30: This index is not reasonable, because it can not distinguish between Eastern and Central Pacific ENSO events. Only CP ENSO can impact the SH polar vortex. Previous studies (Hurwitz et al. 2011; Rao and Ren 2020) have reported that EP ENSO is not related with the SH stratosphere. Please change to use Nino3 and Nino4 index and revisit the possible impact of ENSO on the SH polar vortex edge.

We addressed this comment in our answer to the reviewer's major comment #1

We have changed the figure description of the section 4.2.3 for El Niño Southern Oscillation as follows, and have added a sentence:

Page 16 lines 8-9: "The polar vortex breaks earlier during the warm phase of ENSO, and especially during the maxSC years with a breakup in November. These results are in agreement with the literature (Li et al. 2016 (https://doi.org/10.1175/JCLI-D-15-0816.1); Domeisen et al. 2019).

Table 2 was changed as follows:

Proxies	eQBO	wQBO	cENSO	wENSO
maxSC	5	10	~~8~~ 5	~~7~~ 3
minSC	10	10	~~11~~ 7	~~9~~ 5

L31: This sentence can be removed. It has been mentioned earlier.

The sentence has been removed.

Page 5 lines 6-8 have been modified as follows: "For our study, we averaged the 10.7 cm solar flux and other proxies over the May - November period, which corresponds to the time period when the Southern polar vortex is formed."

L33: This classification of ENSO state is also weird. 21 warm ENSO and 21 cold ENSO. Why is there no neutral ENSO state? Rather weird and unacceptable.

Please see the answer to the previous comment on page 5 lines 20-22.

We have changed the sentence as follows:

Page 5 lines 20-22: "Then mean ENSO over the period is sorted to distinguish La Niña, characterized by negative values smaller than -0.5 MEI.v2 (cold ENSO), and El Niño by positive values higher than +0.5 MEI.v2 (warm ENSO). Then 10 wENSO and 14 cENSO years are considered in this study."

P5 Table 1: ENSO index should be changed.

As indicated previously, we did not change the index, only the calculation method.

L5: The position of the edge is in the unit of EL, rather than as a function of EL degree. Please correct throughout the paper. The authors might misunderstand the function. The edge is a single value, independent of the EL. Edge = edge(theta, time). But PV = PV(EL, theta, time). Mathematically, the description is incorrect.

The sentence referred to is page 6 lines 3-5 on the original document: "the method described in Nash et al. (1996) is used, which consists in determining the position of the edge from the maximum PV gradient weighted by the wind mean speed as a function of EL."

We find that "as a function of EL" is correct here because it addresses how the vortex edge is determined (from the maximum of grad(PV/EL) x wind(EL)).

However, we agree that throughout the text as in description of figures (e.g. figures 2 and 3), the wording is not correct and have changed "as a function of equivalent latitude" to "in equivalent latitude".

L11-12: PV is not an output for the NCEP/NCAR reanalysis. I do not think the authors clearly know and understand what they read. If the PV is also obtained from MIMOSA driven by the NCEP/NCAR reanalysis, please clarify.

Again, the authors understand and can read scientific articles. In the Manney et al., 1994c (https://doi.org/10.1029/94GL02368) study, the authors do not use MIMOSA driven by the NCEP/NCAR reanalysis. Manney et al., 1994c use data from the US national Meteorological Center and PV on isentropic surfaces calculated from NMC data describe in their previous article (Manney et al., 1994b) (https://doi.org/10.1175/1520-0469(1994)051<2973:OTMOAT>2.0.CO;2) and explain as follows: "Sixteen years of geopotential height and temperature data from the US National Meteorological Center (NMC) [Finger et al. 1993 and references there in] are used. Rossby-Ertel potential vorticity (PV) on isentropic surfaces calculated from NMC data [e.g., Manney et al. 1994b] is used to describe the evolution of the lower stratospheric vortex."

So in Manney et al., (1994c) they use PV **computed from** the NCEP/NCAR reanalyses, previously known as "US National Meteorological Center (NMC)". We have clarified the sentence as follows:

Page 6, lines 10-12: "Manney et al. (1994) first determined that the breakup date corresponds to the date when the EL of a chosen PV contour at the 465K level is greater than 80°, using PV data **computed from** the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) reanalyses."

P6L6: I did not see any special value of using so many thresholds. The results are different for those thresholds. Which one should readers believe?

The sentence is “In this study, we use the Nash et al. (1996) method to determine the vortex onset and breakup dates, used also in WMO (2019), with three threshold values (15 m.s^{-1}, 20 m.s^{-1}and 25 m.s^{-1}) following Akiyoshi et al. (2009).”

Akiyoshi et al., (2000) (https://doi.org/10.1029/2007JD009261) do not specify clearly why they use the horizontal wind speeds of 20 and 25 m.s^{-1} added to the one use by Nash et al., (1996). But they compared Nash et al., (1996) threshold value method with the Langematz and Kunze (2006) (https://doi.org/10.1007/s00382-006-0156-2) method which consist in defining the breakup date as the day of the year when the zonal mean westerlies at 65°S and 50 hPa decrease below a threshold value of 10 m.s^{-1}. Our objective of using different thresholds is thus to evaluate the sensitivity of the onset and breakup dates to the selected threshold values.

We have changed the sentence to:

Page 6, lines 26-28: “In this study, we use the Nash et al. (1996) method to determine the vortex onset and breakup dates, also used in WMO (2018). Two threshold values (20 m.s^{-1} and 25 m.s^{-1}) following Akiyoshi et al. (2009) are added to this method, in order to evaluate the sensitivity of the onset and breakup dates to the chosen threshold values (see section 5).”

L11: See above. What is function?

Page 7 line 5: We changed with “in EL”.

P7L6: Add discussion for the 2019 SSW in SH. Please inserted relevant references.

This comment has been addressed in our answer to the reviewer’s major comment # 2.

Figure 2: See above. Function is misleading.

After the suggestion of reviewer 2, we have changed the legend of Figure 2 as follows:

Page 10 legend: “Evolution of daily position of the vortex edge in equivalent latitude as a function of time over the 1979 - 2020 period, from top to bottom: 675 K, 550 K and 475 K. Median values are represented by the black bold curve. Blue filled areas show values between 20 and 80 percentiles, while thin black curves represent the maximum and minimum values over the period.”

P8L4: Those are factors which might control the interannual variation of the polar vortex. This sentence should be rephrased.

The sentence mentioned is “Proxies such as the solar cycle, QBO and ENSO are used to describe the polar vortex edge interannual variation over the 1979 - 2020 period.”

We have changed to:

Page 11 lines 2-3: “Factors such as the solar cycle, QBO and ENSO are used to describe the interannual variability in the temporal evolution of the polar vortex edge over the 1979 - 2020 period.”

P9L10: How did you test the difference for the medians? The difference for the mean can be tested using the t-test. Which test is used for the medians? Please clarify.

Indeed, the purpose of the t-test is to observe the difference between means. For the medians, I therefore used the Mann-Whitney test.

We have changed the end of the paragraph from:

"The t-test results indicate that differences are significant from mid-September to the end of October with a mean p-value of 0.023 at 675K, from September to late November with p value of 0.032 at 550 K, and during the same period with a p-value of 0.023 at 475 K." page 9 line 10 of the original document.

to:

Page 11 lines 13-16: "A Mann-Whitney test was performed to characterize the significance of these differences. The Mann-Whitney test results indicate that differences are significant from 27 September to 26 October at 675 K, from 9 to 24 September and from 3 October to 21 November at 550 K, and from 19 September to 15 October and from 11 to 26 November at 475 K."

P10L1: delete "statistical"

We have deleted "statistical" and have changed to "composite analysis".

L8: How did you test the difference for the medians?

As for the previous comment, we have modified the test method and have used the Mann-Whitney test.

We have changed the end of the paragraph from:

"Differences between the medians are largest during the July - August period at 550K with a mean p-value of 0.03" page 10 line 8 of the original document.

to:

Page 13 lines 5-7: "The difference between the medians was assessed by a Mann-Whitney and differences are significant from 9 to 18 September at 675 K, from 18 July to 11 August and from 27 August to 7 September at 550K, and from 15 to 20 June at 475 K."

Section 4.2.2, 4.2.3: The two subsections still focused on the impact of solar cycle on the polar vortex edge. I prefer to seeing the results for the composite for ENSO and QBO directly. Can you also show?

The two following figures are the composite analysis for QBO and ENSO only, represented as for the SC in Figure 3.

The composite analysis of QBO alone does not highlight any different behavior between the QBO phases so we did not include it in the article.

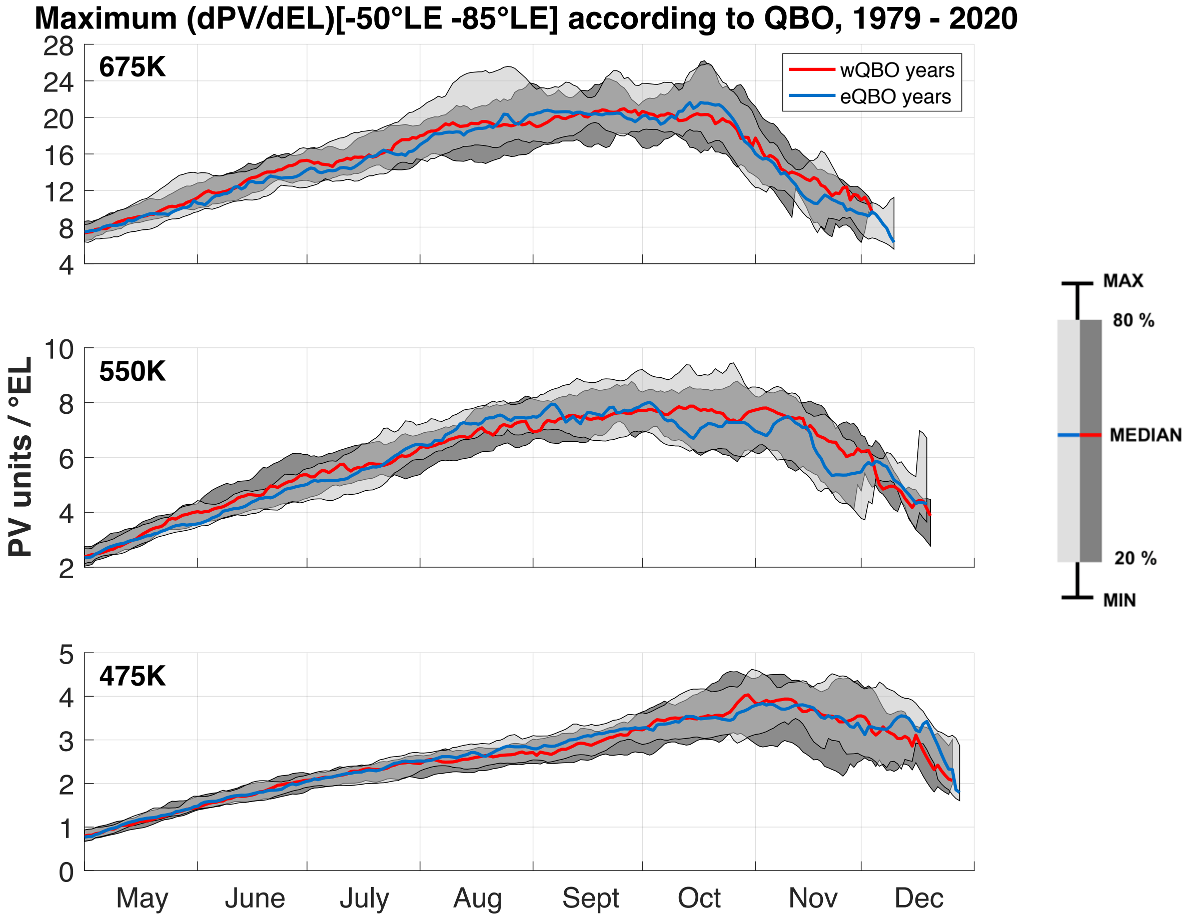


Figure: QBO composites of vortex edge intensity's annual seasonal evolution for the 1979 – 2020 period, from top to bottom: 675 K, 550 K and 475 K. Red (blue) curves represent median values for wQBO (eQBO) years. Dark (light) grey-filled areas indicate values between 20 and 80 percentiles for wQBO (eQBO) years.

ENSO alone shows us that the vortex edge is stronger during the cold ENSO phase, especially at the 550 K and 475 K levels. Earlier breakups are also observed during the warm ENSO phase. We have not included this figure in the text because Figure 6 shows very well that we have a stronger vortex edge during the cold ENSO phase and an early break up during warm ENSO.

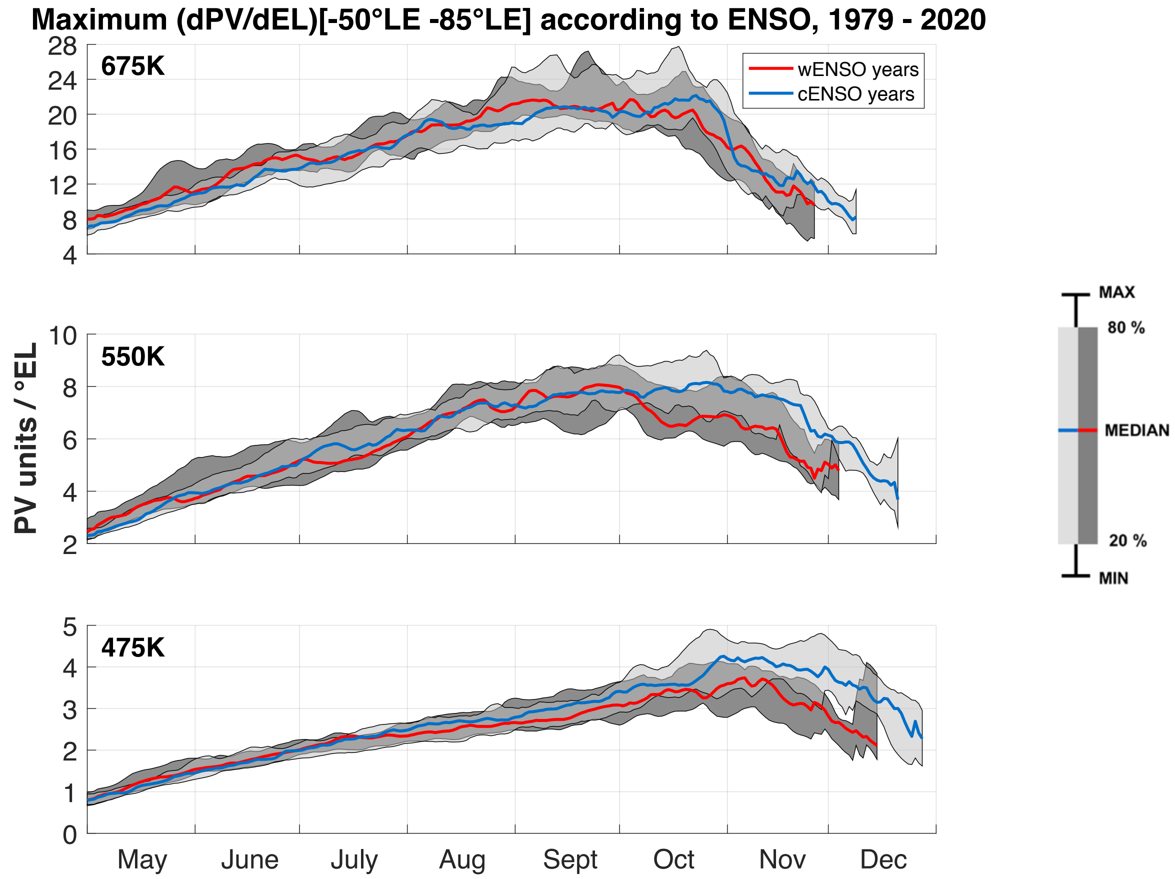


Figure: ENSO composites of vortex edge intensity's annual seasonal evolution for the 1979 – 2020 period, from top to bottom: 675 K, 550 K and 475 K. Red (blue) curves represent median values for wENSO (cENSO) years. Dark (light) grey-filled areas indicate values between 20 and 80 percentiles for wENSO (cENSO) years.

P14L5: In my understanding, the maximum day is different from year to year. But you fixed from 15 September to 15 October. If so, remove this sentence as is misleads readers.

We have fixed periods of maximum intensity from 15 September to 15 October at 675 K, in October at 550 K and from 15 October to 15 November at 475 K.

We do agree what the paragraph between lines 1 and 7 on page 14 of the original version is not clear. The following paragraph:

"As seen in section 4.1, the maximum median intensity is reached from September to late October at 675K, from September to early November at 550K, and early November at 475K. In order to study the interannual evolution of the maximum intensity and position of the vortex edge during these periods, we identified the day when the maximum was reached at each level and averaged the parameters over ±15 days around this date. Figure 7 represents the inter-annual evolution of the polar vortex edge maximum intensity at each isentropic level over the 1979 - 2020 period, averaged over September 15 – October 15, October and October 15 – November 15 at 675K, 550K and 475K respectively."

has been changed to:

Page 17, lines 2-6 and page 18 line 1: "As seen in section 4.1, the maximum median intensity is reached during the September – November period depending on the isentropic level. In order to study the interannual evolution of the intensity and position of the vortex edge during these periods, we identified the day when the maximum was reached at each level and averaged the parameters over ±15 5 days around this date. Figure 7 represents the inter-annual evolution of the polar vortex edge maximum intensity at each isentropic level over the 1979 - 2020 period, averaged over September 15 – October 15, October and October 15 – November 15 at 675K, 550K and 475K respectively".

L9-11: The discussion is useless. Those so-called decrease and increase reflect the interannual variation, rather than any trend.

We do not agree with this comment. We observe a visible trend at 550 K and 475 K between 1980 and 2000 in Figure 7, as quantified in our manuscript. Bodeker et al., (2002) (https://doi.org/10.1029/2001GL014206) documents well the intensification of the dynamical containment of Antarctic ozone depletion during the 1980s and 1990s, which can be related to what we observe.

L19-20: The final solar cycle is weak, mention in Rao et al. 2019 JGR.

We have added the Jiang et al., 2015 reference as this study is based on the last 11 years cycle of solar activity less vigorous than the previous three cycles.

The sentence with the reference added is as follows:

Page 18 lines 13-16: "It should be noted that the latest solar cycle (cycle number 24) was less intense than the previous ones (Jiang et al., 2015) (https://doi.org/10.1088/2041-8205/808/1/L28) and the maxSC years of the last cycle correspond to intermediate years between minimum and maximum years of the previous cycles so the modulation of the vortex edge intensity by the latest solar cycle is potentially weaker than by the earlier cycles."

P15L3: Figure => figure

The word has been changed.

P16L2: Rao et al. 2020JGR also reported the 2019 SSW in SH.

This sentence refers to the link between the ozone hole and the 2019 SSW. The reference Rao et al., (2020) in JGR does not refer to the ozone hole, only to the 2019 SSW.

P18L1: You show the final warming date. In my understanding, this is another method of determining the final warming date. The mean date is consistent with Rao and Garfinkel 2021CD. You might mention the reference to support your results.

The mentioned sentence is: "Figure 10 shows the day when the polar vortex breaks up in Spring due to the final vortex warming, at 475K, 550K and 675K isentropic levels."

We have removed the part "due to the final vortex warming," of the sentence:

Page 23 lines 1-2: Figure 10 shows the day when the polar vortex breaks up in Spring at 475K, 550K and 675K isentropic levels."

L16: Figure => figure

The word has been changed.

P20L2: as a function of => in the units of

Changed to “in equivalent latitude”.

P21L5: => in the future study.

Done.