Spatiotemporal patterns of the fossil-fuel CO_2 signal in central Europe: Results from a high-resolution atmospheric transport model

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We would like to thank the reviewer for the efforts to review this manuscript and the thoughtful comments and remarks. All of the referee's comments have been carefully examined and addressed in the revised manuscript.

Referee #1

General comments:

My main concern is related to the description/handling of the background contribution (L212-217) as derived from the CarbonTracker data set and used to prescribe the boundaries. Do you use mixing ratios or fluxes at these boundaries? Because CarbonTracker data contains CO2 mixing ratios for sources within and without your model domain (which is central and southern Europe) I have a feel- ing that your boundary conditions contain both information although the CO2 contribution from the inside should be resolved by your model. I am not sure but it looks like for the boundary conditions you would take into account the "same type of information" twice: from your simulation and from the CarbonTracker data. At least, would be good to have a more detailed description, how you handle bound- ary conditions and especially this point.

Authors: We thank the reviewer for this comment and the associated questions, as our description of our handling of the boundary conditions was indeed not detailed enough. This will be rectified in the revised version.

Concretely, we are using a relaxation boundary condition for all tracers, although with slightly different details depending on whether the tracer enters the domain from the outside (e.g., the background CO_2) or whether it has sources and sinks inside

the domain (e.g., the different fossil fuel tracers and the terrestrial biosphere CO_2). In the former case, i.e., for the background CO_2, we are using a "full" relaxation boundary condition. This means that we are restoring the modeled mixing ratio toward the value provided by CarbonTracker across a transition zone, with the relaxation increasing in strength from the inner to the outer border of this zone. In COSMO, this option is provided by the "T_RELAX_FULL" switch. In the latter case, i.e., for fossil fuel and the biosphere CO_2, we are using a partial relaxation. In this case, the tracer is relaxed to the boundary condition only at the outermost grid cells of the domain and only when the wind is directed toward the inside of the domain (in COSMO, this option is provided by the switch "T_RELAX_INFLOW"). Through this option, we avoid creating a situation where the zero concentration boundary condition is propagated (erroneously) against the flow back into our domain. While we consider this partial relaxation to be the better option for our fossil fuel and biosphere tracers, we suspect at the same time that the impact of this choice is relatively small, i.e., that the results would not differ much had we selected the full relaxation option, because the domain is large in comparison to the transition zone.

Our choice of boundary condition coupled with our separating the total CO_2 into its different components has indeed some implications for the "double counting" that the reviewer correctly identifies as an issue to pay attention to. In an ideal case, we would have run the same set of tracers in both the global CarbonTracker and the regional COSMO simulations with two way coupling, as this would not have caused any inconsistencies at all. In our one-way coupling mode plus CarbonTracker incorporating also the fossil fuel signal from Europe into its background, there is indeed a chance for a mismatch between what is considered "background" and what is considered a "fossil fuel signal". This becomes evident when considering an air parcel containing a fossil fuel signal from within Europe to leave the domain and then to return back into our domain. In such a case the fossil fuel signal loses its identity by leaving the domain, and becomes a background signal in CarbonTracker's modeling the region outside of Europe. This signal would then enter the domain again as a background signal through our restoring the background CO_2 toward CarbonTracker's results. Thus, our handling of the boundary conditions does not lead to a double counting, but a potential underestimation of the total fossil fuel signal and a potential overestimation of the background CO2.

In response, we added the following texts to the methods

"At the lateral boundaries, we employ a partial relaxation boundary condition for these 17 tracers. In such a partial relaxation, the tracer is relaxed to the boundary concentration only at the outermost grid cells of the domain and only when the wind

is directed toward the inside of the domain (in COSMO, this option is provided by the switch "T_RELAX_INFLOW"). Since we are interested in the fossil fuel signal emanating from emissions in Europe only, the lateral boundary concentration was set to zero. Through this option, we avoid creating a situation where the zero concentration boundary condition is propagated (erroneously) against the flow back into our domain."

"[...]For this tracer, we use a "full" relaxation boundary condition. This means that we are restoring the modeled mixing ratio toward the value provided by CarbonTracker across a transition zone consisting of around 13 grid cells, with the relaxation increasing in strength from the inner to the outer border of this zone. In COSMO, this option is provided by the "T_RELAX_FULL" switch."

"[...] The lateral boundary conditions for these two tracers were handled the same way as those for the fossil fuel signal, i.e., a partial relaxation toward a zero concentration at the boundary."

Specific comments:

1.L14 "...their co-variance leads to a fossil-fuel diurnal rectifier.." –

For "no-experts" difficult to understand.

Authors: We changed the sentence to "The covariance of the fossil fuel emissions and atmospheric transport on diurnal timescales leads to a diurnal fossil-fuel rectifier effect as large as 9 ppm compared to a case with time-constant emissions.."

2.L82 Maybe you should explain with 1-2 sentence what is "rectification".

Authors: To make it clearer, we extended our explanation to " Of particular relevance are the diurnal and the seasonal changes in emissions, since they tend to co-vary with atmospheric transport, which can lead to annual mean atmospheric CO_2 concentration gradients that differ from those attained if the emissions were held constant. This difference, which arises solely from the co-variation between fluxes and transport, is called a "rectification effect" in analogy to the rectification of an AC voltage in an electrical circuit by a diode ".

3. *L113 You mean "potentially reduced emissions".*

Authors: Yes. Changed to "potentially reduced emissions"

4. *L155-57 It would be nice to understand this formula without checking other literature. What is K? I think K should be the highest level of the model ?. Would be good to have this formula as a separate equation.*

Authors: K is the total number of vertical model levels (K=60). We added this explanation and also formatted the equation now as a separate equation in the text.

5. *L349 Maybe: "by the diurnal and seasonal variations" and remove the last part of the sentence.*

Authors: The objective of the sentence is to demonstrate the importance of the diurnal transport. Thus, we prefer to make no change to the sentence.

6. *L385 ...uniform negative distribution for XCO_2 in Fig. 6c contrasts...*

Authors: Done.

7. *L445 ...in particular, what is the contribution of diurnal (and seasonal)...*

Authors: Done.

8. *L490 ...Figure Fig....*

Authors: Done

9. *L724 "...up to 110%...". Not clear what does it exactly mean. Please explain.*

Authors: We rephrased this sentence to:

"In some places, it even contributes significantly to the total (including background) CO2, particularly in large urban centers and along power plant plumes."

10. *Figure 4 Figure 4a shows the anomaly and not the absolute value. You should explain how this anomaly is defined (in caption and main text). Same for Figure 4b. Figure 4d does not show any structure (maybe you should change the color bar). It is not clear for me what should I see. Impact of the boundaries on the main*

domain of your model? See also my major point.

Authors: This must be a misunderstanding, since Figures 4a (fossil fuel component) and c (biosphere) are showing the actual (absolute) value of these components and not their anomalies. The confusion might emerge from the way the lateral boundary conditions are set for these two tracers, i.e., they are set to zero, as their variations reflect just the sources minus sinks within the domain. We hope that our response and changes to the text in response to the major comment by this reviewer takes also care of this comment.

Figure 4d shows the "background CO_2" component, i.e., that part of the variation in the total CO_2 that is determined through the lateral boundary conditions. We use the same color scale for both panels b and d to show that the variations imprinted by the background has a small impact on the spatial pattern of the total CO_2 concentration within the domain.

11. *Figure 5 Please add notation: a), b), c) d).*

Authors: Done.

12. *Figure 6 Please explain/define the anomalies*

Authors: The same as Figure 4. These panels show the actual (absolute) values, not the anomalies. Again, we hope that our additional text in response to the main comment by this reviewer clarifies this issue.

13. *Figure 8 Please add that all panels are for the surface layer (10m)*

Authors: We modified the figure caption to read " Maps of the contribution of fossil fuel CO2 variability to total atmospheric CO2 variability within the lowest model layer (0-20 m, center at 10 m) on various timescales in percent."

14. *Figure 9 There are some lines which look like ship connections. Maybe you would like to explain it.*

Authors: These lines are indeed due to the fossil fuel emissions stemming from marine transportation. A comment was added to the caption to this effect:

"The negative correlations over the ocean stem from the fossil fuel emissions by ships."

15. *Figure 11 This figure is not mentioned in the text. Also you write sometimes "Figure" and sometimes "Fig."*

Authors: We changed Fig. into Figure throughout the manuscript. Figure 11 is actually discussed in the text, but we were erroneously referring to Figure 10 instead of Figure 11. This was fixed.

16. *Figure 13a There are enhanced values in north-east (over the North Sea). Maybe you should explain this feature in the text.*

Authors: We added the following text:

"Owing to the dominance of this mode of electricity production in northern Europe, this signal is particularly strong there. This is most evident over the North Sea, where the advection of the emitted CO_2 from the power plants in the UK and the Netherlands creates a particularly visible plume over the ocean."