Review: CO2 variability and seasonal cycle in the UTLS: Insights from EMAC model and AirCore observational data

Summary

The present work by Johannes Degen et al. studies the distribution and seasonal cycle of CO2 in the upper troposphere-lower stratosphere (UTLS) based on observations as well as model results in the time range of 2000 to 2024. Observational data is obtained via in-situ AirCore measurements; the global distribution of CO2 is simulated using the Atmospheric Chemistry model EMAC using CO2 tracers, from which the seasonal signal is derived. Overall, observed and modeled CO2 mixing ratios agree very well with each other. The CO2 seasonal cycle exhibits a dampening and time lags with altitude, as well as a tilt, which is related to the subtropical transport barrier. Both a vertical and a horizontal (latitudinal) tape recorder are presented, revealing information on the seasonality of the BDC tropical upwelling and shallow branch.

General comments

Relevance and Overall Quality

CO2 is of high relevance to climate studies not only due to its impact on radiative balance, but also as an almost passive tracer, revealing information on large-scale transport through its distribution and via Age of Air. The UTLS is of special importance due to the strong radiative response to changes in its GHG composition. This study provides a unique comparison of highly resolved in-situ measurements of vertical CO2 profiles in the UTLS with global Chemistry Climate Model results, as well as an innovative approach to disentangling the seasonal cycle from trends and other variability modes using model tracers. The presented findings are closely related to the seasonal variability of the BDC and the subtropical jet, rendering this study extremely valuable for understanding global circulation and the composition of the UTLS. Overall, I find the methods, results and discussion in this work outstanding; the manuscript is also well-written and features excellent graphical representations of the data.

Strengths

- The comparison between model and observational data reveals valuable information on detailed vertical profiles, as well as the global distribution of CO2. Both complement each other well, and it is interesting to see how closely they match.
- Thorough comparison between different boundary conditions
- Excellent, clear and original representation of data in plots
- Comprehensive analysis of CO2 seasonal cycle depending on latitude and altitude. Interesting to see a horizontal as well as a vertical tape recorder.
- Results are thoroughly discussed and linked to dynamical processes
- The deseasonalized CO2 tracer is a novel approach to disentangling the seasonal CO2 cycle from long-term trends and interannual variability
- AirCore observations provide composition profiles that are more highly resolved than satellite measurements and reach farther into the stratosphere than aircraft measurements

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

Specific comments

Text

- 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?
- 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.
- 348: With "compared data", do you mean the AirCore observations, since they only cover specific regions? If yes, please clarify that in the text.
- 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).
- 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.
- 371: Could you briefly mention/discuss why this region shows enhanced seasonality?
- 384: Clearer: "contribution of tropical air in the extratropical LMS…" or "export of tropical air into the extratropical LMS…"
- 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.
- 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?
- 390: Which characteristics of the shallow BDC branch (e.g., hemispheric differences and seasonal variability) can you see in your results?
- 399: …the long-term trends and seasonal cycle of CO2 sources and sinks?
- 433-434: refer to panels, e.g., a) and f)
- 436: envelope of the curves in Figure 6a)?
- 442: Please specify in which pressure region the free troposphere lies
- 442-445 and 446-448: Please refer to individual panels; are these sentences discussing Fig. 6a?
- 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.
- 463: By the "findings described above", do you mean the negative residual?
- 472: with decreasing pressure?
- 492: "15 km", please use altitude coordinates consistent with the figure (or add a km scale to the figure).
- 504: What do you mean by "features that are not so pronounced"?
- 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.
- 526: "…in the extratropical LMS throughout all months/seasons…"
- 532: Is this related to Fig. 8?
- 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.
- 544: "its distinctiveness" -> "the distinctiveness of the seasonal cycle"? Suggest rephrasing the sentence for clarity.
- 546: Suggest explicitly mentioning the hemispheric differences

- 563-566: A more detailed description of interannual variabilities would be interesting
- 568: "spring to autumn …", "October": Please indicate that you are referring to the NH(?) and relate the observations to the corresponding subfigures.
- 569: Suggest to explicitly mention that the BDC is stronger in winter
- 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?

Figures

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.
- 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 ;)).
- 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?

4)

- Please add letters a)…f) to each panel.
- 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?
- 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.
- It would help adding theta annotations to the contours in every plot
- I 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.
- Suggest rewording the caption: "…of EMAC CO2 tracer (CO2_MBL_pbl)", "…potential temperature surfaces indicating the UTLS."

5)

- Red and orange might be difficult to discern for colourblind readers
- Caption: "…these pressure levels…"
- Do the symbols represent individual AirCore flights or averages thereof?
- Otherwise, trends and seasonal cycle are very well represented here

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
- Can observations be added to this plot, or would that over-clutter it?

8)

- Add subfigure letters a)…f)
- Consistency: Why are odd months selected here, while even months are shown in Figure 4?
- Please give the time range of the climatology in the caption

Technical corrections

- "WMO tropopause" spells without a dash; please correct throughout the manuscript (also in the figures).
- Throughout the manuscript, "Figure" needs to be spelled out at the beginning of a sentence.

- 181/182, 202, 204, 232 etc.: Reference instead of inline link
- 211: corresponds
- 233: Spelling: “analysed” is British English, “summarized” American English
- 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
- 324: Again, characteriZed spelled with z, use either AE or BE
- 329: no comma after “… vegetation period”
- 335: no comma after “… cases”
- 340: No return behind “… UTLS well.”
- 341: Despite the fact that…
- 345: Suggest rewording for clarity: These vertical shifts also appear for other simulated species…
- 352: remove comma in “opportunities for analysis, that are”
- 381: remove comma after “CO2”
- 414, 415: Suggest writing values with uncertainties like this: (2.44 +/- 0.16) ppm/yr
- 435: climatological
- 498: simultaneous
- 500: remove comma after “both”
- 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 …”
- 511: Suggest rewording: “As can be seen from the panels…”
- 519: “Hadley cell” is spelled without dash
- 517, 522-524 and 541: The parts in brackets disturb the flow; suggest formulating as actual clauses
- 546: for different latitudes