Response to the comments by Anonymous Referee #2

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

Weaknesses

- Some parts of the discussion could be clarified further, see detailed comments below. Especially during the discussion of figures, it would be helpful to refer to individual subplots more often.
- Some of the figures require minor polishing (see "Figures" section below)
- Grammar could be refined in some places, also decide between American and British English

Thank you for the general comments on how to improve the manuscript. We understand that closer connections to the text, i.e. referring to individual subplots more often, would help the discussion of figures. We have incorporated such references in several parts of the results sections and tried to clarify the parts of the discussion mentioned in the specific comments (see response to them for details). The very helpful suggestions regarding individual figures (addressed in the Figure section in detail) have certainly improved the graphical presentation of our results (e.g. adjusted colour-blindness-friendly colour scheme in Fig. 6, extended information in legends and captions). Thank you for the feedback on Grammar in the technical corrections section.

Specific comments

Text

Line 267: Please provide a bit more detail on the statistical methods. Which correlation coefficient are used; e.g., Pearson's/Spearman's? Were the assumptions for computing correlation coefficients checked, e.g., normality? How is the Mean Absolute Deviation (MAD) computed here?

We initially calculated Spearman's correlation coefficient, as normality was not given for every comparison (Shapiro-Wilk-test to test for this; especially for the profiles where the AirCore reached not that high, the population after down-sampling to EMAC levels was sometimes quite small: < 50 per flight). During the analysis, it became clear that correlation is not necessarily a good indicator of the similarity between AirCore and EMAC CO_2. We found that even in cases with significant/visible deviations the coefficient was often quite high due to the "underlying" vertical CO_2 gradient that is in both measurements and simulations. So, in this application correlation does not tell us too much about the individual match and is quite prone to misinterpretation. For these reasons we used the other metrics (MAD and σAD). We realized while answering this question and providing additional information on the statistical methods that the correlation coefficient is not used in the results anymore. So, we delete the listing of the correlation coefficient in the sentence on statistical methods as it is not relevant for the manuscript anymore and we simply missed to remove it previously.

We added the equations we used to calculate the MAD and its standard deviation to the manuscript and extended their description in the text.

"*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). Both metrics were calculated for each profile using the following equations:*

$$MAD_{x,profile\ (i)} = \frac{1}{N}\sum_{j=0}^{N} \left|x_{j,EMAC} - x_{j,AirCore}\right| \quad (2)$$

$$\sigma AD_{x,profile\ (i)} = \sqrt{\frac{1}{N-1}\sum_{j=0}^{N}\left(\left|x_{j,EMAC} - x_{j,AirCore}\right| - MAD_{profile\ (i)}\right)^2} \quad (3)$$

where i is representing the individual profile comparison, j refers to the information in the respective pressure levels of the comparison and x is the selected quantity (measured trace gas species and corresponding model tracer). This was done not only for the complete profiles but also separately for individual pressure ranges of the profiles (including UTLS) in order to determine differences in model performance as a function of altitude." (Line 267-275)

Line 336-339: Did I understand the reasoning here correctly such that a weak tropopause leads to enhanced transport of CO2-rich air into the stratosphere, which is seen in AirCore observations, but not in the model, leading to the deviations between both datasets? That would seem plausible to me. If so, please clarify that in the text, since I found the connection between "weak tropopause" and "scale problem" not so obvious.

Thank you for your suggestion. Yes, this is exactly the reasoning we had in mind, and we agree that this needs to be made clearer in the text. We have amended the paragraph accordingly.

"[...]. However, for most of these exceptions, the accompanying meteorological data from the AirCore flights indicate a rather unstable atmospheric stratification during sampling. So, a weak transport barrier at the tropopause might have led to enhanced transport of CO_2-rich tropospheric air into the stratosphere. Probably such a phenomenon occurs only on smaller scale, so it is captured by AirCore while the model is not able to resolve this variability. Nevertheless, EMAC reproduces the (large-scale) features of the CO_2 distribution in the UTLS well." (Line 344-348)

Line 348: With "compared data", do you mean the AirCore observations, since they only cover specific regions? If yes, please clarify that in the text.

Yes, we refer to AirCore data and changed this as suggested.

"To evaluate the accuracy of the model simulations correctly, it should be noted that the AirCore observations used for the comparison are not globally representative." (Line 355)

Line 365: Is this related to the figure? If yes, it's better to start with, e.g., "Figure 4 shows...". Also, if this is part of the figure discussion, please use the same height coordinate as in the figure (between 8-35 km -> use pressure instead).

This part of the text relates to the results presented in Fig. 4. We therefore adopt your suggestion of starting the description with the figure name and using the same height coordinate as in the figure.

"The results presented in Fig. 4 illustrate that the CO_2 mole fraction generally decreases with increasing altitude between 350 hPa and 10 hPa." (Line 374)

Line 365: "hemispheric spring", which hemisphere is meant here? Or reword to "spring in each hemisphere". Also please refer to individual subfigures to support your point.

Reworded to "spring/early summer in each hemisphere". We added panel labels to Fig. 4 and refer to them, where appropriate. Following a suggestion by Reviewer #1 we also included a box to highlight the concerned region of the reversed vertical gradient in the figure and prepared a supplementary figure with an alternative representation of this feature.

"*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 371: Could you briefly mention/discuss why this region shows enhanced seasonality?

As the whole next paragraph (Line 376-387) deals with the seasonality of CO_2 in the extratropical UTLS (probably related to the variability of the transport barrier strength of the subtropical jet) we would not like to repeat this information here. We mention this feature of the global CO_2 distribution at this point in the text, because it is a key characteristic and to underline that the EMAC simulation agrees with our common knowledge and previous findings in literature.

To make this clearer, we include a reference:

"In the extra-tropics above 300 hPa and up to 50 hPa, there is a region with very clear seasonal variations (details on this are discussed later on). These main characteristics of the simulated CO_2 in EMAC agree with […]" (Line 382)

Line 384: Clearer: "contribution of tropical air in the extratropical LMS..." or "export of tropical air into the extratropical LMS..."

Thank you, changed as suggested.

"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 395)

Line 385-387: Please refer to individual subfigures for clarity. Also, which layer is meant here? Are you referring to the decrease of CO2 near the surface as seen in the 2019-08 plot? Is the main point here that, in summer, fast quasi-isentropic mixing of CO2-rich air into the extratropics counteracts the CO2 sink due to photosynthesis, or that a layer of low CO2 (biogenic) can be observed below the CO2-rich air (mixing) in the LMS? Please clarify.

We incorporated a reference to Fig, 4d (2019-08 plot) as we refer to the tropospheric layer of low CO_2 in NH summer, that is caused by biogenic uptake. This layer is not limited to the surface as even at 300 hPa the mole fraction is significantly reduced in comparison to Fig. 4c (2019-03). The main point here is that we observe such a low CO_2 layer below the CO_2-rich air in the LMS (which itself is likely due to quasi-isentropic mixing of CO_2-rich TTL air into the extra tropics). This might be even better visible in Fig S3e (2019-09 plot), as the tropospheric CO_2 minimum becomes more pronounced towards the end of the vegetation period due to the accumulative effect. Upon reflection, the statement on fast quasi-isentropic mixing in the LMS in the following sentence lacks contact to the rest of the paragraph and therefore may cause some confusion as well. As it is discussed later on (Line 525 of the original manuscript) we deleted it here.

"[…] Particularly in the northern hemisphere (NH), this layer of CO_2-rich air in the extratropical LMS contrasts with the simultaneously decreasing tropospheric CO_2 due to the biospheric uptake by photosynthesis during the terrestrial vegetation period (Fig. 4d, Fig. S3e)." (Line 397)

Line 389: Please elaborate on the hemispheric asymmetries with regards to jet strength. E.g., which hemisphere usually shows the stronger jet, and how does that influence the CO2 distribution?

Thank you for this feedback. We think a detailed discussion of quantitative aspects of the hemispheric asymmetries is beyond the scope of this section, which focuses on demonstrating qualitative features of the global CO_2 distribution. This is even more the case as we have AirCore measurements available almost exclusively in the NH.

"Asymmetries between the hemispheres regarding the CO_2 variability in the UTLS are visible throughout all seasons and can partly be related to the hemispheric differences in the strength and persistence of the jets." (Line 401)

Line 390: Which characteristics of the shallow BDC branch (e.g., hemispheric differences and seasonal variability) can you see in your results?

Details of the characteristics of the shallow BDC branch are better visible in the results of the isolated CO_2 seasonal signal than in the CO_2 simulation itself. They are discussed in section 4.4. in more detail (e.g. Line 581-583 in the original manuscript, Fig 9+10). We included a reference for this.

"Furthermore, the shallow branch of the BDC influences the CO_2 distribution in the lower stratosphere. As the effects of its characteristics (e.g. seasonality, hemispheric differences) become better visible in the results of the isolated CO_2 seasonal signal than in the CO_2 simulation itself, they are discussed in section 4.4." (Line 403)

Line 399: ...the long-term trends and seasonal cycle of CO2 sources and sinks?

Although the seasonality of the CO_2 sources and sinks imprints the seasonal cycle near the ground, the atmospheric CO_2 observations contain only their combined effects (net effect). As we mainly focus in our analyses on the CO_2 seasonal cycle far away from the ground (UTLS and above), we do not think that the seasonality of sources and sinks should be mentioned here.

Line 433-434: refer to panels, e.g., a) and f)

Done.

"As a result, the profile is reversed in terms of the sequence of lower and higher mole fractions relative to the deseasonalised CO_2 (Fig. 6a). In the NH mid-latitudes, the maximum of the seasonal cycle in the troposphere is in April/May, and the lowest values are found in August/September (Fig. 6a and Fig. 6f). (Line 447-450)

Line 436: envelope of the curves in Figure 6a)?

This addition in brackets was just to highlight where the range of fluctuation of the seasonal signal can be seen in Fig. 6a. We changed it slightly to be more precise.

"Close to the surface the climatological range of fluctuation of the CO_2 seasonal signal at this location, which is graphically represented by the width of the envelope of all the curves in Fig. 6a, reaches approximately 15 ppm, [...]" (Line 450)

Line 442: Please specify in which pressure region the free troposphere lies

We refer to the free troposphere (in the context of Fig. 6) as approximately 800-300 hPa. This is the pressure range (for mid-latitudes) which is throughout the year very likely not above the tropopause (see newly added shaded area representing the range of the monthly mean tropopause heights, as suggested by Reviewer #1) and rarely within the PBL (which varies in heigh form a few hundred meters above ground or even less in nighttime to up to 2 km in thermal turbulent conditions in the afternoon in summer, see Engeln and Teixeira, 2013).

For clarity, we added this pressure range to the sentence.

"In the free troposphere (800-300 hPa), the seasonal signal is already slightly attenuated and lags somewhat behind the processes near the ground, [...]" (Line 458)

Line 442-445 and 446-448: Please refer to individual panels; are these sentences discussing Fig. 6a?

Yes, all these sentences discuss the results shown in Fig. 6a. References to the figure have been added, where appropriate.

"[...] which is nicely visible in Fig. 6a when the biosphere moves from net CO_2 sink to source (September/October) or vice versa (May/June), indicating propagation processes (rapid, but not instantaneous tropospheric transport and mixing)." (Line 459)

"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)

Line 455: What exactly does the stratospheric residual mean/ how can we interpret it? From Eq. 1, I understand that CO2_seas is the seasonal deviation from the deseasonalized "baseline"; so does that mean the seasonal signal of CO2 in the stratosphere is permanently negative? How exactly can we infer negative CO2 flux into the stratosphere from that? I do understand the reasoning in the following lines (455-463), but still, the meaning of the residual isn't clear to me.

Yes, our findings from the EMAC simulation suggest that the CO_2 seasonal signal, as given by Eq. 1, is permanently slightly negative in the stratosphere. This stratospheric residual is explained by the input of airmasses into the stratosphere. It is not a negative flux into the stratosphere. While for the deseasonalised CO_2 the seasonal variation of airmass flux to the stratosphere does not impact the average input, this is not the case for the CO_2 tracer with seasonal cycle. In this latter case, the average input will differ if the flux into the stratosphere occurs mainly during months where CO_2 is below (or above) the seasonal average. This is explained in the paragraph starting on Line 455. To make this clearer we have changed the text to now read as follows:

"[…]. The variation is approximately sinusoidal. While this seasonally varying mass flux has no effect on a tracer without a seasonal cycle, like e.g. the deseasonalised CO_2 tracer in the model, it will affect a tracer that shows a seasonal cycle in the input region, like CO_2, as different months are weighted differently. The mean CO_2 seasonal cycle […]" (Line 474)

The observation of the negative stratospheric residual implies that the existence of the CO_2 seasonal cycle delays the occurrence of a certain CO_2 mole fraction in the stratosphere by one month (0.2 ppm residual/2.5 ppm increase per year ≈ 1 month), without meaning that transport changed or is slower. Therefore, the findings regarding the stratospheric CO_2_seas residual might be important for studies using CO_2-derived AoA in the stratosphere. The transport is faster than suggested by the CO_2 mole fraction. We changed the explanation of the meaning of the residual in the text slightly:

"The finding of a negative stratospheric residual implies that the existence of the CO_2 seasonal cycle slightly delays the occurrence of a certain CO_2 mole fraction in the stratosphere. The residual of -0.2 ppm is not considered when calculating mean age from observations, so this could lead to an underestimation of about one month in CO_2-derived mean age, as it corresponds roughly to the long-term increase of CO_2 in one month at current increase rates." (Line 483-486)

Line 463: By the "findings described above", do you mean the negative residual?

Yes. For clarity we re-phrased this sentence.

"When both factors are weighted to calculate a mean CO_2 input into the stratosphere using only the seasonal signal, the result is clearly negative. This is consistent with the negative stratospheric residual from the EMAC simulations described above." (Line 478)

Line 472: with decreasing pressure?

Of course, "with decreasing pressure" is correct.

"Above this level, the cycles are no longer in phase with the lower troposphere and there is a fast temporal shift of the extremes with decreasing pressure." (Line 493)

Line 492: "15 km", please use altitude coordinates consistent with the figure (or add a km scale to the figure).

We decided to consistently stay with pressure for the EMAC model results altitude coordinate.

"But this time gap between the location of the extreme values also begins to change at higher levels of the atmosphere (< 100 hPa), resulting in an almost complete reversal at 50 hPa." (Line 512)

Line 504: What do you mean by "features that are not so pronounced"?

With this wording, we wanted to point to features that occur briefly or occasionally, or that change quickly in terms of location, so that they may not or hardly be visible in a climatological perspective, as it is presented in Fig. 6a.

For example, this applies to the effects of inter-annual circulation variability e.g. due to ENSO or QBO, that are smeared out looking only at a climatological average of CO_2_seas. This is why we at least put the standard deviation of the monthly mean to the seasonal signal plots (panels b-f). We changed the text slightly to be more precise.

"One must bear in mind that the climatological perspective presented here reveals general relationships very well, but can mask features that are less pronounced, because they occur only occasionally or relocate quickly." (Line 524)

Line 513: "expected" because of the larger land coverage and therefore stronger sources and sinks in the NH? Also, it would help to explicitly describe the hemispheric differences in this sentence, i.e., stronger seasonal signal in the NH.

Thank you for this hint. We included both the explanation for the "expected differences" and explicitly named how they look like.

"In the troposphere, the hemispheric differences in the distribution of CO_2_seas are very clear, with a much stronger seasonal signal in the NH compared to the SH. This is in line with expectations and is due to the larger land coverage and therefore stronger sources and sinks in the NH." (Line 536)

Line 526: "...in the extratropical LMS throughout all months/seasons..."

Changed as suggested.

"Unlike the gradient across the STJ, the dispersion and fairly uniform distribution of the seasonal signal in the extratropical LMS throughout all months indicates quite fast quasi-horizontal mixing." (Line 550)

Line 532: Is this related to Fig. 8?

Yes, this description is related to Fig. 8. We included a reference to this figure to clarify (see next comment for details as it deals with the same paragraph)

Line 533: Homogeneous in what sense? From looking at Fig. 8, I can still see strong variations in the seasonal signal with both latitude and height.

Thank you for your feedback. You are right, this is confusing. Of course, there are strong variations of CO_2_seas in the tropical tropopause region throughout the year. We wanted to emphasize that in each individual month (different panels of Fig. 8) in the vicinity of the tropical tropopause (130-80 hPa) the variation with altitude is quite the same for the whole latitudinal range of the tropical reservoir (20° S – 20° N). So, the CO_2_seas distribution in this region is horizontally quite homogenous in space.

"In the vicinity of the tropical tropopause (located at approximately 100 hPa, 20° S to 20° N), the EMAC derived seasonal CO_2 signal for an individual month (different panels of Fig. 8) is horizontally relatively homogeneous in space, which is in line with observations (e.g. Park et al., 2007)." (Line 557)

Line 544: "its distinctiveness" -> "the distinctiveness of the seasonal cycle"? Suggest rephrasing the sentence for clarity.

Thank you, changed as suggested.

"These differences in the weakening of the seasonal signal with altitude, especially the distinctiveness and traceability of CO_2 seasonality depending on latitude, can be seen particularly well by comparing the vertical tape recorder images of CO_2_seas in Fig. 9." (Line 568)

Line 546: Suggest explicitly mentioning the hemispheric differences

We have expanded the paragraph to include a brief description of the two main hemispheric differences.

"[…] Hemispheric differences and inter annual variabilities are apparent at first glance. The former are mainly characterized by the significantly more pronounced CO_2 seasonal signal in the NH compared to the SH and the delay in the sequence of negative and positive signals by half a year between the hemispheres." (Line 571)

Line 563-566: A more detailed description of interannual variabilities would be interesting

Thank you for your feedback. We agree that the interannual variation of the CO_2_seas upward propagation is an interesting feature. Particularly because such variations might be associated with effects of the quasi-biennial oscillation (QBO) or fluctuations in the tropical upwelling tied to El Nino – Southern Oscillation (ENSO) events, a more detailed discussion of the variabilities would inevitably require a greater amount of background information on these circulation phenomena. We think this topic is beyond the scope and would rather distract from the section's overall focus on obtaining a global overview of the CO_2_seas distribution.

Line 568: "spring to autumn ...", "October": Please indicate that you are referring to the NH(?) and relate the observations to the corresponding subfigures.

We modified the text slightly by including the hemispheric seasons and again refer to the subfigures more often.

"Based on the positive CO_2 seasonal signal associated with the NH late summer maximum at 100 hPa we estimate […]" (Line 585)

"While the positive signal at the tropical tropopause is traveling only slightly upwards from NH spring to NH autumn (see Fig. 9a), an accelerated vertical transport (steeper slope of the isolines) takes place from October onwards." (Line 593)

Line 569: Suggest to explicitly mention that the BDC is stronger in winter

Changes as suggested.

"This is in line with our current understanding of the climatological structure of the tropical upwelling part of the BDC (Randel et al., 2008; Yang et al., 2008), which is stronger in NH winter." (Line 595)

Line 571-574: I have difficulties following this part of the discussion: AMA should, as far as I know, accelerate upwelling and mixing into the stratosphere -- but in NH summer. Why is the ascent starting from January linked to AMA here? Also, in "the transport from the (sub)tropics is likely to be the main origin for this feature", which feature exactly is meant here?

Thank you for your feedback. You are right, AMA should accelerate upwelling and mixing into the stratosphere in NH summer and not in NH winter. We want to state that in principle effects of the Asian monsoon anticyclone might contribute to the CO_2_seas/be visible in the vertical tape recorder image for the NH mid-latitudes (Fig. 9b), as we calculated zonal averages. This was not meant to be related to the description of the ascent of the positive seasonal signal in the first sentence of the paragraph, but more to be a general statement (which is - as you mentioned - most relevant for NH summer).

In the sentence stating that “the transport from the (sub)tropics is likely to be the main origin for this feature”, we are referring to the differences in CO_2_seas propagation patterns, more specifically the faster rise of the negative seasonal signal in NH summer compared to the slower rise of the signal in other seasons (i.e. the positive signal in winter, or even the negative signal in late autumn).

So, we changed the sequence of sentences in this paragraph to clear up the confusion and adjusted the text to be more precise.

“The NH mid-latitude vertical tape recorder image (Fig. 9b) shows an initially slow ascent of the positive seasonal signal from the local tropopause (black line) starting in January, which is followed by a faster rise from late NH spring onwards. The transition to the negative signal, which dominates the source region for this flushing in NH summer, is rapid and therefore this signal seems to propagate much faster upwards in the vertical tape recorder. Even if the effects of the Asian monsoon anticyclone (accelerated upwelling and mixing into the stratosphere during NH summer) might be visible in the presented zonal averages, the described features in CO_2_seas are not necessarily associated with vertical processes exclusively. Instead, the transport from the (sub)tropics is likely to be the main origin for these different propagation patterns. As the flushing of the NH extratropical LMS with tropical air and fast quasi-horizontal mixing across the STJ is larger in summer and autumn, this might also be reflected in a faster rise of CO_2_seas. The change in the propagation of the positive CO_2_seas above the 380 K potential temperature surface (grey line), which is clearly visible from May onwards, suggests that also other (meridional transport) processes are involved, influencing the distribution of the seasonal signal.” (Line 597-607)

Figures

Thank you for your detailed feedback on individual figures or panels. We adopted most of the suggestions and this aided in improving the graphical representation of the results.

Figure 3. Very nice plot clearly showing the agreement between observation and model data.

Subfigure 3e)

- Annotation of UTLS plot in light blue is hard to read; please choose a darker colour.
  Done.
- Spell out "Mean Absolute Deviation" in the figure caption and/or mention again that this is a metric for determining the deviation/similarity between modeled and observed data (not everyone reads the Methods chapter ;)).
  Done. See changed version of the caption in the response to the next comment.
- A legend and additional description in the caption would help to interpret the box plots: Which data range do the coloured boxes cover, which errors are included in the error bars (only standard deviation or including systematic errors?) and what do the open circles mean (outliers?)? Do the vertical lines in the coloured boxes represent the medians?

The data range for the coloured boxplots from the different pressure subsections is already given in the y-label. The representation is a commonly used 'standard' Box-Whisker-Plot. So, we do not add a legend, but as suggested we put information on its different parts to the caption.

*"Comparison of the vertical CO_2 profiles derived from AirCore with the EMAC model output (CO_2_MBL_pbl). Panels (a-d) show four example flights; panel (e) the statistics of the mean absolute deviation (MAD, metric for determining the similarity between simulated and observed data) per profile from all individual flights, either for the total profiles or according to subsets of specific pressure ranges representing the troposphere, UTLS and stratosphere. The boxes of the Box-Whisker-Plot extend from the first quantile to the third quantile with a line at the median. The whiskers include all data points lying within 1.5 times the interquartile range, points are outliers." (*Caption Fig. 3)

Figure 4.

- Please add letters a)...f) to each panel.
  Done.
- Since these are quite many plots: is there a specific reason why you chose to show individual months instead of seasonal averages, which might be better suited to show seasonal differences?
  We chose individual months, because the distribution of the CO_2 seasonal signal varies quite fast over time. Many features would already become blurred in seasonal averages (e.g. using DJF, MAM, etc…).
- In the text discussing the figure, you refer to "8-35 km", while the figure uses a pressure scale. Suggest to add a geometrical height scale to the figure, or change the discussion accordingly.
  We have decided to change the text accordingly and now consistently use pressure as altitude coordinate for EMAC model results discussions (see specific comment regarding Line 365).
- It would help adding theta annotations to the contours in every plot
  We added annotations to every panel but only labelled every second level to avoid overloading the plots.
  also recommend annotating selected wind contours with values, or at least stating the lower threshold in the figure caption. Please also specify in the caption and/or legend whether you considered zonal or horizontal wind speeds.
  We added information about the wind (zonal windspeed) to the legend and the caption (see also next comment).
- Suggest rewording the caption: "...of EMAC CO2 tracer (CO2_MBL_pbl)", "...potential temperature surfaces indicating the UTLS."
  Change as suggested for the former adjustment.
  "Monthly averaged zonal mean latitude-pressure cross section plots of the diagnostic EMAC CO_2 tracer (CO_2_MBL_pbl) for even months of 2019. The black line is the WMO tropopause. Grey contour lines indicate jet positions (zonal wind speed; lower threshold is 20 m s^{-1}, 5 m s^{-1} spacing) and white lines represent selected potential temperature surfaces." (Caption Fig. 4)

Figure 5.

- Red and orange might be difficult to discern for colourblind readers
  We agree that red and orange might be difficult for colour-blind readers to discern. We tested different versions of the plot with other colour schemes and checked them using the Coblis simulator. However,

we found that this representation is still the best compromise, and we would therefore prefer to keep the figure as it is.

- Caption: "...these pressure levels..."
  Done.
- Do the symbols represent individual AirCore flights or averages thereof?
  Each symbol represents the results from an individual AirCore flight (average of the observations of that flight for the specified pressure range). To clarify we changed the caption and the text slightly.
  "Symbols represent AirCore measurements from individual flights for comparable pressure ranges." (Line 418)
  "Temporal evolution (2019-2023) of zonal mean EMAC CO_2_MBL_pbl simulation results (lines) at different pressure levels for the 35° N to 55° N latitudinal band with their standard deviation as shaded areas. Symbols represent AirCore observations from individual flights in the vicinity of these pressure levels (mean over the pressure intervals with standard deviation as error bars)." (Caption Fig. 5)
- Otherwise, trends and seasonal cycle are very well represented here

Figure 6.

- Excellent representation of phase shifts and dampening of seasonal cycle
- Red/green colour contrast might be difficult to read for some users, suggest checking figure with a colourblind simulator or switching to explicitly colourblind-friendly palettes
  We switch to a colourblind-friendly palette.
- Can observations be added to this plot, or would that over-clutter it?
  It would be very nice to compare this plot directly to a CO_2 seasonal signal derived from AirCore measurements and we would have liked to do so. However, 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.

Figure 8.

- Add subfigure letters a)...f)
  Done.
- Consistency: Why are odd months selected here, while even months are shown in Figure 4?
  We agree that it would be in principle better to consistently show the same months in Fig. 4 and in Fig. 8 and include the other months in the supplement. We decided to switch between even and odd months because the relevant features that we want to describe in the corresponding paragraphs are better visible in either even months (e.g. CO_2 reversed gradient in the SH polar middle stratosphere in Fig 4e) or in odd months (meridional CO_2_seas gradient differences between end of NH winter vs. NH summer in Fig. 8b and 8d). We would therefore like to keep the selection of the subplots as it is.
- Please give the time range of the climatology in the caption
  Done (time range is the same as for Fig. 4: 2000-2023).

"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." (Caption Fig. 8)

Technical corrections

Thank you for reading through the manuscript so carefully and for your detailed feedback. All the spelling inconsistencies (British English vs. American English), typos and grammar have been corrected in the revised version of the manuscript.

"WMO tropopause" spells without a dash; please correct throughout the manuscript (also in the figures).

Done.

Throughout the manuscript, "Figure" needs to be spelled out at the beginning of a sentence.

Done.

Lines 181/182, 202, 204, 232 etc.: Reference instead of inline link

We try to reduce the number of inline links. We simply removed the zendo links for the datasets, since the references are already there. The same applies to the CMIP6 boundary conditions. For the other two cases, we would prefer to keep the inline links, as we think this is not uncommon and we will discuss this with the editorial team during further processing of the manuscript.

"Moreover, details on the exact methodology and specifications for each individual AirCore flight is given as part of the NOAA and GUF data sets that are available from Baier et al. (2021) and Degen et al. (2025)." (Line 181)

"The model setup is based on the EMAC CCMI-2022 setup (Jöckel et al., 2024), but with purely Coupled Model Intercomparison Project Phase 6 (CMIP6) boundary conditions for Ozone Depleting Substances and based on the SSP245 scenario after 2014 (Meinshausen et al., 2017, 2020)." (Line 203)

Line 211: corresponds

Done.

Line 233: Spelling: "analysed" is British English, "summarized" American English

We decided to use consistently British English.

Line 321: Suggest using "beneath" instead of "below" to clarify that the considered region is situated below 350 hPa in the sense of altitude, not pressure

Done.

Line 324: Again, characteriZed spelled with z, use either AE or BE

Done (BE).

Line 329: no comma after "... vegetation period"

Done.

Line 335: no comma after "... cases"

Done.

Line 340: No return behind "... UTLS well."

We deleted the return before, as the sentence belongs to the previous paragraph.

Line 341: Despite the fact that...

Done.

Line 345: Suggest rewording for clarity: These vertical shifts also appear for other simulated species...

Changed as suggested.

"These vertical shifts also appear for other simulated species such as CH_4 and can be seen in the temperature profiles or the position of the tropopause." (Line 352)

Line 352: remove comma in "opportunities for analysis, that are"

Done.

Line 381: remove comma after "CO2"

Done.

Lines 414, 415: Suggest writing values with uncertainties like this: (2.44 +/- 0.16) ppm/yr

Done.

Line 435: climatological

Done.

Line 498: simultaneous

Done.

Line 500: remove comma after "both"

Done.

Line 507: The "again" in "definitely more complex again" reads a little awkward here; suggest moving it to the beginning of the sentence: "Again, the short-term variability ..."

Changed as suggested.

"Again, the short-term variability of the CO_2 distribution and of the CO_2 seasonal signal is definitely more complex and cannot be resolved by the global EMAC model." (Line 529)

Line 511: Suggest rewording: "As can be seen from the panels..."

The entire sentence was changed in response to Reviewer #1's reasonable suggestion that the paragraph should not begin by referencing a supplementary figure.

Line 519: "Hadley cell" is spelled without dash

Done.

Lines 517, 522-524 and 541: The parts in brackets disturb the flow; suggest formulating as actual clauses

We rephrased lines 522–524, but we decided to retain the brackets in line 517 with reduced content. The sentence in line 541 was deleted related to a comment from Reviewer #1.

"The impact of the NH, where the near-surface fluctuation range of the seasonal cycle is 5-10 times higher as in the SH (see peak-to-peak amplitude plot in Fig. S7 for details), extends partly to around 40° S." (Line 541)

"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 545)

Line 546: for different latitudes

Done.

References

Engeln, A. von and Teixeira, J.: A Planetary Boundary Layer Height Climatology Derived from ECMWF Reanalysis Data, https://doi.org/10.1175/JCLI-D-12-00385.1, 2013.