Response to the comments by Anonymous Referee #1

We thank the reviewer for thorough reading of the manuscript and for providing valuable feedback. The comments and remarks have aided in improving the analysis and manuscript.

All comments are addressed in detail in the following (Reviewer's comments in black, responses in blue and quotations of the corresponding revised text passages in *italic*). The line numbers mentioned in the response refer to the revised version of the manuscript.

General comments

This is an original and generally well-written study (although it could perhaps be streamlined) that describes a number of interesting features pertaining to how the CO2 seasonal cycle propagates into the stratosphere. I have two major comments, one of which is practical and calls for specific, generally minor revisions to make the paper easier to follow. The other is more of an overall conceptual criticism, which doesn't necessarily need to be addressed and indeed may not be possible to address.

1) Practical. The text points out many detailed features of the figures, referencing the pressure level in hPa where they occur. Yet the figures have a sparse Y axis that is labeled only at 10^3, 10^2, and 10^1 hPa. This makes it challenging for the reader to locate the feature being described. I would suggest including more Y axis labels on the right as well as guiding lines or contours that delineate key relevant features like the STJ, the LMS, and the tropopause. This comment pertains in particular to Figures 6-8 -see also my specific comments.

We agree that a more extensive labelling of the y-axis and some additional guiding lines will improve the readability and traceability of single features in the figures. We therefore increased the tick length and adjusted the labelling to 10, 100, 1000 hPa in the figures concerned having a pressure y-axis. As suggested, we included additional y-axis labels for altitude regimes discussed in detail in the text where possible, but due to space constraints in the figures with many subplots this was not always possible. According to your tip we also introduced a box in Fig. 4 to highlight key features and added tropopause information to Fig. 6 and Fig. 7. Please note that following a suggestion from the Reviewer #2, we refer to individual subplots more frequently throughout the text in order to provide further clarification on certain aspects of the discussion.

2) Conceptual. The use of AirCore data is somewhat limited and the paper is based mainly on ECAM model output, particularly the tracer CO2_seas. This approach is justified in Figures 3 and 5, in which ECAM is shown to simulate well the observed CO2 profiles at selected latitudes (Fig 3) and the AirCore seasonal cycles at different pressure levels (Fig 5). The abstract states that CO2_seas "is a very useful diagnostic tool" but it is not clear if and how CO2_seas can be derived from AirCore observations. The authors only address this issue in the very last paragraph of the conclusions, where they admit that, "such an approach is challenging."

We understand the conceptual criticism that the aspect of calculating the CO_2_seas from observational data is left open in the manuscript and the discussion of the seasonal signal is mainly based on the EMAC model results. Indeed, we would have liked to include a comparison to CO_2_seas derived from AirCore only, but for now the seasonal cycle cannot be unambiguously separated from the combined effect of transport and long-term increase in CO_2 in observations. This requires further information which is not available. In particular, the lack of CO_2-

independent transport information for most AirCore flights inhibits the profound isolation of the seasonal CO_2 signal from observations, which was only enabled in the EMAC model simulations due to the specially implemented artificial tracer. Nevertheless, we are convinced that it is in principle possible to make a comprehensible and accurate calculation of a (climatological) CO_2_seas using (AirCore) measurement data. And this would be – as correctly implied by your comment – a key aspect to take the full advantage out of using the CO_2 seasonality as a transport tracer/diagnostic tool.

To address the concerns and to explain how CO_2_seas could be derived from observations we slightly extended the last paragraph of the conclusion.

"[…] worthwhile objective to isolate the seasonal signal in observational data as well. However, such an approach is challenging. Detailed strategies for separating the seasonal signal in observations must address the problem that a CO_2-independent Age of Air information would be imperative to disentangle seasonality from the combined effect from transport and long-term increase. For reliable results a good coverage and representativeness of CO_2 measurements is required - not only at ground level, as is achieved with global measurement networks, but also at higher altitudes. Especially for regions that cannot be reached by aircraft, AirCore provides a very cost-effective sampling option that makes it possible to regularly obtain high quality trace gas data. Thus, the high-reaching AirCore vertical profiles are in principle promising to constrain the seasonality of CO_2 in the UTLS and above from observations." (Line 678-685)

Specific Comments

Line 16. Please spell out EMAC (assuming ACP has a policy of no undefined acronyms in the Abstract).

Thank you, this has been changed as suggested. (Line 15)

Section 2. What is the vertical resolution of the AirCore profiles? (Later sections describing EMAC emphasize its "coarse resolution" of 90 vertical levels.)

Typical values for AirCore vertical resolution are given in Sect. 2.1 (Lines 178-179 of the original manuscript). They range from 1000 m in the lower stratosphere (~50 hPa) to less than 300 m in the UTLS and troposphere.

Please note that we only describe the overall spatial resolution of EMAC (in the sense of considering all spatial directions) in our discussion as "coarse", and not its vertical resolution alone. The horizontal EMAC resolution of approximately 2.8° in latitude and longitude primarily determines whether small-scale (vertical) features captured by AirCore can be resolved by the model. Indeed, describing the EMAC vertical resolution as "coarser" than the AirCore would not be correct for all the pressure levels discussed. In case of the EMAC set-up used in this study, the hybrid sigma-pressure coordinate scheme results in a vertical resolution of 500-700 m in the lower stratosphere and beneath. To enable an easier comparison of the vertical resolutions for the reader we slightly amended the EMAC set-up description.

"[…] and the hybrid sigma-pressure coordinate scheme contains 90 vertical levels up to 0.01 hPa (Jöckel et al., 2016), resulting in a vertical resolution of 500-700 m in the lower stratosphere and beneath." (Line 211)

Upon reflection, we realised that our usage of the term "resolution" in Sect 2.4 is partly misleading as we mixed up the definition of resolution as an independent data point with spatial (vertical) coverage actually intended. Accordingly, we modified the section concerned in the manuscript:

"Subsequently the AirCore profile data were fitted to the vertical resolution of EMAC." (Line 255)

Line 196-198 and 222-228. Please state more clearly whether the seasonal cycle of CO2 is prescribed in the standard configuration or calculated prognostically based on couple land and ocean carbon cycle modules. (Many readers will not be familiar with the details of the CMIP6 protocols.) Is the prognostic CO2 seasonal cycle from the coupled land/ocean/atmosphere model being "nudged" to the prescribed observed seasonal cycle?

The seasonal cycle of CO_2 is prescribed, as it is included in the input fields for the standard configuration. As the simulation is a pure atmospheric model simulation without simulated sources and sinks of CO_2, CH_4 and other atmospheric trace gases, there is no prognostic seasonal cycle from a coupled (e.g. carbon cycle) module.

For clarity we changed the general model description slightly and specified how the seasonal cycle is prescribed in section 2.3, which is focusing on details of the CO_2 simulation.

"In this way, interactions e.g. with the land surface and the ocean as well as anthropogenic influences and feedback mechanisms can be included (Jöckel et al., 2010)." (Line 198)

"[…] As a simulation with the EMAC set-up-described in the previous section is a pure atmospheric model simulation without coupled land/ocean or carbon cycle components, the mole fractions at the surface are prescribed, using the submodel TNUDGE for tracer relaxation towards prescribed values (Kerkweg et al., 2006). Due to the monthly time resolution of the input data, these tracers directly include a seasonal cycle. The GHG mole fractions seen by other model components, such as the radiation scheme, are based on input fields from the CMIP6 protocols (Meinshausen et al. 2017, Meinshausen et al. 2020). In addition to the 'standard' CO_2 tracer affecting radiation we included two diagnostic CO_2 tracers in the simulation, which differ only with regard to the lower boundary conditions. Thus, using the NOAA marine boundary layer data set (NOAA MBL reference, Lan et al., 2023a) as prescribed lower boundary mole fractions in combination with two tracer relaxation vertical regions, namely (I) only at the surface to the atmosphere or (II) within the entire planetary boundary layer (PBL), results in a total of three different CO_2 output variables from the simulation (CO_2_standard, CO_2_MBL_srf, CO_2_MBL_pbl)." (Line 221-230)

Table 1 last row, last column, It would be better to describe CO2_seas as "CO2_MBL_pbl minus CO2_deseas" in the table rather than the more vague "based on CO2_MBL_pbl and CO2_deseas"?

We agree and the revised phrasing has been implemented in Table 1.

"*EMAC seasonal CO_2 signal calculated via CO_2_MBL_pbl minus CO_2_deseas, see Eq. 1*" (Table 1)

Line 264 change "It is calculated" to "The weighted average was calculated"

Done. (Line 264)

Line 266 What are "The two analysed species"?

We refer to CO_2 and CH_4. However, as the EMAC vs. AirCore comparison for CH_4 is not addressed elsewhere in the manuscript, we have decided to remove this part of the sentence to avoid confusion. Note that the entire section slightly changed, because we have added more details on the statistical methods according to a comment by Reviewer #2.

"*To enable a comparison of the large number of AirCore flights, the agreement of the datasets was quantified using the mean absolute deviation (MAD) and its standard deviation (σAD). [...]*" (Line 267)

Line 312. What is meant by "on top of it"?

The phrase "on top of it" was used to mean "additionally". So, we wanted to express that (1) a global model can hardly resolve regional or local effects of CO_2 sources and sinks, which are visible in AirCore profiles, and (2) that this is even more the case because the model uses a background-like input (NOAA MBL).

"While the deviations in the UTLS and above are generally less pronounced, the largest deviation is found in the troposphere. This can be attributed to the impact of regional CO_2 sources and sinks on the lower parts of the snapshot-like AirCore profiles, which can hardly be resolved in the global model using a background-like input such as NOAA MBL." (Line 315-318)

Line 366. These reversed gradients are not obvious in Figure 4. Could they be shown better with vertical profile line graphs?

We agree that the reversed CO_2 gradients in the polar middle stratosphere are not easy to see in Fig 4. To improve this, we highlighted the concerned region in the plot with a box. Based on a suggestion from Reviewer #2 we added panel letters to the figure and slightly adjusted the associated paragraph to more precisely describe where exactly the relevant information can be found in the figure.

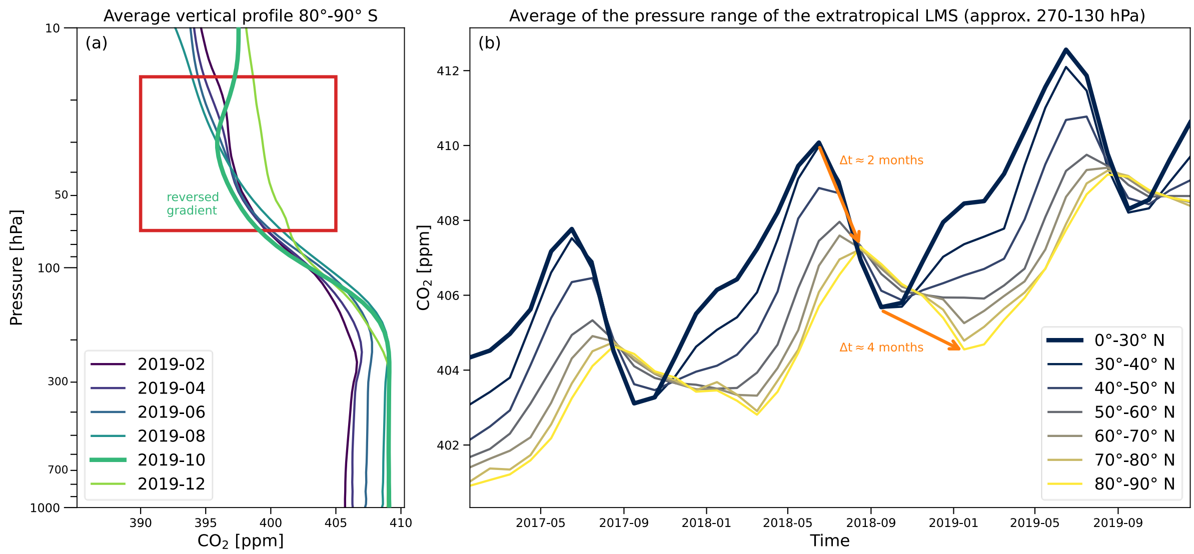
Thank you for your helpful suggestion to try to better illustrate this feature using a vertical profile line graph. We added such a representation of the phenomenon in the supplement (Fig. S4, panel (a), see plot in next comment) and a corresponding reference to the paragraph.

"*Only in spring/early summer in each hemisphere there are, albeit weakly pronounced, (middle) stratospheric areas in polar latitudes with reversed vertical CO_2 gradients (e.g. highlighted by the red box in Fig. 4e). This phenomenon varies in intensity inter-annually, is more distinct in the southern hemisphere (SH) and can be associated with the polar vortices. As the feature is not easily visible in the monthly mean representation of Fig. 4, a more detailed visualisation is provided by the vertical profile plot for high latitudes shown in supplementary Fig. S4a*" (Line 375-379)

Line 382. Similarly, this feature is not obvious in Figure 4 and perhaps could be shown in a line graph. Also, please define the approximate altitude range of the LMS.

Thank you, you are right that a range for the LMS will help the readers to follow our description and discussion of the CO_2 distribution results in Fig. 4. We have therefore added this to the text.

Similarly to the feature mentioned in the last comment we try to make the expansion of CO_2 from the tropical tropopause layer to the mid-latitude LMS and the different timescales that it takes in summer or winter clearer by preparing a line plot. This plot is added to the supplement (Fig. S4b) and is referenced in the manuscript.



"During the summer months the relatively high CO_2, that has reached the tropical tropopause layer (TTL) and lower stratosphere via convection and upwelling expands to the mid latitude LMS (located between the local tropopause and approx. 130 hPa). This is consistent with other observations (Hoor et al., 2005; Sawa et al., 2008) and the conclusions by Bönisch et al. (2009), emphasising the stronger contribution of tropical tropospheric air in the extratropical LMS in this season due to increased quasi-horizontal tracer transport across the weaker STJ (see also Fig. S4b)." (Line 393-397)

Line 405. By "information" do you mean "AirCore information"?

Yes, with "information" we mean "AirCore information". We changed this as suggested.

"For clarity AirCore information is not added for every level." (Line 419)

Figure 6a. The lines on the right Y axis are helpful. But why not actually label them? There would be room if the width of 6a is reduced slightly. Also, could the same labeled lines be added to Fig 7a?

Thank you for your valuable suggestions. We have adopted both (and have also included the labelled lines to the other two panels of Fig. 7).

Line 446. What exactly is meant by the "strongest modulation"?

The formulation "strongest modulation" refers to where in the average monthly vertical profiles of CO_2_seas the strongest change with altitude occurs. We changed the wording for clarity (please note that, upon reflection, we adjusted the pressure ranges in the paragraph slightly).

"As it can be seen in Fig. 6a, the strongest modulation of the average monthly vertical CO_2_seas profiles with altitude occurs quite independently of season in the range between 300 hPa and 70 hPa, which is within the extent of the extratropical UTLS region." (Line 462)

Additionally, we adjusted the same formulation in the conclusions:

"The tropospheric CO_2 seasonal cycle propagates upwards into the lower stratosphere and is weakened by mixing processes during transport. In the NH mid-latitudes, the strongest modulation with altitude occurs in the UTLS region, characterized by a dampening of 50 % of the amplitude of the seasonal cycle and a 4-month phase shift between 300 hPa and 100 hPa." (Line 653)

Line 448. Should 20 km be expressed in hPa, since everything else is.

Done.

"Nevertheless, the seasonal signal is clearly visible up to 50 hPa (approx. 20 km), highlighting the importance of and need for such high-reaching observational data as can be provided by balloon-flights with AirCore." (Line 465)

Line 454. A "residual influence of -0.2 ppm seems to remain". Is this simply CO2_seas as defined in Equation 1? Or has there been further processing of the model output? Please explain more clearly how the curves in Figure 6 are normalized/detrended to create a "climatology."

Yes, this is simply CO_2_seas as defined in Equation 1 with no further processing of the model output.

In our approach using the artificial deseasonalised CO_2 tracer we do not need further detrending or normalization to calculate a climatology of the seasonal signal of CO_2, as it is already disentangled from the long-term increase. We explained how the curves in Fig. 6 are derived in Line 422-424. For clarity we changed this description slightly.

"To investigate the CO_2 seasonal cycle and its upward propagation from the troposphere across the UTLS into the LMS, we constructed a climatology of the EMAC-derived CO_2 seasonal signal. Therefore, we first calculated monthly means of CO_2_seas, in order to subsequently compute the average behaviour per calendar month over the entire simulated time period 2000-2023. No further normalisation or detrending was necessary, since CO_2_seas, as given by Eq. 1, is already disentangled from the long-term increase." (Line 435-439)

Figure 6a and 7. Perhaps a black line showing the position of the tropopause would be useful, especially since the Y axis label has only 3 tick marks.

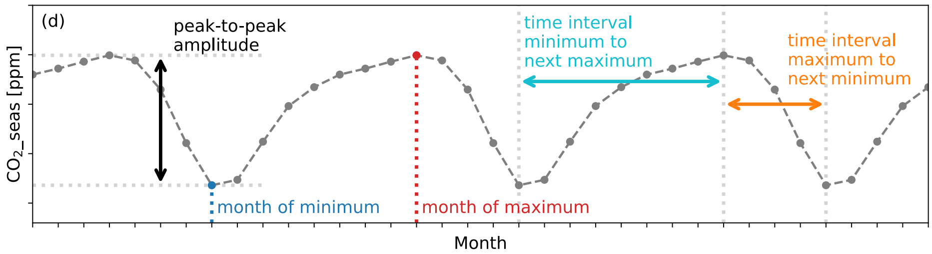
Thank you for your suggestion. We have incorporated the position of the tropopause to both figures (again also to the other panels of Fig.7). Please note that, since the height of the tropopause varies throughout the year, the figures show shaded areas indicating the lowest and highest monthly mean values of the WMO tropopause. We changed the caption accordingly.

"(a) Climatological EMAC-derived CO_2 seasonal signal vertical profiles per calendar month for NH mid-latitudes. The shaded area shows the seasonal variation in WMO tropopause height. Grey lines on the right vertical axis represent selected pressure levels for which 'traditional' seasonal cycle plots of the same data are shown in (b)-(f). Note the different scales. The mean behaviour (2000-2023) is displayed together with its standard deviation (thin lines) and extremes." (Caption Fig. 6)

Figure 7c. This figure is confusing. If it is not illustrating an essential point, please consider deleting.

The main reason for Fig. 7c is to show that there is a distortion of the seasonal cycle of CO_2, which can carry additional information on atmospheric transport. The shape of the seasonal signal is tilted above 100 hPa, which is hardly visible in the traditional seasonal signal plots in Fig. 6 b-f, due to the dampening and phase-shift that is happening simultaneously. That is why we think the representation of this tilt in this separate panel (Fig 7c.)

contains useful information, even if it might be hard to understand. We have added a pictogram to the figure to make it easier to follow what is shown in panel (c) (and in the other panels). This illustrates the quantities from Fig. 7 a-c by showing their meaning schematically in a classical seasonal cycle view. Accordingly, we made small adjustments to the figure description and caption.



"Figure. 7 illustrates the key characteristics of the EMAC derived seasonal signal as a function of altitude for the example location introduced in Fig. 6. Panel (d) provides a schematic representation of the quantities form the other panels in the context of a classical seasonal cycle view. Apart from the obvious change in amplitude with decreasing pressure […]" (Line 487-489)

"Key features of the climatological EMAC-derived CO_2 seasonal signal for the same location as in Fig. 6 with information on the vertical distribution of (a) peak-to-peak amplitude, (b) months of maximum and minimum and, (c) the time interval between the extremes. The illustration in (d) shows a schematic representation of the quantities form the other panels in the context of a classical seasonal cycle view" (Caption Fig. 7)

Line 511. "As can be seen"

The whole sentence was changed because of the next comment to not begin the paragraph referencing a supplementary figure.

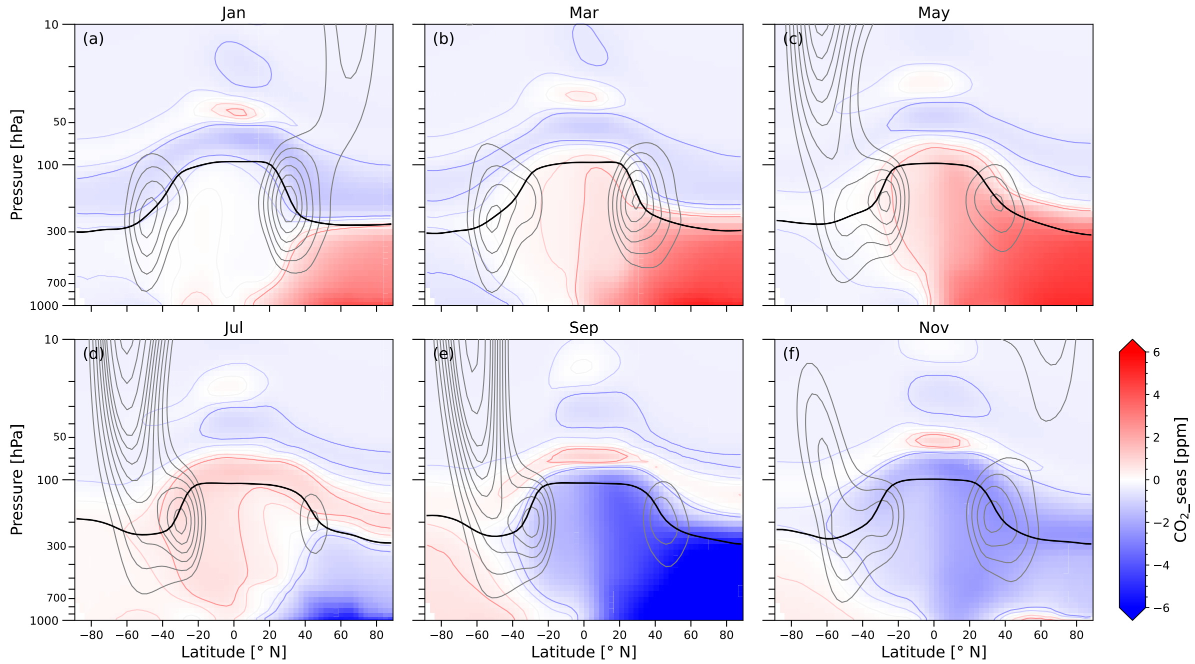
Line 511. Probably better not to begin the paragraph referencing a supplementary figure that most readers won't see.

Thank you for your suggestion, we changed the structure of this paragraph.

"The vertical distribution of the CO_2 seasonal signal strongly depends on latitude. Details on this in form of CO_2_seas vertical profile plots for selected locations from polar and mid latitudes as well as from the subtropics and tropics can be found in the different panels of Fig. S5. To provide a global overview, Fig. 8 shows the zonal mean cross-sections of the EMAC derived climatological average of the seasonal signal for odd months (even months in Fig. S6)." (Line 533-536)

Figure 8. Can you draw in the STJ (as done in Fig 4) for March and July to illustrate the points described in Lines 520-525? It is not obvious that the gradient is stronger in March.

From our perspective the gradient in CO_2_seas becomes too difficult to distinguish in doing so. To demonstrate this, we included a version of the figure containing the STJ contours (zonal wind isolines).



Nevertheless, we adjusted the related paragraph slightly to be more precise.

"Focusing on the shape of the gradients of CO_2_seas in the UTLS at about 30° N to 40° N, differences over the course of the year are prominent, again indicating an annual variation in the coupling of the tropics and extra-tropics. In March (end of NH winter) a very pronounced meridional gradient is observed implicating a distinct transport barrier. In this period, the CO_2_seas isolines in the STJ region run parallel to the tropopause. In contrast, during July (NH summer) the gradient is much weaker, and the CO_2_seas isolines intersect the tropopause." (Line 544-548)

Furthermore, we have amended Fig. S6 (the even-month version corresponding to Fig. 8) to include zonal windspeed isolines and added a reference to this in the figure caption.

"Zonal mean latitude-pressure cross-sections of the EMAC-derived climatological average (2000-2023) of the CO_2 seasonal signal for odd months. The black line indicates the WMO- tropopause. See supplementary Fig. S6 for even months including contour lines indicating jet positions (zonal windspeed)." (Caption Fig. 8)

Line 541. Is 5hPa even shown on Figure 8? If not, maybe delete this sentence.

Thank you for the hint. You are right. This feature cannot be seen in the figure (this was only true for an older version of the plot). So, we deleted this part of the sentence.

Figure 10. I am not an expert on "tape recorder" effects, but it seems like it might be a stretch to call Figure 10 a "horizontal tape recorder." Is there a precedent for this in the literature with H2O or other trace gases? Can the authors really be sure of what causes the hemispherical symmetry at and above 127 hPa? For the tropical signal to mix equally into both hemispheres seems at odds with the Brewer Dobson Circulation, which upwells in the tropics and descends into the winter hemisphere.

In analogy to the well-known water vapour vertical tape recorder (Mote et al., 1996) we refer to the dispersion of the CO_2 seasonal cycle originating in the TTL as a vertical and horizontal (to be more precise latitudinal) tape recorder.

The horizontal dispersion of the water vapour imprint is presented in detail in Randel and Jensen (2013). As the term "horizontal tape recorder" was not actually used in the publication by Randel and Jensen, we changed the text to state that we refer to this picture as horizontal tape recorder, as it shows a similar pattern, i.e. a seasonal signal imprinted at the tropical tropopause which then propagates and disperses in the stratosphere. In order to make this clearer we have eliminated the term horizontal tape recorder from the caption to Fig 10 and from Line 590 and added the explanatory phrase to the main text in Lines 599-602 in the original manuscript:

"In this case, a horizontal cross-section provides a much better view of the dispersion of CO_2_seas." (Line 617)

"Slightly above the tropical tropopause (81 hPa, Fig. 10e) the CO_2 seasonal signal propagates rapidly from the tropical reservoir into both hemispheres. This feature is consistent with the results by Boering et al. (1996). In analogy to the propagation of the seasonal cycle of water vapour, which occurs both vertically (Mote et al., 1996) and also horizontally (Randel and Jensen, 2013), we refer to this signal as horizonal (latitudinal) tape recorder. The transit time of the EMAC CO_2_seas mode to 50° at this level is about 4 months, which is close to, but tends to be slightly longer than that visible from the horizontal water vapour dispersion (dry mode, Randel and Jensen, 2013)." (Line 627-632)

With respect to the hemispheric symmetry mentioned by the reviewer which would be in contrast to the Brewer Dobson circulation (BDC), we refer (i) to the observation of the very similar signal in water vapour (Randel and Jensen, 2013) and (ii) to the fact that this is driven by quasi-horizontal transport which is expected to occur during all seasons.

Lines 632-634. I don't follow this argument. Is it important enough to be in the conclusions? In general, the conclusions should probably be trimmed to focus on the most key points.

We think it is important to keep the sentence "While the seasonal signal outside the tropics vanishes at the transition to the middle stratosphere, it can be clearly traced travelling up to 10 hPa within slightly more than a year in the tropical reservoir." in the conclusions, as it corroborates the finding of isolated tropics and mid-latitudes in the lower stratosphere.

References

Mote, P. W., Rosenlof, K. H., McIntyre, M. E., Carr, E. S., Gille, J. C., Holton, J. R., Kinnersley, J. S., Pumphrey, H. C., Russell III, J. M., and Waters, J. W.: An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor, Journal of Geophysical Research: Atmospheres, 101, 3989–4006, https://doi.org/10.1029/95JD03422, 1996.

Randel, W. J. and Jensen, E. J.: Physical processes in the tropical tropopause layer and their roles in a changing climate, Nature Geosci, 6, 169–176, https://doi.org/10.1038/ngeo1733, 2013.