

Reply on RC1

Antje Hoheisel et al.

Author comment on "Comparison of atmospheric CO, CO₂ and CH₄ measurements at the Schneefernerhaus and the mountain ridge at Zugspitze" by Antje Hoheisel et al., Atmos. Meas. Tech. Discuss., <https://doi.org/10.5194/amt-2022-298-AC1>, 2023

General Comments:

- [Referee #1] The authors attribute the CO₂ spikes to anthropogenic contamination, namely in the abstract. Is it possible to attribute those spikes only to anthropogenic sources? Or the complex topography and/or wind patterns may also play an important role as mentioned (Lines 259-260). Maybe that the authors should stress the difficulty they encountered when disentangling both processes.
[Hoheisel et al.] Thank you for pointing this out. The CO₂ spikes, which are then flagged by the station manager, are most certainly caused by local anthropogenic sources such as snow cats, snow blowers and humans. In addition to these identifiable CO₂ spikes, we can observe a difference in CO₂ levels between the mountain ridge and Schneefernerhaus in the data (especially in the mean diurnal cycles). This difference occurs especially during the day and in winter. As discussed in chapter 3.5 and 3.6, we cannot clearly explain the underlying cause of this difference. The most likely scenarios are that the known local CO₂ sources (in this case anthropogenic) cause the increase and their influence could not be completely removed by filtering the peaks, as the influence is not recognisable as spikes. On the other hand, the fact that the elevation occurs mainly in winter during the day also suggests that CO₂-enriched air is transported from the valley to the Schneefernerhaus and that, due to the elevated position of the mountain ridge and the complicated topography, the mixing is not large enough to reach the mountain ridge. In the second consideration, most of the additional CO₂ comes from more regional CO₂ sources. These could be, for example, anthropogenic emissions from heating.
- [Referee #1] Data flagging: I understand that CO and CH₄ spikes can be easily flagged (essentially due to snow clearing); however, how are the CO₂ spikes manually flagged? Except for scientists working on the terrace, is there any other CO₂ contamination flagged? Is it possible to quantify the influence of scientists working on the terrace?
[Hoheisel et al.] CO, CH₄ and CO₂ spikes, are in principle flagged in the same way. For this purpose, as described in chapter 2.4, the station manager uses meteorological data, other trace gases such as NO and NO₂ and the station logbook in which, for example, work at Schneefernerhaus and on the measurement terrace is recorded. In addition to CO₂ spikes caused by scientists and workers, CO₂ contamination also occurs during the use of snow clearing equipment.
- [Referee #1] The paper would benefit in general from a few more appropriate references. As for instance in Section 3.6.
[Hoheisel et al.] We added a few addition references on different sections of the paper. However, in section 3.6 we only discuss the CO₂ data of Schneefernerhaus and the

mountain ridge, which we measured in this study. Therefore, we see no need for additional references here.

- [Referee #1] The figure captions could be extended with more detailed information so that we can understand them alone.
[Hoheisel et al.] We appreciate the recommendation and we have improved and expanded the figure captions so that they can be understood on their own.

Detailed Comments and Questions:

- [Referee #1] Lines 17-18: Add countries to station's name
[Hoheisel et al.] We included the countries to the station's name and as suggested by Referee#2 also references for the cited stations. We changed the sentence to:
"Historically, most measurement stations are located on coasts, such as Mace Head, Ireland (Bousquet et al., 1996), island mountains, such as Mauna Loa, Hawaii (Keeling et al., 1976) or Izana, Spain (Navascues and Rus, 1991; Gomez-Pelaez et al., 2019) or continental mountains, such as Mount Cimone, Italy (Ciattaglia, 1983), Jungfraujoch, Switzerland (Sturm et al., 2005; Schibig et al., 2016) or Schauinsland, Germany (Schmidt et al., 2003)."
- [Referee #1] Line 37: and tourism
[Hoheisel et al.] Unfortunately, the intention of this comment is not entirely clear to us. The second part of the sentence of line 37 is:

"..., such as Pic du Midi, where a small sewage treatment facility near the air intake of the analyser causes local CH₄ peaks (El Yazidi et al., 2018), or Jungfraujoch, where the CO₂ measurement shows an influence of local anthropogenic activities, potentially by visitors and tourism (Affolter et al., 2021)."

- [Referee #1] Lines 41-42: Is there a local reference paper? You may want to cite Bukowiecki et al., 2021. DOI 10.1088/2515-7620/abe987
[Hoheisel et al.] Thanks to the comment, we realised that we had not expressed ourselves clearly in the manuscript. With the sentence in lines 41-42, we did not intend to make a general statement, but to draw attention to the influence of snow groomers and gasoline snow blowers that we found in the Schneefernerhaus data, which in our case are noticeable as CO peaks. We changed the sentence to: *"In particular, in winter, snow groomers and gasoline snow blowers lead to strong CO peaks in the Schneefernerhaus time series, which must be flagged manually to prevent an influence on the records."*
- [Referee #1] Line 44: Isn't it 126 m higher?
[Hoheisel et al.] We have checked the difference in altitude between mountain ridge and Schneefernerhaus again. The actual sampling altitude at the mountain ridge is 2825m a.s.l. and the sampling altitude at Schneefernerhaus for CO, CO₂ and CH₄ is 2669 m a.s.l. Thus, we came up with 156m. Since ²²²Rn at Schneefernerhaus is not measured with the same intake line than CO, CO₂ and CH₄ and the exact elevation of the intake at the mountain ridge probably changed since 2014, after a new intake line was installed, we have relativised the sentence to:
"Therefore, since 2014 they have used an ambient air inlet at the mountain ridge approximately 150m uphill Schneefernerhaus for their measurements of ²²²Rn (Frank et al., 2017)."
- [Referee #1] Line 61: You mention an elevation of 2669m a.s.l. for the air inlet located at the 5th floor. In the abstract, you mention an elevation of 2666m a.s.l. for the station. Is it correct?
[Hoheisel et al.] We have checked the elevations again. The air inlet for the CO, CO₂ and CH₄ measurements at Schneefernerhaus is installed at the research terrace on the fifth floor at an elevation of 2669 m above sea level. The Schneefernerhaus altitude is

given as 2650 m above sea level, so we changed the value in the abstract. The former value of 2666m a.s.l. we had written in the abstract is the elevation of the Schneefernerhaus lab, where CO, CO₂ and CH₄ are measured.

- [Referee #1] Lines 63-64. A reference is missing here. Or you mean that it is shown in this paper?

[Hoheisel et al.] Yes, we meant that it is shown in our paper. To clarify, we changed "The analysis" to "Our analysis" in line 63.

- [Referee #1] Lines 73-74: add ZSF and ZGR. Throughout the text you mostly use "Schneefernerhaus" and only a few times "ZSF" (for instance lines 110, 112, 154). Stick maybe to "Schneefernerhaus". The same with "mountain ridge" and sometimes "ZGR" (lines 110,111).

[Hoheisel et al.] Thank you, we had not noticed that before. We have now tried to stick to the words "Schneefernerhaus" and "mountain ridge". However, in some cases it is necessary to give more precise information, such as "ZSF QC", in order to clarify exactly which dataset is being used.

- [Referee #1] Lines 164-166. Can you mention the restriction? Did it lead to the cease of tourism for a while? It could also be interesting to show on Fig. 2 from when to when these restrictions occurred. The covid pandemics could possibly be discussed and used in this study to a greater extent, as it is supposed to have noticeably reduced pollution events.

[Hoheisel et al.] Yes, tourism on the Zugspitze was temporarily suspended and work at Schneefernerhaus and the ski resort was reduced to a minimum. During the COVID-19 pandemic restrictions at the time of our comparison measurements, it was unfortunately not possible for us to measure CO in the ambient air of Schneefernerhaus, as our measuring device was being validated at the ICOS Atmosphere Thematic Centre (ATC) Metrology Laboratory as part of the ICOS labelling process at that time. Therefore, we were not able to carry out an evaluation of the influence of the restriction on our measurements as detailed as we had hoped. Instead of CO, we thus examined NO₂ and CO₂ and were able to determine a reduced occurrence of spikes in the measured time series. Later restrictions at the Zugspitze, which no longer fall within the time frame of our comparison measurements, also showed a lower number of CO peaks at the Schneefernerhaus due to the restrictions. However, as these measurements are not part of our comparison measurements, we have decided to discuss the effects of the COVID-19 restrictions only briefly. We have revised the relevant section again to avoid inconsistencies and misunderstandings.

"In 2020, the COVID-19 pandemic led to temporary restrictions on tourism at Zugspitze and a reduction in work at Schneefernerhaus and the ski resort. Unfortunately, our CO analyser for ambient air from Schneefernerhaus was being validated at the ICOS ATC Metrology Laboratory as part of the ICOS labelling process at that time. Instead, we analysed NO₂ measured at Schneefernerhaus. Especially for NO₂ but also for CO₂ a decrease in the occurrence of NO₂ and CO₂ peaks was observed in the measured time series at Schneefernerhaus, indicating a reduction of local pollution events."

- [Referee #1] Line 170: Is it a CH₄ reverse "spike" or more generally a longer excursion?

[Hoheisel et al.] Yes, these are reverse/inverse CH₄ spikes as explained in more detail in section 3.3 and are shown in Figure 4.

- [Referee #1] Line 205: "to the QC datasets reported to national and international databases". Not clear, precise.

[Hoheisel et al.] Yes, we have excluded this sentence in the text and added another one in section 2.4 for better understanding.

"The half-hourly, hourly, daily and monthly averages of CO, CO₂ and CH₄ mole fractions at Schneefernerhaus reported to national and international databases such as the World Data Centre for Greenhouse Gases (WDCGG) are also based on one-minute averaged data where local pollution events have been flagged as invalid in addition to artefacts and outliers."

- [Referee #1] Lines 264-265: Shouldn't it then be explained by other mechanisms

compared to Jungfrauoch?

[Hoheisel et al.] We have probably not been entirely clear in this section. In the paragraph above lines 264-265 we discussed our observations and their causes at Schneefernerhaus. Then, as a comparison, we refer to the observations as well as their causes at Jungfrauoch. We have now made minor changes in the text to make this clearer. The last sentence should then highlight the differences between the influences at the Zugspitze and at the Jungfrauoch.

"Other mountain stations also show local influences, which depend on the season and time of day. At Jungfrauoch, the diurnal cycle of CO₂ between measurements at the usual location and a less polluted site deviate up to 0.4ppm in winter and up to 1.3ppm in summer (Affolter et al., 2021). Thus, the CO₂ measurement at Jungfrauoch is more strongly influenced in summer, which is probably due to the larger number of tourists. At Schneefernerhaus, on the other hand, the strongest influence was observed in winter."

- [Referee #1] Lines 267-268: Are there other possible explanations?

[Hoheisel et al.] We have changed the paragraph slightly in order to clarify our statement. The CO and CO₂ spikes found in the time series at Schneefernerhaus are most certainly caused by local anthropogenic sources such as snow cats, snow blowers and humans.

"In this study, a more frequent occurrence of CO and CO₂ spikes during the day was found, which can be attributed to anthropogenic activities. In addition to the diurnal dependence, these local pollution events also have a week dependence. Thus, 92% of the data points that were manually excluded due to local pollution occur on weekdays and not on weekends."