Answers to reviewer 2: (in violet in the "tracking" version)

We would like to thank the reviewer for taking the time to correct mistakes in our article and for suggesting improvement in the writing of the manuscript. We have taken these suggestions into account and modified the text. Here are our answers to the reviewer's major and minor comments.

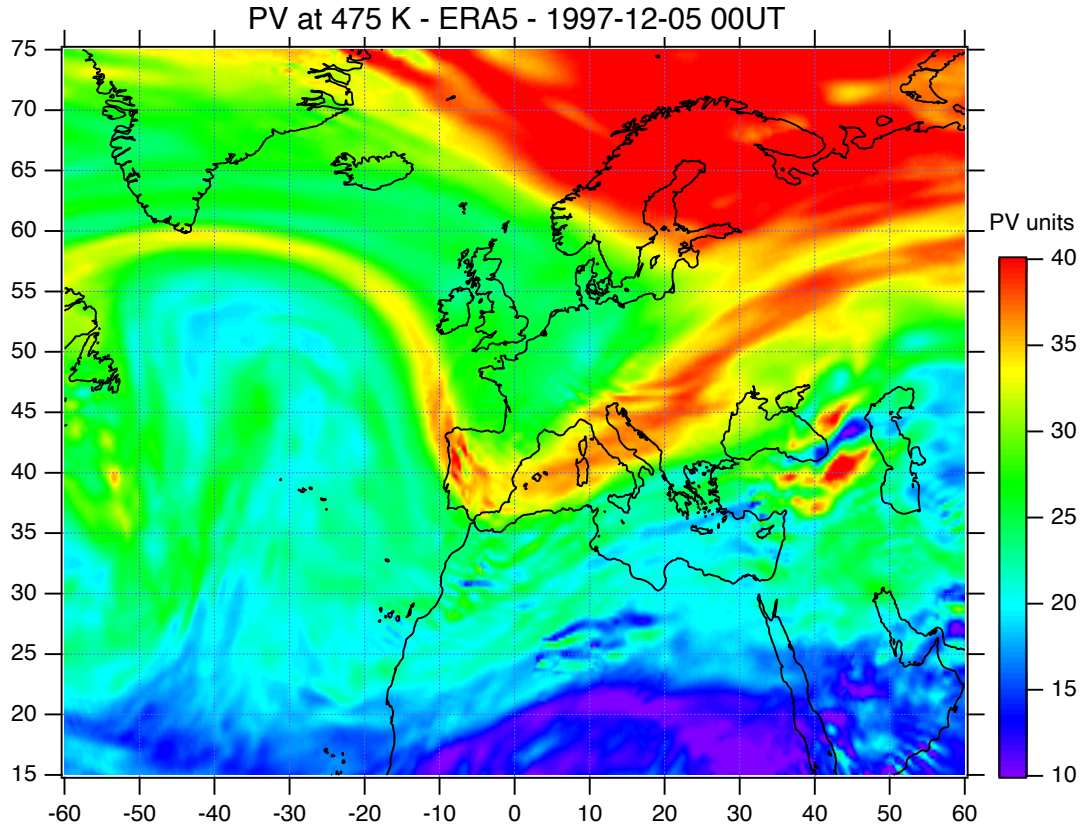
Major comments

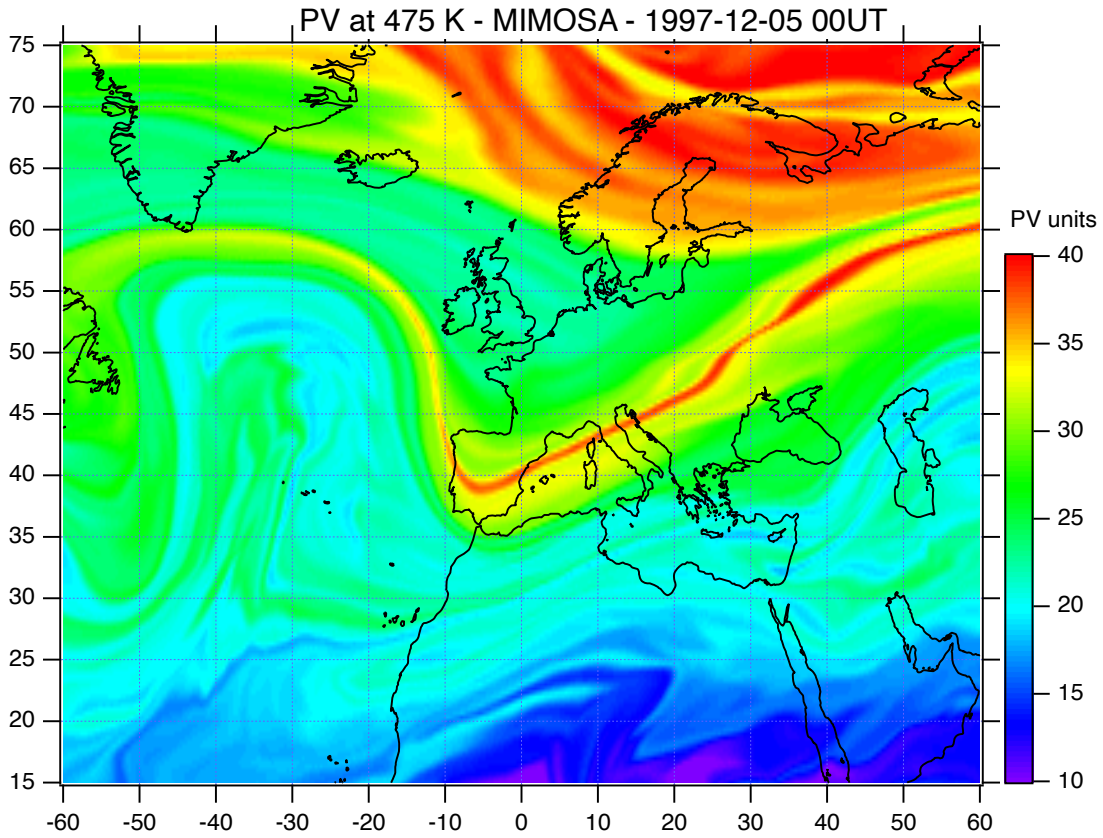
Section 2.1: Why is the MIMOSA model needed to determine PV fields. It can be determined directly from the ECMWF data. Does MIMOSA provide higher time and spatial sampling?

We use the MIMOSA model to obtain higher spatial resolution PV fields. The MIMOSA model allows better tracking of polar air masses (the continuity of vortex-related structures, such as filaments for example).

For example, in the first figure below, the PV fields of ERA 5 are used directly, at 475 K with a resolution of 0.25° on 5 December 1997 at 00UT.

In the second figure, the ERA5 fields are used on the same date, but as inputs to the MIMOSA model. The noisy filament seen running from 60°N/60°E to 40°N/10°W across Europe on the second figure is better represented by MIMOSA fields. We can also see some dubious high PV values in the ERA5 figure around 40°N/45°E that are not visible in the MIMOSA figure.





Reviewer 1 asked for more information about the model for the readers, and to give better explanations on how it works. So we have changed the entire paragraph as follows in section 2.1 pages 4 and 5:

"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) (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. 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) (https://doi.org/10.1029/2001JD000491). 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) (https://doi.org/10.1029/2000JD900459), and to predict the extension in the

lower mid-latitude stratosphere of polar and subtropical air masses (Heese et al., 2001) (https://doi.org/10.1029/2000JD900818). In Pazmino et al. (2018) (https://doi.org/10.5194/acp-18-7557-2018), 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 surfaces."

Section 2.2: For the definitions of years with QBOe and QBOw as well as SCmin and SCmax, the upper and lower third of the distribution, is used, but why is this not done for ENSO (no intermediate years). Why is the one-third limit for each solar cycle determined separately?

The lower and upper third of the distribution is used for the Solar Cycle only, not for the QBO. For the QBO, the east and west phase are determined with positive values (wQBO) and negative values (eQBO). For ENSO, as recommended by NOAA (https://psl.noaa.gov/enso/mei/) and thanks to reviewer 1's comments, the MEI.v2 index for ENSO has been calculated with MEI.v2 values between the - 0.5 and + 0.5 MEI.v2 representing the intermediate (neutral) years. 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 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."

The one third limit for each solar cycle is determined separately because of the variability of the different cycles (for example the 25th cycle does not reach the same maximum values as the 22th, 23th and 24th ones).

p6,l2: "other studies", please cite them here (see also introduction)

Page 6, section 3.2, lines 23-24, we added some citations which refers to the ozone depletion on the polar vortex lifetime.

"The authors joined other studies (Atkinson et al. 1989 (https://doi.org/10.1038/340290a0); Müller et al. 2008 (https://doi.org/10.5194/acp-8-251-2008); Zhang et al. 2017 (https://doi.org/10.1155/2017/3078079)) in concluding that the vortex lifetime is influenced by the ozone depletion during spring."

Conclusion: Are the trends in the breakup dates after 2000 (the tendency for earlier breakup dates) a new result? Should it not be then highlighted in the abstract? Also, "trends are not halted" just by adding one year (2020) which has been extreme.

To our opinion, the trends in the breakup dates after 2000 are the sign of decadal variability rather than a long-term trend. So we have not added this result in the abstract.

About the 2020 late breakup, we wrote in the initial manuscript "A seemingly decreasing trend in the breakup dates after 2010 was halted by the very long vortex duration in 2020, which set a record at the 675K level."

We have changed the sentence to:

On page 25 lines 12-14: “We see a decreasing trend in the breakup dates after 2010 but this decrease was halted by the very long vortex duration in 2020, which set a record at the 675 K level, and also by the late breakup in 2021.”

Minor comments in the acp-2021-676-RC2-supplement.pdf

We thank very much the reviewer for the time taken to suggest accurate corrections and questions in our manuscript file. We have implemented the suggested changes in spelling and grammar suggested by the reviewer. We will not list each small point in this document. The answers to questions in the pdf file are listed here.

P1.L5: A bit hard to understand, you mean the vortex area has the lowest day-to-day(?) variability. Or could this be due to larger uncertainties in the vortex parameters before and after this period.

The sentence refers to the variability of the position of the vortex edge in equivalent latitude. The vortex edge position has indeed the lowest year to year variability during the period of maximum intensity as shown in Figures 1 & 2. Since the southern polar vortex is well formed before and after this period, this feature is not due to larger uncertainties during these periods.

In order to clarify the statement, the following paragraph:

"The vortex edge is stronger in late winter, over September - October - November with the period of strongest intensity occurring later at the lowermost level. A lower variability of the edge position is observed during the same period."

Has been changed to:

Page 1 lines 4-6: "The vortex edge is stronger in late winter, over September - October - November with the period of strongest intensity occurring later at the lowermost level. At the same period, we observe a lower variability of the edge position."

P2.L28: "~~wind module~~" -> "wind mean speed"

We have changed "wind module" throughout the paper to "wind mean speed".

P2.L28: This is correct but not a good explanation, suggest to rephrase by describing: EL defines the latitude limit of the (polar cap) area which exceeds a certain PV value (Maximum PV is then given at EL=90degs). A PV field sorted by EL will then make the polar vortex concentric around the pole

Thanks for the suggestion, which better explains the notion of equivalent latitude. we have included in our manuscript. The changed part of the paragraph is as follows:

Page 2 lines 34-35 and page 3 lines 1-3: "Numerous studies on the vortex boundary definition have been performed. Nash et al. (1996) (https://doi.org/10.1029/96JD00066) defined the vortex edge as the location of the maximum PV gradient as a function of equivalent latitude (EL), weighted by the wind module. EL defines the latitude limit of the polar area which exceeds a certain PV value (maximum PV is then given at EL = 90 degrees e.g. Butchart and Remsberg (1986) (https://doi.org/10.1175/1520-0469(1986)043<1319:TAOTSP>2.0.CO;2)). A PV field sorted by EL will then make the polar vortex concentric around the pole. This is the method used in this study."

P4.L11/12: somehow disconnected to the sentence, please reword (or just ommit)

We do agree this sentence is too long on page 4 lines 7-12 of the original document:

“The MIMOSA model is a three-dimensional high-resolution PV advection model (Hauchecorne et al., 2002) 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), to predict the extension in the lower mid-latitude stratosphere of polar and subtropical air masses (Heese et al., 2001), 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). For this study, PV fields are computed at 675K, 550K and 475K isentropic surfaces.” Page 4 lines 7-12 of the original document.

This sentence has been changed to:

Page 4 lines 26-30: “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.”

P4.L30: not clear what is said here. Bi.-monthly averages reflect the time-delayed response to ENSO. What is meant with "seasonality of ENSO"?

We do agree this is not a good explanation. This was reformulated as follows:

Page 5 lines 18-20: “Referring to the NOAA description of the MEI.v2 index (see data availability [4]): “The EOF are calculated for 12 overlapping bi-monthly “seasons” in order to take into account ENSO’s seasonality, and reduce effects of higher frequency intra-seasonal variability.””

Where the reference [4] correspond of the NOAA website in the paper in « data availability » https://www.esrl.noaa.gov/psd/enso/mei

P4.L33: why not define only upper and lower third of the distribution as cENSO and wENSO (like QBO and solar flux).

Please refer to the answer to the second major comment above.

P5.L5: “~~wind module~~” -> “horizontal wind”

After the reviewer’s suggestion in page 2 line 28 of the original document, we have changed “wind module” throughout the paper to “wind mean speed”.

P5.L7: W is the wind speed

Please see the answer to the comment above.

P6.L2: references

Please see the answer to the reviewer’s third major comment above.

P6.L12: not clear to me. you mean that 80% of all years fall within the the upper and lower limit (why 20%).

The blue filled area indicates daily values between 20 and 80 percentiles over the whole period (1979 – 2020). The upper curve of the blue area refers to the 80 percentiles and the lower curve of the blue area refers to the 20 percentiles. We mean that the complete blue area represents 80-20 = 60 inter-percentiles of the total values.

P7.legend: show ~~between 20 and~~ 80 percentiles

This suggestion was made throughout the text. We do not agree with that because values in blue represents values between the 20th and 80th percentiles.

P7.L3: maximum vortex edge position". sounds awkward, wouldn't it be better to say "maximum vortex area"

This is not a vortex area but the position of the edge at the maximum PV gradient forced by the wind mean speed. We do agree this is not the maximum vortex edge position, but only the vortex edge position.

We have changed the sentence by removing the word "maximum" now in page page 8 line 2.

P7.L5 : cannot be both, here minima.

We agree that it is a mistake. We have removed the word "maxima" now in page page 8 line 5.

P8.legend: "~~maximum~~"

We have removed the word "maximum".

P8.legend: "~~as a function of equivalent latitude~~"

As suggested, we have replaced "as a function of equivalent latitude" with "in equivalent latitude as a function of time".

P9.L5: "represents ~~values between 20th and~~ 80th percentiles"

We do not agree with that suggestion. Please see answers to comments on page 6 line 12 and page 7 legend, in the original version.

P9.L6: "strong vortex edge" "vortex edge intensity". The terms sound to me a bit strange. The higher the PV gradient (wind speed) at the vortex edge, the more stable is the polar vortex. Not the vortex edge is stronger, but the entire vortex is stronger and more stable.

In this study, we focus on the edge of the polar vortex and did not consider other parameters such as the mean PV value within the boundary of the vortex, which could be the scope of another study with other parameters such as the mean temperature within the vortex.

P10.legend: "~~annual~~" -> "seasonal"

We have changed « annual » to « seasonal » throughout the text.

P11.titre figure: "~~Maximum~~ EL of the vortex edge according to SC, 1979 – 2020"

We have removed the word "maximum" in the titles of the Figures 2 and 4.

P14.L6-7: These periods do not agree with the periods from the first sentence in this paragraph.

As reviewer 1 also noted it was not clear, we have changed the following paragraph from:

"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 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."

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 level. 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 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 675 K, 550 K and 475 K respectively".

P15.L1: "Figure 8 represents the inter-annual evolution of the ~~maximum~~ polar vortex edge position with years sorted according to the SC as described in Figure 7"

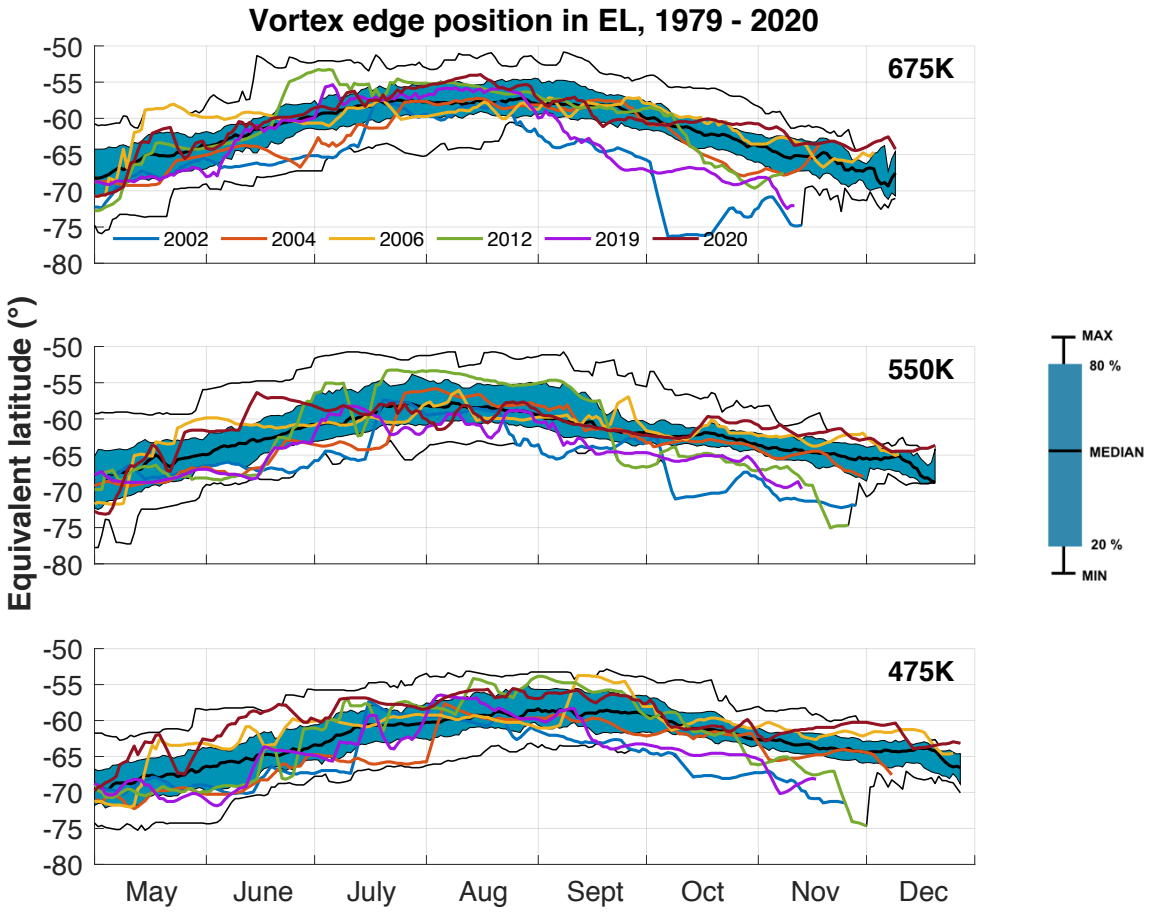
We have removed the word "maximum".

P16.L4: it may exceed normal values later than the period considered in Fig. 8.

Thanks for this relevant comment. Please see the figure below, with some special winters plotted, including the 2019 winter in violet.

We have modified the sentence to:

Page 20, lines 7-11: "In contrast, the year 2020, which was characterized by a strong ozone hole with a very long duration (see section 5) does not show a particularly strong maximum vortex edge intensity value nor an outstanding value of the edge position during the respective periods of maximum intensity. Later in the winter, it impacts the maximum intensity curve during a few days at the three isentropic levels."



P17.L3: why is this expected? Explain

The original sentence is: "As expected, the vortex forms earlier at the highest levels: the average day of the year the onset date occurs for all thresholds combined is on days 90, 98 and 108 at 675K, 550K and 475K respectively."

We have completed the sentence to answer to this question:

Page 22 lines 3-6: "Due to the stronger radiative processes in the upper stratosphere, the temperature contrast between the polar region and mid-latitudes is stronger and the polar vortex forms more rapidly with a faster wind. Thus the vortex forms earlier at the highest levels: the average day of the year the onset date occur for all thresholds combined is on days 90, 98 and 108 at 675 K, 550 K and 475 K, respectively."

P17.L9: not logical, the major warming occurred after the onset. A bit more explanation is needed here.

The sentence mentioned is: "This year was however characterized by the first major warming observed in Antarctica, as mentioned previously."

We have changed this sentence and have added more explanation as follows:

Page 22 lines 10-13: "For example, the winter of 2002 was characterized by a difference of one and a half months between the two extreme threshold values, as the wind at the beginning of

the winter was weaker compared to other winters. This is actually the first winter in which an SSW was observed, as mentioned previously."

P17.L10: why is it important?

The sentence mentioned is: "Also, the inter-annual variability of onset dates is rather important at 475 K."

We have added more explanation as follows:

Page 22 lines 13-15: "Due to the slower and less stable wind at 475 K, the vortex forms slowly and there is an important inter-annual variability of onset dates with an average difference of 32.9 days between 15.2 $m.s^{-1}$ and 25 $m.s^{-1}$ during the whole period."

P17.L1: which level?

This is at 475 K.
We have changed "at this level" to "at 475 K" in page 22 line 15.

P18.L14: express this in days after the mean breakup date.

The mentioned sentence is: "Finally, the year 2020 is noticeable for its exceptionally late breakup date, with an average breakup for the three thresholds on days 360, 355 and 354 at 475K, 550K, and 675K, respectively."

It has been changed to:

Page 23, lines 13-15: "Finally, the year 2020 is noticeable for its exceptionally late breakup date, with a breakup date occurring 20, 21 and 29 days after the mean threshold dates at 475 K, 550 K, and 675 K, respectively."

P18.L17-18: Are these standard deviations?

These are not standard deviation but the average difference between onset dates for the two extreme threshold values (15.2 $m.s^{-1}$ and 25 $m.s^{-1}$) at 475 K, 550 K and 675 K compared to the breakup dates line 17. The standard deviation for the mean threshold values are 10.6, 10.2 and 10.4 days for 475 K, 550 K and 675 K for breakup dates (see page 24 lines 3-4).

P19.L7: It seems to me that the trend is rather negative (shorter duration) after 1999 apart from the very extreme years as stated in the next sentence.

The mentioned sentence is "The vortex is thus persisting later after 1999." and is about Figure 10.

We have changed the sentence to:

Page 24 lines 7-9: "Just after 1999 the vortex breaks up earlier. Then we observe a later breakup of the vortex between the mid-2000s and 2010. After 2010, we observe again that the vortex breaks up earlier, ending with the very long duration of the 2020 vortex."

P20.L15: A trend is not halted just because of one extreme year at the end of the period.

The mentioned sentence is "A seemingly decreasing trend in the breakup dates after 2010 was halted by the very long vortex duration in 2020, which set a record at the 675K level."

We have reworded the sentence as follows:

Page 25 lines 12-14: "We see a decreasing trend in the breakup dates after 2010 but this decrease was halted by the very long vortex duration in 2020, which set a record at the 675 K level, and also by the late breakup in 2021."

P20.L17-19: sentence too long, split it.

The mentioned sentence is "Stronger vortex edge intensity is observed in years of solar minimum. QBO and ENSO further modulate the solar cycle influence on the vortex edge, especially at 475K and 550K: during wQBO phases, the difference between vortex edge intensity for minSC and maxSC years is smaller than during eQBO phases."

We have separated the sentences as follows:

Page 25 lines 16-18: "Stronger vortex edge intensity is observed in years of solar minimum. QBO and ENSO further modulate the solar cycle influence on the vortex edge, especially at 475 K and 550 K. During wQBO phases the difference between vortex edge intensity for minSC and maxSC years is smaller than during eQBO phases."

P20.L21 : make a separate sentence out of it

The mentioned sentence is "Regarding ENSO, which has a lower impact than the QBO, the vortex edge intensity is somewhat stronger during cENSO phases for both minSC and maxSC, and the difference between minSC and maxSC medians is larger."

We have separated the sentences as follows:

Page 25 lines 19-21: "Regarding ENSO, which has a lower impact than the QBO, the vortex edge intensity is somewhat stronger during cENSO phases for both minSC and maxSC. During this phase, the difference between minSC and maxSC medians is larger."

P20.L31: better to cite papers on 20202 Antarctic ozone depletion from the JGR/GRL special issue.

We have removed both links (https://public.wmo.int/en/media/news/2020-antarctic-ozone-hole-large-and-deep and https://public.wmo.int/en/media/news/record-breaking-2020-ozone-hole-closes) and supported the sentence with a new citation from (Stone et al., 2021) (https://doi.org/10.1029/2021GL095232).

The new sentence is:

"This very long-lasting vortex was also characterized by a strong ozone destruction (Stone et al., 2021). It will be interesting to see how the southern polar vortex evolves in the coming years."